International Field Validation of CALMIM: A Site-Specific Process-Based Model for Landfill Methane (CH_4) Emissions Inclusive of Seasonal CH_4 Oxidation

J. Bogner[1], K. Spokas[2], and M. Corcoran[3]

[1]*Dept. of Earth & Environ. Sciences (EAES), Univ. of Illinois at Chicago (UIC), Chicago, IL*

[2]*Agricultural Research Service, U.S. Dept. of Agriculture (ARS-USDA), St. Paul, MN*

[3]*Graduate student EAES-UIC, now U.S. EPA, Region 5, Chicago, IL*

Contact: Jean E. Bogner, Research Professor, Dept. of Earth & Environmental Sciences (EAES), University of Illinois at Chicago (UIC), 2440 SES (Science & Engineering South), MC 186, 845 W. Taylor, Chicago IL 60607-7059

jbogner@uic.edu, 630-915-8872 (mobile)

KEYWORDS: greenhouse gas inventory, climate change, methanotrophy, soil gas transport, soil gas processes.

FINAL REPORT

Prepared for the

Environmental Research and Education Foundation

EREF

July, 2014

Table of Contents

TABLE OF CONTENTS ..... **II**

LISTING OF FIGURES ..... **IV**

LISTING OF TABLES ..... **VII**

1. EXECUTIVE SUMMARY **1**

2. INTRODUCTION **5**

2.1. BACKGROUND AND OBJECTIVES 5
2.2. HISTORICAL PERSPECTIVE 8
2.3. NEW CALIFORNIA DATASET: EXAMINING THE APPLICABILITY OF THE FIRST ORDER DECAY (FOD) MODEL FOR LFG GENERATION AND RECOVERY. 20
2.4. JUSTIFICATION FOR CALMIM MODEL DEVELOPMENT AND IMPLEMENTATION 23

3. METHODS **25**

3.1. CALMIM OVERVIEW AND IMPROVEMENTS DURING EREF PROJECT 26
3.1.1. Model Structure and Components *26*
3.1.2. Overview of Model Structure and Site-Specific Inputs *31*
3.2. DIRECT COMPARISON OF CALMIM MODEL RESULTS TO FIELD MEASUREMENTS OF LANDFILL CH_4 EMISSIONS FROM U.S. AND INTERNATIONAL RESEARCH GROUPS 32
3.3. LATITUDINAL GRADIENT FOR LANDFILL CH_4 EMISSIONS USING CALMIM SIMULATIONS FOR STANDARDIZED COVER SOILS. 37
3.4. CALMIM SIMULATIONS FOR LANDFILL CH_4 EMISSIONS UNDER FUTURE CLIMATE CHANGE SCENARIOS FOR SELECTED GLOBAL CITIES (SRES SCENARIOS A2 AND B1 FOR 2020, 2050, AND 2100). 39
3.5. FIELD PROJECT, INDIANA LANDFILL. 42
3.6. NEW 2010 CALIFORNIA GHG INVENTORY USING CALMIM AND SITE-SPECIFIC COMPARISONS TO CALIFORNIA FIELD MEASUREMENTS. 45

4. RESULTS AND DISCUSSION **47**

4.1. SPECIFIC CALMIM IMPROVEMENTS DURING EREF PROJECT TIMELINE (2011-2013). 47
4.1.1. Overall Program Enhancements: *47*
4.1.2. Specific Program Improvements *48*
4.2. DIRECT COMPARISON OF CALMIM MODEL RESULTS TO FIELD MEASUREMENTS OF LANDFILL CH_4 EMISSIONS FROM U.S. AND INTERNATIONAL RESEARCH GROUPS. 53
4.2.1. Overview of measured vs. modeled results *53*
4.2.2. Overview of techniques and historic results for field measurement of landfill CH_4 emissions. *56*
4.2.3. Site-specific results *59*
4.3. LATITUDINAL GRADIENT FOR LANDFILL CH_4 EMISSIONS USING CALMIM SIMULATIONS FOR STANDARDIZED COVER SOILS. 66
4.4. CALMIM SIMULATIONS FOR LANDFILL CH_4 EMISSIONS UNDER FUTURE CLIMATE CHANGE SCENARIOS FOR SELECTED GLOBAL CITIES 84
4.5. FIELD PROJECT - INDIANA LANDFILL 94
4.5.1. May and August, 2012 field campaigns to quantify CH_4 and O_2 soil gas concentration gradients and variability for daily and intermediate cover soils *94*

4.5.2. Comparison of default and custom data entry for CALMIM modeling: How are CALMIM modeled CH_4 emissions with and without oxidation affected by the differing soil gas profiles? *100*
4.6. NEW 2010 CALIFORNIA GHG INVENTORY USING CALMIM AND SITE-SPECIFIC COMPARISONS TO CALIFORNIA FIELD MEASUREMENTS. 103
4.6.1. 2010 CALMIM California GHG Inventory *103*
4.6.2. Spatial distribution of CALMIM predictions *106*
4.6.3. Factors influencing CALMIM predictions *113*

5. CONCLUSIONS AND RECOMMENDATIONS **124**

5.1. GENERAL TECHNICAL CONCLUSIONS AND RECOMMENDATIONS FOR USING CALMIM. 124
5.2. HOW TO USE CALMIM *127*
5.3 SUGGESTIONS FOR FUTURE WORK *128*

6. ACKNOWLEDGEMENTS **129**

7. REFERENCES **130**

VIII. APPENDICES **141**

APPENDIX A. USER MANUAL FOR CALMIM MODEL 141
1.0 INTRODUCTION 144
2.0 INSTALLATION GUIDE 147
3.0 MAIN SCREEN 157
4.0 SITE LOCATION/MAPS & TOTAL AREA SCREENS 161
5.0 SITE PROPERTIES PANEL 164
6.0 COVER EDITOR PANEL 171
8.0 MODEL CALCULATION SCREEN 188
9.0 FINAL RESULTS SCREEN 189
10.0 CHANGE LOG 201
APPENDIX B. REPRINT OF : 209
APPENDIX C. LIST OF PROJECT DELIVERABLES GENERATED AT THE TIME OF FINAL REPORT SUBMISSION 263
APPENDIX D. SUPPORTING INFORMATION THAT IS NOT APPROPRIATE TO INCLUDE IN MAIN REPORT (E.G. ADDITIONAL TABLES, FIGURES, RAW DATA, ETC.) 266
Table D.1. Individual Site Reports Comparing Field Measurements to Modeled Results Using CALMIM Version 5.4 ..... *267*
Table D-2 CALMIM modeling results *391*
Table D-3. Comparison of the top ten CALMIM emitting California sites *404*
Table D-4. Comparison of the top ten CARB emitting California sites. *405*

Listing of Figures

FIGURE 1.COMPARISON OF 2010 CALMIM LANDFILL CH4 EMISSION INVENTORY TO 2010 CALIFORNIA RESOURCES BOARD (CARB) INVENTORY. 1
FIGURE 2. RELATIONSHIP BETWEEN WASTE IN PLACE (1 T = 1000 KG = 1 MG) AND AVERAGE ANNUAL TOTAL LANDFILL GAS RECOVERY RATE (A) ALL FOR 129 CALIFORNIAN SITES USING DATA FROM CALRECYCLE (WALKER, 2012) AND (B) SAME DATA WITH PUENTE HILLS LANDFILL DATA POINT OMITTED (HIGH OUTLIER). 21
FIGURE 3. RELATIONSHIP BETWEEN WASTE IN PLACE (1 T = 1000 KG = 1 MG) AND TOTAL LANDFILL METHANE RECOVERY RATE FOR ONLY THE SITES IN THE CALIFORNIA DATABASE (WALKER, 2012) WHERE THE CH_4 CONCENTRATION WAS GIVEN (VALUES BETWEEN: 5-57%) AND WITH THE PUENTE HILLS DATA POINT REMOVED. 22
FIGURE 4. EFFECTS OF SOIL TEMPERATURE ON RELATIVE RATES OF CH4 OXIDATION [FIGURE TAKEN FROM SPOKAS AND BOGNER (2011)]. 27
FIGURE 5. EFFECT OF SOIL MOISTURE CONTENT ON RELATIVE RATES OF CH_4 OXIDATION AS A FUNCTION OF SOIL TEMPERATURE (A) <5^{O}C, (B) 5-40^{O}C, AND (C) >40^{O}C. [FIGURE TAKEN FROM SPOKAS AND BOGNER (2011)]. 27
FIGURE 6. LOCATION OF THE GLOBAL SITES USED IN THE CALMIM VALIDATION STUDY. 36
FIGURE 7. LATITUDINAL STUDY USING CALMIM. 38
FIGURE 8. SUMMARY OF SRES SCENARIOS [IMAGE TAKEN FROM TECHNICAL SUMMARY, IPCC 3RD ASSESSMENT REPORT, WORKING GROUP III: MITIGATION (BANURI ET AL., 2001)]. 41
FIGURE 9. PHOTO OF STAINLESS STEEL FLUX CHAMBER USED FOR INDIANA FIELD PROJECT 43
FIGURE 10. PHOTO OF THE GC-MS SYSTEM (PERKIN-ELMER MODEL 600T GAS CHROMATOGRAPH-MASS SPECTROMETER) USED TO ANALYZE THE INDIANA FIELD GAS SAMPLES IN THE USDA-ARS LABORATORY IN ST. PAUL, MN. 44
FIGURE 11. IMPROVEMENTS IN CALMIM MAIN MENU SCREENS. 47
FIGURE 12. IMPROVEMENTS IN CALMIM SITE SELECTION SCREENS 48
FIGURE 13. OVERLAYING OF SATELLITE IMAGERY TO IMPROVE LANDFILL SITE SELECTION. 48
FIGURE 14. SELECTION BOX FOR NEW MAP TILE SERVERS NOW AVAILABLE IN CALMIM. 49
FIGURE 15. IMPROVEMENTS IN CALMIM WIZARD PROGRESS BUTTONS. 50
FIGURE 16. OUTPUT EXCEL^{TM} FILES FOR EACH CALMIM RUN. 50
FIGURE 17. ILLUSTRATION OF CALMIM ON-LINE HELP SYSTEM. 51
FIGURE 18. EXAMPLE ILLUSTRATION OVERLAYING MEASURED FIELD DATA ON PREDICTED CALMIM RESULTS FOR AN INTERMEDIATE COVER AREA AT A SOUTH AFRICAN LANDFILL, ALONG WITH THE ANNUAL CYCLES FOR AIR TEMPERATURE, PRECIPITATION, AND PREDICTED DIFFUSIVE CH4 EMISSIONS WITH AND WITHOUT OXIDATION. 54
FIGURE 19. DIRECT COMPARISON OF CALMIM MODEL RESULTS TO FIELD MEASUREMENTS FOR (A) DEFAULT MODEL PARAMETERS VERSUS MEASURED EMISSIONS FOR MODELED EMISSIONS WITH OXIDATION, (B) DEFAULT MODEL PARAMETERS FOR EMISSIONS WITHOUT OXIDATION FLUX VERSUS MEASURED EMISSIONS, (C) SITE-SPECIFIC SITE SOIL GAS PROFILE FOR EMISSIONS WITH OXIDATION VERSUS MEASURED EMISSIONS, AND (D) SITE-SPECIFIC SOIL GAS PROFILE FOR MODELED EMISSIONS VERSUS MEASURED EMISSIONS. 63
FIGURE 20.OVERALL MEAN AND STANDARD DEVIATIONS FOR ALL THE SITE COMPARISONS CONDUCTED IN THIS REPORT (SEE APPENDIX A). OVERALL, THERE WAS NO STATISTICAL DIFFERENCE BETWEEN THE FIELD AND MODEL AVERAGES BY COVER TYPE ACROSS ALL THE SITES (N=104). FOR THE INTERMEDIATE COVER, THE OVER-PREDICTION OF CALMIM IS RELATED TO THE INCLUSION OF VERY THIN AND "NO COVER" SIMULATIONS IN THE COMPARISON DATA SETS. 64
FIGURE 21. METHANE EMISSIONS FOR A GLOBAL LATITUDINAL COMPARISON USING CALMIM. 67
FIGURE 22.RELATIONSHIP BETWEEN AVERAGE ANNUAL CH_4 EMISSIONS WITH OXIDATION FOR GLOBAL LATITUDINAL SITES AND (A) AVERAGE ANNUAL PRECIPITATION, (B) AVERAGE ANNUAL AIR TEMPERATURE INCLUDING THE 3 DRIEST SITES, AND (C) AVERAGE ANNUAL TEMPERATURE EXCLUDING THE 3 DRIEST LOCATIONS. 69
FIGURE 23.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +70 ^{O}N (NORWAY). 71
FIGURE 24.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +60 ^{O}N (FINLAND). 72
FIGURE 25.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +50 ^{O}N (VANCOUVER, CANADA). 73

FIGURE 26.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +40 ^{O}N (REDDING, CALIFORNIA). 74
FIGURE 27. TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +30 ^{O}N (ENSENADA, MEXICO). 75
FIGURE 28.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +20 ^{O}N (PUERTO VALLARTA, MEXICO). 76
FIGURE 29.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +10 ^{O}N (PUNTARENO, COSTA RICA). 77
FIGURE 30.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT +0 ^{O}N (MACAPA, BRAZIL)....78
FIGURE 31.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT -10 ^{O}N (HUACHO, PERU). 79
FIGURE 32. TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT -20 ^{O}N (IQUQUE, CHILE)....80
FIGURE 33.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT -30 ^{O}N (COQUIMBO, CHILE)....81
FIGURE 34. TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT -40 ^{O}N (VALDIVIA, CHILE)....82
FIGURE 35.TYPICAL ANNUAL CYCLE FOR EMISSIONS, PRECIPITATION, AIR TEMPERATURE, SOIL GAS PROFILE, SOIL MOISTURE, AND SOIL TEMPERATURE FOR THE LOCATION AT -50 ^{O}N (RIO GALLEGOS, ARGENTINA). 83
FIGURE 36.LULEA, SWEDEN. (A) IMPACT OF CLIMATE CHANGE A2 SCENARIO ON LANDFILL METHANE EMISSIONS WITH OXIDATION, (B) THE CORRESPONDING PERCENT CH_4 OXIDATION FOR THE A2 SCENARIO, (C) IMPACT OF SCENARIO B1 ON LANDFILL EMISSIONS WITH OXIDATION AND THE (D) CORRESPONDING PERCENT CH_4 OXIDATION. 85
FIGURE 37.CAIRO, EGYPT. (A) IMPACT OF CLIMATE CHANGE A2 SCENARIO ON LANDFILL METHANE EMISSIONS WITH OXIDATION, (B) THE CORRESPONDING PERCENT CH_4 OXIDATION FOR THE A2 SCENARIO, (C) IMPACT OF SCENARIO B1 ON LANDFILL EMISSIONS WITH OXIDATION AND THE (D) CORRESPONDING PERCENT CH_4 OXIDATION. 87
FIGURE 38.RESULTS OF CLIMATE SCENARIO A2 MID-DEPTH SOIL MOISTURE (V/V) AND SOIL TEMPERATURE [C] OVER THE ANNUAL CYCLE FOR CAIRO SAND SIMULATIONS FOR SRES SCENARIOS A2 (A AND B) AND B1 (C AND D). 88
FIGURE 39.MACAPA, BRAZIL. (A) IMPACT OF CLIMATE CHANGE A2 SCENARIO ON LANDFILL METHANE EMISSIONS WITH OXIDATION, (B) THE CORRESPONDING PERCENT CH_4 OXIDATION FOR THE A2 SCENARIO, (C) IMPACT OF SCENARIO B1 ON LANDFILL EMISSIONS WITH OXIDATION AND THE (D) CORRESPONDING PERCENT CH_4 OXIDATION. 90
FIGURE 40.CAPE TOWN, SOUTH AFRICA. (A) IMPACT OF CLIMATE CHANGE A2 SCENARIO ON LANDFILL METHANE EMISSIONS WITH OXIDATION, (B) THE CORRESPONDING PERCENT CH_4 OXIDATION FOR THE A2 SCENARIO, (C) IMPACT OF SCENARIO B1 ON LANDFILL EMISSIONS WITH OXIDATION AND THE (D) CORRESPONDING PERCENT CH_4 OXIDATION. 92
FIGURE 41. FIGURE OF SOIL TEXTURE RELATIONSHIP TO SOIL MOISTURE POTENTIAL 93
FIGURE 42.OVERVIEW OF FIELD MONITORING LOCATIONS AT INDIANA SITE IN-1, INCLUDING LOCATIONS FOR SOIL GAS PROBES, STATIC CHAMBER FLUXES, AND ASSOCIATED GAS RECOVERY WELLS AND OTHER INFRASTRUCTURE IN INTERMEDIATE COVER AREA (MAY 2012) AND EXTENDED DAILY COVER AREA (AUGUST 2012). 95
FIGURE 43. GEOSPATIAL LOCATION OF ALL CALIFORNIA LANDFILLS INCLUDED IN THE DATABASE (WALKER, 2012). 104
FIGURE 44.SPATIAL DISTRIBUTION OF THE (A) CALIFORNIA WASTE-IN-PLACE ESTIMATES FROM THE WALKER (2012) DATABASE AND (B) THE ARB 2010 LANDFILL CH_4 EMISSION ESTIMATES (MG CH_4/YR). NOTICE THE LINEAR RELATIONSHIP BETWEEN WASTE-IN-PLACE AND THE ARB INVENTORY VALUES, AS CLEARLY SHOWN IN (C). 105
FIGURE 45.COMPARISON OF ESTIMATED 2010 EMISSIONS USING CALMIM (MG CH_4 Y^{-1}) TO (A) ARB 2010 INVENTORY ESTIMATES AND (B) TOTAL WASTE IN PLACE (TONS). 107

FIGURE 46.COMPARISON OF THE SPATIAL DISTRIBUTION OF THE (A) CALMIM ESTIMATIONS AND THE (B) CARB 2010 INVENTORY. VALUES ARE IN MG CH_4/YR FOR EACH SITE. 108
FIGURE 47.COMPARING LOCATIONS OF THE TOP ELEVEN EMITTING SITES WITH (A) CALMIM AND (B)ON THE ARB 2010 INVENTORY. 109
FIGURE 48.PREDICTED 2010 CALMIM CALIFORNIA LANDFILL CH_4 SOURCE STRENGTH BY MONTH. 110
FIGURE 49.PREDICTED 2010 CALMIM TOTAL MONTHLY LANDFILL CH_4 OXIDIZATION IN LANDFILL COVER SOILS. 111
FIGURE 50.SPATIAL AND TEMPORAL VARIABLE IN CALMIM 2010 LANDFILL EMISSIONS (MONTHLY SEASONALITY). 111
FIGURE 51.RELATIONSHIP BETWEEN PREDICTED INTERMEDIATE COVER EMISSION RATE (G/M^2/DAY) AND THE SITE-SPECIFIC (A) AVERAGE ANNUAL PRECIPITATION AND (B) THE AVERAGE AIR TEMPERATURE. 114
FIGURE 52.AREA NORMALIZED INTERMEDIATE COVER EMISSIONS (G CH_4 M^{-2} D^{-1}) FOR ALL CALIFORNIA LANDFILLS. NOTE THE CLUSTERING OF SIMILAR EMISSION VALUES. 115
FIGURE 53.GEOSPATIAL DISTRIBUTION OF ANNUAL MEAN (A) PRECIPITATION (MM OF WATER) AND (B) AIR TEMPERATURE (^OC) FOR CALIFORNIA LANDFILL SITES. 116
FIGURE 54.PREDICTED SEASONAL (MONTHLY) EMISSIONS FROM A LOAMY SAND INTERMEDIATE COVER WITH THICKNESS VARYING FROM 12" TO 48" FOR (A) EMISSIONS WITHOUT SOIL OXIDATION AND (B) EMISSIONS WITH SOIL CH_4 OXIDATION. TYPICAL ANNUAL CYCLE FOR SIMULATED CALIFORNIA LANDFILL (36.9 ^{O}N; 121.8 ^{O}W). THE ERROR BARS ARE THE STANDARD DEVIATIONS FOR THE MONTHLY MEANS. 118
FIGURE 55.PREDICTED CH_4 OXIDATION FROM THE SAME INTERMEDIATE COVER [FIG. 4-44] WITH VARIABLE THICKNESS IN (A) AREAL NORMALIZED RATES AND (B) % OXIDATION FOR SIMULATED CALIFORNIA LANDFILL (36.9 ^{O}N; 121.8 ^{O}W). 119
FIGURE 56.(A) AVERAGE NET SOIL OXIDATION RATE AND (B) SURFACE EMISSION RATES AS A FUNCTION OF SOIL THICKNESS FOR THE SAME INTERMEDIATE COVER [FIG. 4-44] AT A SIMULATED CALIFORNIA LANDFILL (36.9 ^{O}N; 121.8 ^{O}W). 120
FIGURE 57.SCATTER PLOT COMPARING SITE-SPECIFIC 2010 CALMIM LANDFILL CH_4 EMISSIONS TO 2010 ARB LANDFILL CH_4 EMISSIONS FOR ALL CALIFORNIA SITES. NOTE LOG-LOG SCALE. 122
FIGURE 58.SCATTER PLOT COMPARING SITE-SPECIFIC 2010 CALMIM LANDFILL CH_4 EMISSIONS TO 2010 ARB LANDFILL CH_4 EMISSIONS FOR 10 SELECTED CALIFORNIA SITES WITH FIELD EMISSIONS DATA. 123
FIGURE 59.COMPARISON OF MODELED TO MEASURED CH_4 EMISSIONS (VARIOUS DATES 2006-2012; METHODS INCLUDE STATIC CHAMBERS, VRPM, TRACER METHODS, MICROMETEOROLOGICAL METHODS, AND AIRCRAFT-BASED MASS BALANCE METHODS). SEE APPENDIX B FOR DETAILED SITE INFORMATION. HIGH RESULTS FOR OLINDA-ALPHA AND PUENTE HILLS ARE BOTH FROM PEISCHL ET AL., 2013. 123

Listing of Tables

TABLE 1. SHORTCOMINGS OF IPCC FOD (FIRST ORDER DECAY) METHOD (IPCC, 2006) AND OTHER FIRST ORDER MODELS FOR SITE-SPECIFIC LANDFILL CH_4 EMISSIONS AND URBAN-SCALE GHG INVENTORIES. 13
TABLE 2. OVERVIEW OF CALMIM INPUT PARAMETERS, BUNDLED MODELS, AND OUTPUTS. 28
TABLE 3. LISTING OF US AND INTERNATIONAL LANDFILL SITES THAT WERE USED FOR THE CALMIM VALIDATION 35
TABLE 4. RESULTS OF US AND INTERNATIONAL LANDFILL SITES THAT WERE USED FOR THE CALMIM VALIDATION 61
TABLE 5. AVERAGE CLIMATIC AND SURFACE EMISSION RATE PREDICTION FOR THE VARIOUS SITES 68
TABLE 6.SOIL GAS CONCENTRATIONS AT BASE OF INTERMEDIATE COVER. NOTE: AREA HAS FULL GAS RECOVERY USING VERTICAL WELLS [SEE FIGURE 4-6]. 96
TABLE 7.SUMMARY OF STATIC CHAMBER FLUXES FROM INTERMEDIATE COVER AREA. COUNT INCLUDES AVERAGED REPLICATES AND FLUXES PASSING SIGNIFICANCE CRITERION OF $R^2 = 0.9$ FOR LINEAR REGRESSION OF CONCENTRATION VS. TIME. 97
TABLE 8.FIRST GAS SAMPLE FROM MAY CHAMBER MEASUREMENTS (TIME=0). APPROXIMATE AIR CONCENTRATIONS (V/V) NEAR GROUND SURFACE. 98
TABLE 9.BASE OF COVER SOIL GAS CONCENTRATION DATA FOR "EXTENDED DAILY COVER" AREA. 99
TABLE 10.SUMMARY OF STATIC CHAMBER FLUXES FROM EXTENDED DAILY COVER AREA. COUNT INCLUDES AVERAGED REPLICATES AND FLUXES WITH $R^2 > 0.9$ FOR THE LINEAR REGRESSION OF CONCENTRATION VS. TIME. 99
TABLE 11.CONTRASTING MEASURED EMISSIONS TO MODELED EMISSIONS USING CALMIM FOR DEFAULT AND CUSTOM SOIL GAS PROFILES. 101
TABLE 12.MONTHLY TOTALS (MG CH_4/MONTH) FOR THE CALIFORNIA STATEWIDE INVENTORY SUMMARIZING THE AMOUNT OF METHANE OXIDIZED, PERCENT OXIDATION, AND THE ESTIMATED SURFACE EMISSIONS WITH AND WITHOUT SOIL OXIDATION. 112

1. Executive Summary

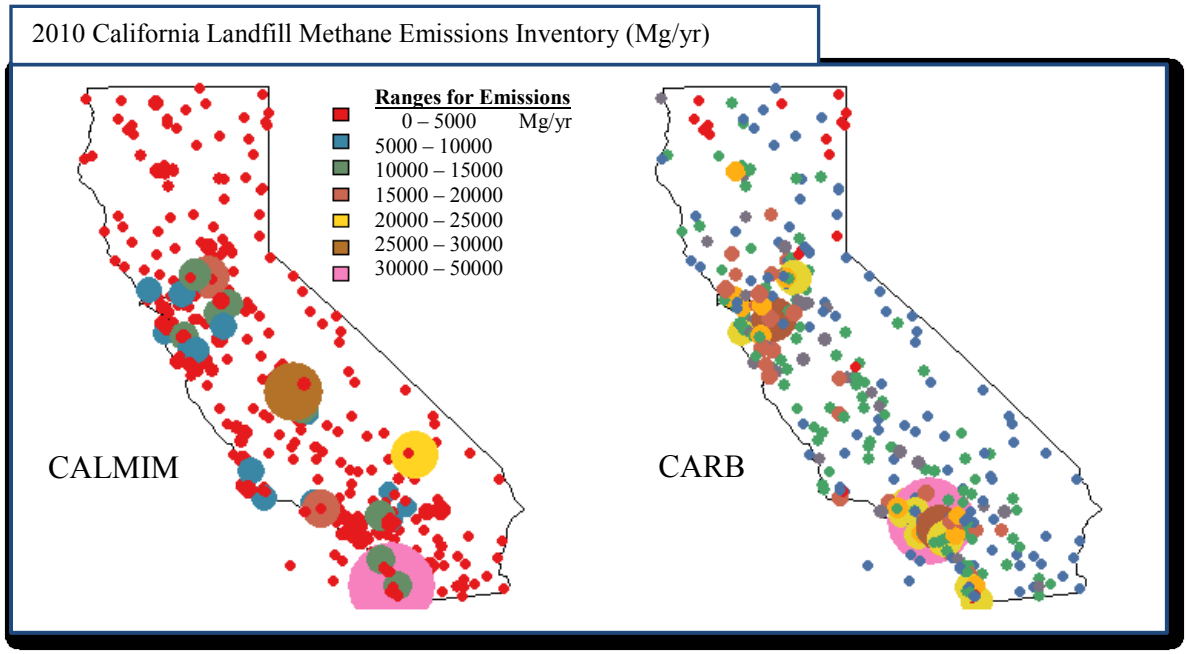


Figure 1.Comparison of 2010 CALMIM landfill CH4 emission inventory to 2010 California Resources Board (CARB) inventory.

The waste industry needs science-based, field-validated methodologies to provide realistic emission estimates for annual greenhouse gas (GHG) inventory reporting at national, regional, and site-specific scales. Predating the majority of field measurement campaigns, the current methodology for landfill CH_4 emissions[1] has not fundamentally changed over the last 20 years—relying on a first order kinetic model to estimate CH_4 generation from the annual mass of landfilled waste, then partitioning the generated CH_4 into fractions recovered, oxidized (maximum 10%), and emitted. Field data on landfill CH_4 emissions have failed to confirm a robust relationship between the mass of waste-in-place and site-specific CH_4 emissions--thus the current method yields misleading guidance for climate change policy decisions. Importantly, the current methodology excludes the 3 major drivers for landfill CH_4 emissions, now known from literature:

- Area, thickness, and physical properties of site-specific cover soils;
- Seasonal variability of methanotrophic CH_4 oxidation rates in site-specific cover soils; and
- Direct effect of engineered gas recovery on soil gas CH_4 profiles in cover soils.

[1] - including both the (1) multicomponent Intergovernmental Panel on Climate Change (IPCC) "First Order Decay (FOD) model [IPCC, 1996; 2006: IPCC Guidelines for National Greenhouse Gas Inventories, Hayama, Japan. [http://www.ipcc-nggip.iges.or.jp/public/2006gl] and (2) the single component U.S. EPA LANDGEM Model. [http://www.epa.gov/ttn/catc/dir1/landgem-v302-guide.pdf]

Like other soil-based GHG emissions, site-specific landfill CH_4 emissions are highly variable due to soil gas transport and oxidation processes related to the seasonal interaction of local soils with local climate at a specific location on the surface of the earth. Moreover, current field campaigns and modeling in many urban areas, which are attempting to partition seasonal CH_4 emissions from multiple, complex anthropogenic and natural CH_4 sources, require a more realistic modeling strategy for landfill CH_4. Thus it is time to reconsider and replace the current methodology, relying on technical literature and modeling tools now available.

This study focused on the international field validation of a site-specific annual GHG (greenhouse gas) inventory model for landfill CH_4 emissions that incorporates both site-specific soil properties and microclimate modeling coupled to 0.5° scale global climate models. Based on 1-D diffusion, CALMIM (**CA**lifornia **L**andfill **M**ethane **I**nventory **M**odel) is a freely available JAVA tool which models a typical annual cycle for CH_4 emissions from site-specific daily, intermediate, and final landfill covers at any landfill site worldwide. CH_4 oxidation is scaled to maximum rates based on soil temperature and moisture at 2.5 cm depth increments and 10-min time-steps. In addition to embedded default values for general GHG inventory purposes, CALMIM can accept user-supplied values for critical parameters for more specialized uses including oxidation & emissions research, scheduling of field campaigns to observe seasonal emissions, providing a decision support tool for alternative cover designs, simulation of regional emissions variability, and prediction of future emissions under climate change scenarios.

This new approach, which is compatible with Intergovernmental Panel on Climate Change (IPCC) "Tier 3" criteria, was originally developed and field-validated for the state of California during the first CALMIM project in 2007-2010 funded by the California Energy Commission. That project included model development with independent field validation at two California sites and limited field validation at three additional California sites (see Spokas et al., 2011; Bogner et al., 2011; Spokas and Bogner, 2011).

The current project, funded by EREF during 2011-2013, significantly improved the CALMIM model and internationally field-validated the revised model for broader U.S. and international applications. Now compatible with PC, MAC, and UNIX platforms, the updated model (CALMIM version 5.4) contains numerous structural and cosmetic improvements as discussed herein. Direct comparisons between modeled and measured emissions for this project focused on 29 international sites with multiple cover types in North & South America, Europe, Africa, Asia, and Australia. The base data for the comparisons was derived from published literature and from collaborations with U.S. and international research groups.

We conclude that, using default parameters, CALMIM provides a conservative order-of-magnitude estimate for "typical annual emissions" from site-specific landfill cover materials which is suitable for inventory purposes. Importantly, through the use of 30-year average climate data, CALMIM replicates the typical annual variability which would be expected for GHG inventory purposes with respect to the site-specific soils and

temperature/moisture-dependent CH_4 oxidation rates. Thus CALMIM can provide an improved estimate for annual emissions based on the major processes which directly control emissions—namely, the thickness and physical properties of cover materials, the presence of engineered gas extraction, and seasonally-variable CH_4 oxidation rates for each cover.

The use of site-specific "custom" data for soil gas profiles, annual weather, and other inputs can improve comparisons with field data for more specialized applications, including critical science questions relating landfill CH_4 emissions to various operational, design, and climatic considerations (including future climate change). Those questions include:

- How would an increase or decrease in the existing cover thickness at a specific location affect emission and oxidation rates?
- What is the relative impact of gas recovery vs. methanotrophic CH_4 oxidation with respect to reducing net CH_4 emissions to the atmosphere?
- What design and operational strategies could be employed at specific sites to reduce emissions to negligible values?
- When should field measurement campaigns be scheduled to quantify typical annual variability in emissions and oxidation?
- How would CH_4 oxidation and emissions change over the longer term for current covers under future climate change scenarios?

As part of the EREF project, in collaboration with Waste Management, Inc. and Purdue University, we also completed a field project at a central Indiana landfill to provide recommendations for developing field-based "custom" soil gas profiles for CALMIM modeling.

As a final product for this project, we completed a new 2010 GHG inventory for landfill CH_4 emissions for the state of California (see Figure 1). This was the first application of CALMIM to a revised regional inventory, enabling direct comparison with the current California Air Resources Board methodology based on the IPCC model with a fixed 10% oxidation. Although the total state emissions were similar, the regional distribution of emissions for specific sites was very different, primarily due to the regional and seasonal variability of CH_4 oxidation. Unlike the current inventory, where the sites with the largest quantity of waste-in-place are the highest emitters, the CALMIM-based California inventory more realistically relates higher emissions to soil temperatures and moisture conditions which are less optimum for oxidation at seasonally dry, hot, and cold (high elevation) sites. Representing the largest % of the waste footprint at individual sites, intermediate covers were responsible for >90% of the state emissions. Modeling results and field data indicated that intermediate covers are characterized by significantly lower emission rates for thicker covers. However, modeling results also suggested that there can be an "optimum" thickness for a specific cover soil and specific soil gas profile at a specific site due to increasing limitations for O_2 diffusion in soils thicker than the optimum. Overall, California cover soils exhibit strong seasonal trends for oxidation over an annual cycle, with temporal variability in % oxidation for intermediate covers over the entire state ranging from <20% to >90%. The lowest values were associated with late summer/early autumn months which are characterized by hotter, drier soils over

much of the state. Detailed comparisons for modeled emissions vs. measured emissions at 10 California sites support recent literature by a number of investigators that the assumed 10% oxidation rate, based on seasonal modeling for one northeastern U.S. site in the mid-1990's, needs to be replaced with a site-specific tool.

In general, CALMIM provides a user-friendly tool for improving GHG inventories for landfill CH_4 emissions consistent with current understanding of the major controls on emissions, addressing research questions related to site-specific design and operational practices, determining timing of field campaigns to address seasonal variability, and simulating future emissions under climate change scenarios.

2. Introduction

2.1. Background and Objectives

Atmospheric methane (CH_4) has multiple anthropogenic sources with high uncertainties (Bousquet et al., 2006), including rice production, ruminant animals, natural gas and coalbed leakages, biomass burning, wastewater, and landfills (Kirschke et al., 2013; Zhuang et al., 2013). According to literature summarized for the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, estimated landfill CH_4 emissions of 0.6 - 0.7 Gt CO_2 equiv. yr^{-1} are equal to approximately 1-2% of total global anthropogenic GHG emissions of 49 Gt CO_2 eq. yr^{-1} (Bogner et al., 2007; Rogner et al., 2007). With the release of the first volume of the IPCC 5th Assessment Report, the 100-year global warming potential (GWP) for CH_4 has now increased from 25 to 28 relative to CO_2 (IPCC, 2013; Wang and Su, 2013; Carraro et al., 2014). Combined with a short atmospheric lifetime of 9-12 years (Forster et al., 2007; Holmes et al., 2013; IPCC, 2013), emission reductions from specific CH_4 sources can thus reduce current atmospheric CH_4 concentrations within decadal timeframes.

Landfill gas (LFG), as generated, contains 50–60% CH_4 (v/v). In the absence of engineered controls (such as gas recovery and well-maintained cover materials), landfills can be potent local sources of atmospheric CH_4. In the U.S., landfills are currently the third largest anthropogenic source of CH_4, after natural gas systems and ruminant animals (USEPA, 2013). However, during the last 2-3 decades, the estimated magnitude of the landfill CH_4 source in the U.S. has decreased due to the expanded implementation of engineered LFG recovery and utilization (now >600 commercial projects utilizing landfill CH_4 ; see http://www.epa.gov/LMOP).

At the present time, in order to provide guidance for more localized GHG mitigation strategies, there is increased impetus within the international research community to develop well-constrained regional- and urban-scale GHG inventories using a variety of "top-down" and "bottom-up" measurement and mathematical modeling strategies (e.g., Bellucci et al., 2012; Wennberg et al., 2012; Miller et al., 2013; Peischl et al., 2013). Thus, it is imperative to get the best estimates for individual sources. This can be a significant challenge due to the topographic complexity (Zitouna-Chebbi et al., 2012), source uncertainty (Kirschke et al., 2013), and immense spatial and temporal variability for CH_4 emission rates at a particular landfill (Bogner et al., 1999; Harborth et al., 2013; Pratt et al., 2013; Rachor et al., 2013). In addition, there can be multiple other interfering anthropogenic and natural CH_4 sources present at a particular location (Bridgham et al., 2013), which can greatly complicate site-specific measurement strategies.

In this project, we focused on the further development and international field validation of a site-specific process-based landfill CH_4 emissions model appropriate for local, regional, and national-scale GHG inventories. This model (CALMIM, **CA**lifornia

Landfill **M**ethane **I**nventory **M**odel) [2] was originally developed and field-validated for California during 2007-2010 in a project supported by the California Energy Commission (CEC) in cooperation with the California Integrated Waste Management Board (CIWMB) and the Air Resources Board (ARB). It is important to emphasize that this model replaces the historic emphasis on landfill methane (CH_4) *generation* modeling for estimation of emissions, replacing it with theoretical process-based 1-D soil gas, temperature, and water transport models—these are further coupled to an empirical oxidation model specifically for landfill CH_4 emissions (Spokas and Bogner, 2011). In so doing, the model accounts for soil and climate interactions on the predicted rate of CH_4 oxidation for individual cover soils at specific sites. Thus, this represents a first step in the scientific advancement of landfill CH_4 emissions estimation. Despite this sound theoretical improvement, there are remaining shortcomings to this approach. CALMIM like all mathematical models is an abstraction and is not meant to replace field assessment. CALMIM only accounts for diffusive transport and does not model spatial heterogeneity (e.g. surface cracks) in the cover soils. CALMIM estimates the surface emissions through 10-min time steps and 2.5 cm (1") depth increments for daily, intermediate, and final cover materials which are then summed to provide total annual site emissions.

CALMIM is a freely-available JAVA model [currently CALMIM version 5.4] which relies on site-specific inputs (especially daily, intermediate, and final cover materials), linkages to internationally-validated climate and soil microclimate models, and the scaling of CH_4 oxidation rates to soil moisture and temperature changes during a typical annual cycle. As developed, this freely-available model is compatible with IPCC (Intergovernmental Panel on Climate Change) guidelines as a higher quality "Tier 3" "validated country-specific method" for emissions. Using CALMIM, site-specific landfill CH_4 emissions can be compared and summed with other CH_4 sources for improved local-, regional-, and national-scale GHG inventories.

With the financial support from Environmental Research and Education Foundation (EREF) during 2011-2013, and as a logical follow-up to the 2007-2010 project, we have completed a broader U.S. and international field validation, as well as a number of CALMIM improvements. The major objectives of this project were:

1. To develop an improved landfill CH_4 inventory model for the U.S. by expanded field validation of the CALMIM model using existing landfill CH_4 emissions & oxidation data from U.S. research groups.

2. To develop an improved landfill CH_4 inventory model for international application under the current IPCC National Inventory Methodology for Waste (IPCC, 2006) including:

    a. CALMIM updates and improvements for application over broad climatic regions; and

[2] - Model is available at http://www.ars.usda.gov/services/software/download.htm?softwareid=300

b. Expanded international field validation of CALMIM using existing field measurements from research groups in Europe, South America, Asia, Australia, and Africa.

To achieve these objectives, we completed the following project activities:

1. We improved and upgraded the CALMIM programming code and user interfaces. (Section 3A).

2. Using published field datasets and alliances with U.S. and international research groups, we compared "default" and "custom" CALMIM modeling to field measurements from a variety of methods at scales ranging from m^2 to km^2. The 29 sites were located on all continents except Antarctica (Section 3B).

   For selected sites and for "generic" sites in selected global locations, we also addressed specific research questions pertaining to seasonal emissions, selection of cover materials to reduce emissions, variability in CH_4 oxidation over a typical annual cycle, the relative impact of gas recovery vs. seasonal oxidation to reduce emissions, and projected emissions under future climate change scenarios as listed below:

3. We investigated global latitudinal gradients for landfill CH_4 emissions using CALMIM simulations for standardized cover soils (Section 3C).

4. We used CALMIM to answer specific research questions related to how cover design and climate-related factors affect landfill CH_4 emissions (Section 3D).

5. In collaboration with Waste Management, Inc. and Purdue University during 2012, we completed a focused field project to enable a detailed comparison of CALMIM modeling to default and customized data inputs using field data from a landfill site in central Indiana (Section 3E).

6. Finally, using a recently-available California state database (Walker, 2012), we developed a new 2010 landfill CH_4 inventory for the state of California and compared the results to the previously-published 2010 California Air Resources Board (CARB) inventory (Hunsaker, 2012 – personal communication), which utilized IPCC (2006) FOD methodology. For 10 California sites, with existing field measurements, we compared CALMIM and CARB to the site-specific field data. We also discussed how CALMIM can provide a more realistic regional allocation of landfill CH_4 emissions inclusive of seasonal CH_4 oxidation (Section 3F).

2.2. HISTORICAL PERSPECTIVE

Development & Shortcomings of Current IPCC First Order Kinetic Model ["First Order Decay"/FOD Methodology] and Related Methodologies for Landfill CH_4 Emissions

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was formed by the World Meteorological Organization (WMO) and the United Nations Environmental Program (UNEP) to assess human-induced climate change (www.ipcc.ch). Coordinated through the IPCC Secretariat in Geneva, Switzerland, the IPCC includes three working groups which focus on the science of climate change (Working Group I), vulnerabilities, impacts, and adaptation to climate change (Working Group II), and mitigation of climate change (Working Group III). For the periodic IPCC assessment reports, these groups convene multiple times over a period of several years to assess and summarize the refereed literature; however, the three working groups do not engage in climate research or monitoring, nor do they recommend specific government policies. Each working group for a particular assessment report is comprised of international experts recommended by their national governments and a Technical Support Unit (TSU). The TSU oversees the technical and administrative quality of each report, monitors compliance with IPCC guidelines (e.g., "policy neutral"; emphasis on peer-reviewed literature), and monitors the internal consistency of reports between working groups. All IPCC reports are freely available at www.ipcc.ch. The three parts of the 4th Assessment Report (AR4) were published in 2007, and the publication of the 5Th Assessment Report (AR5) commenced with the Working Group I report in October, 2013. The AR5 reports for Working Groups II and III will be completed during 2014.

The U.S. participates fully in the IPCC as well as in the United Nations Framework Convention on Climate Change (UNFCCC), the international treaty which entered into force in 1994 with 194 countries/entities. On the other hand, the U.S. does not participate in the Kyoto Protocol of the UNFCCC, which was adopted in 1997, entered into force in 2005 with 191 parties, and set binding obligations for industrialized countries to reduce GHG emissions to "*prevent dangerous anthropogenic interference to the climate system*." The first Kyoto commitment period ended at the end of 2012. The second Kyoto commitment period currently extends through 2020 with fewer countries and continuing discussion regarding Kyoto provisions for this period. As of December, 2013 when this report was completed for EREF and the Conference of Parties (COP) was meeting in Warsaw, Poland, no overall agreement had been finalized for the second Kyoto commitment period. An agreement is currently expected to be finalized by 2015 (Newell et al., 2013).

In addition to the 3 working groups coordinated through the IPCC Secretariat in Geneva, the IPCC also includes a Task Force on National Greenhouse Gas (GHG) Inventories based in Japan (www.ipcc-nggip.iges.or.jp). Working through international review groups and consultation processes, the procedural guidance for national GHG inventories has been historically developed by this taskforce to provide uniform guidance for the 194 countries, including the U.S., which participate in the UNFCCC. The first IPCC guidelines for estimating GHG emissions from a variety of anthropogenic sources were

developed in 1994, subsequently revised, and published as a comprehensive document two years later (IPCC, 1996). These focused on recommendations to estimate *national* GHG emissions. For landfill CH_4 emissions, the first calculations were typically based on composite national quantities of landfilled waste.

The first IPCC (1996) international guidelines for landfill CH_4 emissions permitted either (1) an empirical mass balance approach to estimate the CH_4 generated, recovered, and emitted; or (2) the use of a first order kinetic equation (called "FOD" for first order decay) where, similar to a controlled anaerobic digester, landfill CH_4 generation is assumed to be related to a specific first order equation. The FOD approach incorporated a temporal dimension to CH_4 generation rates from the organic carbon contained in annually-incremented quantities of landfilled waste. In practice, over the next decade, most developed countries used the FOD model for annual reporting to IPCC while most developing countries, for which annual reporting was not required, used the mass balance approach [method (1) above].

In 2006, the revised and most recent IPCC guidelines were issued—these only included the FOD approach and, in addition, provided spreadsheets to facilitate the calculations (IPCC, 2006). As discussed in more detail below, the FOD models in the IPCC (2006) guidelines are multi-component with individual values for CH_4 generation potential from the degradable organic carbon contained in various waste fractions. The original IPCC methodology (IPCC, 2006) was revised in 2007 to include more specific recommendations for various waste fractions and "*k*" (waste degradation constant) values for specific climatic regions (IPCC, 2007). As recommended by these guidelines, the annual modeled CH_4 generation is subsequently partitioned into:

> 1) The mass of measured or estimated CH_4 recovered via engineered gas extraction systems, if present;
>
> 2) The mass of CH_4 oxidized by aerobic methanotrophic microorganisms in landfill cover soils, which is assumed to be either 10% or zero of [estimated generation – measured recovery]—see further discussion below; and
>
> 3) The remainder, which is taken to be the estimated mass of CH_4 emitted to the atmosphere.

Although this approach takes into consideration a temporal dimension for CH_4 generation, it also assumes that the specific form of the selected first order equation is an accurate representation for CH_4 generation in all landfills worldwide, as well as other shortcomings discussed below.

Below we discuss the specific equations currently used for estimating landfill CH_4 emissions internationally (IPCC, 2006). After a subtraction for carbon storage (e.g., landfilled but non-degraded organic carbon), the equation for the general case (IPCC, 2006, p 3.33) is based on the mass of degradable organic carbon in a specific buried waste fraction that will decompose under anaerobic conditions between some previous time (t-1) and current time (t):

$$DDOC_m, decomposed = DDOC_{m0} \bullet (e^{-k(t-1)} - e^{-kt}) \qquad \text{Equation 1.}$$

where:

$DDOC_m$ = the mass of buried degradable organic carbon that will decompose under anaerobic conditions at time *t*, metric tons

$DDOC_{m0}$ = the mass of $DDOC_m$ in the disposal site at time 0, when decomposition begins.

k= kinetic constant, $year^{-1}$

t= time, years

The recommended k values are assumed to be related to climate—ranging from a low value of 0.02 y^{-1} (boreal and temperate, dry, slowly-degrading waste) to a high value of 0.4 y^{-1} (moist & wet tropical, rapidly-degrading waste). Estimates for anaerobically degraded organic carbon from each waste fraction are summed and converted to the total mass of biogas that could be annually produced from that waste. Typically, the biogas is assumed to contain 50% CH_4 (v/v). Then the emitted CH_4 is calculated as follows:

$$CH_4 \ Emissions = [\Sigma \ CH_4 \ generated \ from \ each \ waste \ fraction - R] \bullet [1 - OX] \qquad \text{Equation 2.}$$

where:

CH_4 Emissions = the mass of CH_4 annually emitted (metric tons),

R = the total mass of CH_4 recovered by engineered systems (vertical wells and horizontal collectors), then destroyed in flares, engines, turbines, or other combustion devices (metric tons),

OX = the fraction of residual CH_4 (after R) that is oxidized by aerobic methanotrophic microorganisms in landfill cover materials. As discussed in more detail below, this is currently limited to 0.10 or zero.

Although originally applied to national GHG inventory estimates, the IPCC (1996, 2006) FOD model, as well as the similar U.K. GASSIM model (Gregory and Rosevear, 2005) and various single-component models (e.g., the USEPA LANDGEM model and related country-specific variants), have been increasingly used for specific sites for a variety of purposes—these include site-specific emissions estimates, landfill regulatory programs, and baseline estimates for Kyoto Protocol offset projects in developing countries [Clean Development Mechanism, discussed below]. However, in direct comparisons with an increasing database of site-specific field measurements for CH_4 emissions in the peer-reviewed literature, it has been shown that these models have major shortcomings and cannot consistently replicate either the magnitude or the variability of site-specific emissions during the last 15 years [see discussion in Spokas et al. (2011) and references cited therein].

Over the last 2 decades, we have gained a better understanding of the processes involved in landfill CH_4 emissions. A major failing of the FOD approach for emissions is that the three primary drivers for site-specific emissions are excluded from this methodology, including:

1. Composition and thickness of site-specific daily, intermediate, and final cover materials which physically retard CH_4 emissions to the atmosphere (Abichou et al., 2006a);

2. Physical effect of engineered gas recovery which reduces the CH_4 concentration gradient in cover soils, thus reducing the diffusive flux of CH_4 to the atmosphere (Park and Shin, 2001); and

3. Seasonal variability in methanotrophic CH_4 oxidation which reduces CH_4 emissions from site-specific soils as a function of local climate and soil microclimate (soil moisture/temperature) (Boeckx et al., 1996; Chanton and Liptay, 2000).

Table 1 summarizes the major shortcomings of the IPCC FOD methodology for landfill CH_4 emissions, with particular emphasis on the lack of field validation for emissions, the documented orders-of-magnitude variability in actual site-specific emissions related to seasonal oxidation, and the importance of cover materials & gas recovery to reduce emissions to the atmosphere.

In the remainder of this section we will summarize some of the important points in Table 1, beginning with additional historical perspective. Going back to the mid-1970's, at the time of the first commercial landfill gas recovery projects in the U.S., site-specific first order kinetic models were beginning to be developed and applied to landfill processes for the purpose of predicting future landfill gas recovery from past performance. Empirical models were also proposed using composite data from multiple sites (see discussion in Peer et al., 1993). At that time, however, because they had been successfully used to model more idealized anaerobic digester systems using organic waste substrates (e.g., see Barlaz et al., 1987), a number of first order kinetic models were proposed for specific sites (see Emcon, 1980). These models had various forms (lag/no lag; single stage/multi-stage) but yielded reasonable comparisons with recovered LFG at a specific site over relatively short timeframes. For any one site, a particular first order model was "validated" by comparing predicted to historic landfill gas recovery—typically, this process also involved adjusting model parameters (L_o, yield, m gas m^{-1} waste; k, kinetic constant, t^{-1}) for one or more substrates to optimize the match (e.g., Wang et al., 2013). Therefore, the original first order models were all site-specific and typically named for individual landfills, e.g. the Scholl Canyon Model, the Palos Verdes Model, the Sheldon-Arleta Model—these referred to southern California landfill sites with early (1970's) landfill gas utilization projects (NCRR, 1974; Gardner and Probert, 1993). The models varied with respect to the shape of the production curve, relative temporal rates of decline for gas production, and whether or not a lag time between waste placement and gas generation was embedded in a particular model.

Moving forward to the 1980's, reliance on and use of these models for landfill gas utilization projects diminished somewhat, as the responsible parties (landfill owners & operators; developers) increasingly recognized that there was a multiplicity of operational and engineering factors governing the quantity and quality of recoverable LFG. These factors included an understanding of the spatial variability of waste composition at a specific site, and, importantly, coordinating the installation of gas recovery with landfill expansions, which typically occurred in several stages involving both vertical wells and/or horizontal collectors. Moreover, the purchase of gas utilization hardware based solely on theoretical modeling at a number of sites had resulted in some expensive mistakes. In addition, due to the temporal and spatial variability of landfilled waste, reliance on small pilot programs for gas recovery (e.g., installing a limited number of temporary gas wells plumbed to a temporary flare) was largely discontinued, as these programs can yield misleading information for scale-up. In general, the preferred strategy consists of installing initial vertical wells and/or horizontal collectors, followed by a period of flaring to evaluate sustainable landfill gas quantity & quality, then committing to gas utilization hardware as economically feasible for a specific site. Commercial projects often involve multiple partners. For large U.S. and international landfill sites with long lifetimes, multiple extensions of gas extraction systems became the norm, requiring good coordination of welling plans with site operational and filling plans.

Table 1. Shortcomings of IPCC FOD (first order decay) method (IPCC, 2006) and other first order models for site-specific landfill CH_4 emissions and urban-scale GHG inventories.

Issue	Importance/explanation	References
FOD method does not consider site-specific cover materials.	1. Published literature has emphasized that CH_4 emissions to the atmosphere are dependent on the thickness and physical properties of daily, intermediate, and final cover materials. 2. Cover soils also promote anaerobic conditions in the waste and permit operation of gas recovery systems under vacuum without excessive air intrusion. 3. Methane oxidation in cover soils reduces emissions as a function of seasonal soil microclimate.	Scheutz et al. (2009) Bogner and Spokas (2010) Spokas et al. (2011) Bogner et al. (2011)
FOD method assumes that global landfill CH_4 generation can be described by a single first-order kinetic equation with variable values for CH_4 generation potential (Lo, mass CH_4 mass^{-1} waste or waste component) and kinetic constant (k for waste or waste component for specific climatic regions, t^{-1})	1. A variety of first order equations were historically applied to some of the first commercial landfill gas recovery projects in southern California, beginning in the mid-1970's. At that time, their purpose was to predict future landfill gas recovery at specific sites by selecting a first order equation, as well as Lo and k values, which fit prior recovery data. There was no unique solution for any site; rather, "best fits" with error bars were developed. During the mid- to late-1980's, the U.S. EPA developed the single component LANDGEM model for regulation of landfill emissions under the Clean Air Act amendments (NSPS/EG). IPCC, during the 1990's, adopted a first order multicomponent format based on the degradable organic carbon content of individual waste fractions (IPCC, 1996, 2006). 2. LANDGEM was based on the Scholl Canyon model [EMCON, 1980; see text]. The Scholl Canyon Landfill (Glendale, California, USA) was one of the two major field validation sites for the alternative CALMIM model during 2007-2008. At that time the measured landfill gas recovery at Scholl Canyon was more than double the estimated total generation using the IPCC (2006) FOD model and California-specific inputs, as specified by ARB for the California GHG inventory. 3. In comparison with highly-controlled anaerobic digesters for which biogas generation can be well-described using a kinetic equation, landfills are relatively inefficient digesters for biogas generation.	EMCON (1980) and references cited therein Bogner (1992) IPCC (1996, 2006) Peer et al (1993) Barlaz (1997) Scheutz et al. (2009) Oonk (2010) Spokas et al. (2011)

Table 1. (Continued)

Issue	Importance/explanation	References
FOD method assumes that residual landfill CH_4 emissions to the atmosphere are directly related to the mass of waste-in-place and annual filling rates.	1. Published literature during the last 2 decades and empirical data confirm that landfill gas recovery rates, not residual emissions, are related to waste-in-place. 2. Residual CH_4 emissions are related to the thickness and physical properties of cover soils, the implementation of gas recovery beneath various cover soils, and seasonal variations in CH_4 oxidation in cover soils.	Fig. 1 and discussion (this report) Spokas et al. (2011)
FOD method (IPCC, 1996, 2006) was never field-validated for CH_4 emissions.	1. Historical "field validation" of the FOD method for emissions compared measured landfill gas recovery using engineered systems to modeled gas generation, focusing primarily on European and U.S. landfill sites. Therefore, the FOD method was never directly field-validated for emissions. 2. More recent field data for emissions has shown that emissions routinely vary over several orders of magnitude at specific sites, depending on cover materials, seasonal CH_4 oxidation in various cover materials, and implementation of active gas extraction in some or all of the previously-deposited waste.	Scheepers and Van Zanten (1995) Peer et al. (1993) Oonk (2010) Scheutz et al. (2009)
FOD method does not consider the direct physical effect of landfill gas recovery systems to reduce emissions from various cover systems.	1. Literature has demonstrated that the soil gas CH_4 concentration at the base of the cover is reduced by landfill gas recovery systems, thus reducing diffusive flux to the atmosphere. 2. In cover soils at sites with gas recovery systems, diffusion is the major mechanism for CH_4 emissions to the atmosphere.	Spokas et al. (2011) and Supporting Information

Table 1. (Continued)

Issue	Importance/explanation	References
FOD method allows only one value (10%) for reduction of CH_4 emissions due to methanotrophic CH_4 oxidation in cover materials.	1. When the first IPCC (1996) national GHG inventory guidelines were developed, only one study had estimated the annual effect of CH_4 oxidation at field scale. Czepiel et al. (1996), working at the Nashua, NH (USA) landfill, a 17 ha site without engineered gas recovery, measured CH_4 emissions using static closed chambers, conducted supporting laboratory studies to determine temperature- and moisture-dependent oxidation rates, and used an annual climate model to estimate a 10% *annual* reduction due to oxidation. 2. In contrast, published literature inclusive of field, laboratory, and modeling studies has demonstrated that oxidation varies from 0 to >100% (oxidation of atmospheric CH_4). The oxidation % is highly dependent on the thickness, physical properties, and seasonal variability in soil moisture, temperature, and other dynamic soil properties. Recent field studies using stable carbon isotopic approaches (Chanton et al., 2009) have demonstrated that average oxidation at field sites is approximately 30-40%. 3. The uptake of atmospheric CH_4 by landfill cover soils has been demonstrated at field sites.	Bogner et al. (1995, 1997, 2011) Chanton et al. (2009) Goldsmith et al., (2012) Scheutz et al. (2009)
Due to lack of field validation for emissions, a rigorous technical basis for recent expansions of FOD methods is lacking, including 1) use of FOD model (IPCC, 2006) for Clean Development Mechanism (CDM) methodologies for "avoided CH_4 to landfill"; and 2) more recent use of FOD methods to calculate the Australian carbon tax for landfill CH_4 emissions.	1. CDM is an "Enabling Mechanism" for countries signatory to the Kyoto Protocol which allows crediting of emission reductions in developing countries against Kyoto obligations in developed countries. "Avoided CH_4 to landfill" pertains to waste composting, anaerobic digestion, or landfill aeration projects where a comparison is made between the emissions from the project as opposed to the emissions from conventional landfilling of the waste, basing the assumed "avoided" landfill emissions solely on the FOD model results. 2. As the time of preparation of this report, the Australian Dept. of Climate Change and Energy Efficiency is enacting an annual carbon tax of \$23 (AUS)/ton CO_2 equiv on landfill CH_4 emissions which are determined using the FOD model, Australian-specific waste and climate considerations, and an assumption of 75% collection efficiency, regardless of the actual magnitude of measured gas recovery. Practically, this has been a strong disincentive for LFG recovery where emissions cannot be reduced below the FOD prediction at large sites.	*http://cdm.unfccc.int/methodologies/* especially Small-Scale Methodologies: *AMS-III.E* *AMS-III.F* *AMS-III.L* *AMS-III.AF* *AMS-III.BE* and Large-Scale Methodologies: *AM0083* *AM0093* Kossoy and Guigon (2012) Australia (2012a,b) Black (2012) Dreyfus (2012)

Starting in the late 1980's and continuing to the present time, there was a revival of interest in the first order models to estimate gas generation as the starting point for *site-specific* estimates for three major applications:

- LFG regulatory programs addressing emissions of CH_4 and (in the U.S.) non-methane organic compounds (NMOCs);
- National-scale GHG inventories; and
- By the early 2000's, estimates of recoverable CH_4 for evolving emissions offset programs to monetize carbon credits. These included (1) landfill gas recovery projects in developing countries under the Clean Development Mechanism (CDM) of the Kyoto Protocol—offsets were credited to entities in developed countries with Kyoto compliance obligations; (2) CDM projects involving alternative waste management strategies (e.g., composting) which monetized credits based on the IPCC (2006) model as "avoided methane" from landfilling; and (3) landfill gas recovery projects eligible for a variety of compliance and voluntary carbon market offsets in U.S. state, regional, and international settings.

At this time, site-specific rather than composite national estimates were required and a variety of first order models were implemented in the U.S. and internationally—these included the IPCC model, the GASSIM model, the LANDGEM model, and other model formats. In practice, prescribed regulatory or IPCC default values were typically applied to either the composite waste (one-component models) or to individual waste fractions (multi-component models).

At specific sites, there can be large discrepancies between estimates for gas generation and recovery derived from models compared to measured gas recovery rigorously quantified for commercial projects. After installation of recovery hardware, input parameters for these models including L_o (gas generation potential, mass [gas] mass^{-1} waste or waste fraction) and k (kinetic constant, t^{-1}) are typically adjusted so that the estimated gas generation is more consistent with the measured recovery. This is often accomplished via iterations in a spreadsheet model, yielding multiple non-unique solutions. Other adjustments can be made for the CH_4 content of the gas and a "recovery efficiency" factor. The latter is an assumed ratio between measured landfill gas recovery and estimated "theoretical" landfill gas generation, which cannot be readily measured in field settings (Spokas et al., 2006). Below we specifically address modeling uncertainties associated with three historical site-specific applications—namely, (1) regulation of landfill non-methane organic compound (NMOC) emissions under the U.S. Clean Air Act Amendments and successive legislation; (2) estimation of site-specific landfill CH_4 emissions for the IPCC inventory (IPCC, 1996, 2006) and California GHG legislation; and (3) estimation of recoverable landfill CH_4 at sites in developing countries for monetization of emissions offsets under the Kyoto Protocol Clean Development Mechanism (CDM).

To address (1), during the late 1980's, under provisions of the Clean Air Act Amendments, the U.S. EPA had a congressional mandate requiring the development and

implementation of a monitoring and compliance program for landfill emissions of total non-methane organic compounds (NMOCs). As landfill emissions of NMOCs had not been previously quantified, and in consultation with the landfill industry, the EPA relied on a first order kinetic model to estimate total annual gas generation at individual sites. After subtracting recovery, the remainder was assumed to equal emissions. To that remainder, either a default or site-specific mixing ratio for total NMOCs [EPA method 25c] was applied to estimate the NMOC emissions. The model was based on the Scholl Canyon model (Emcon, 1990) and later formalized into the LANDGEM model. Validation focused on a comparison between measured CH_4 recovery at 21 U.S. sites to 3 first order model scenarios (various Lo and k values) and an empirical model (Peer et al., 1993). In 1996, the final rule was issued under the NSPS (New Source Performance Standards) for the Clean Air Act Amendments. Subsequently, there have been numerous additions and revisions, all of which can be accessed at http://www.epa.gov/ttnatw01/landfill/landflpg.html.

Also in 1996, the first comprehensive IPCC guidelines for national GHG inventory calculations were published (IPCC, 1996). At that time, there were still very few "whole landfill" measurements of CH_4 emissions in the literature and only one site-specific estimate of annual oxidation (Czepiel et al., 1996a). In addition, a multi-component first order model was adopted to estimate CH_4 generation from landfilled waste, based on the degradable organic carbon content of the various waste fractions (Owens and Chynoweth, 1993; El-Fadel et al., 1997). A major contributor to model development was a study of 9 full-scale Dutch landfills, where measured landfill gas recovery was compared to estimated generation using a series of zero order, first order, and second order models, developed in part as a contribution to an International Energy Agency Expert Working Group on Landfill Gas (Oonk and Boom, 1995; Van Zanten and Scheepers, 1995; Oonk, 2012). This study concluded that a first order model gave a reasonable comparison between estimated generation and measured recovery with greater analytical simplicity than higher order models. Therefore the FOD model for "emissions" was not originally validated by a comparison to measured CH_4 emissions, which were just starting to be quantified in the refereed literature, but rather by a comparison between modeled and measured gas recovery from engineered gas extraction systems, thereby returning to the original application for these models. Historic comparisons between modeled generation and measured recovery are also summarized by Oonk (2010).

A third event in 1996 was publication of the first "whole landfill" study for landfill CH_4 emissions and annual oxidation in the peer-reviewed literature (Czepiel et al., 1996a; Czepiel et al., 1996b). Working at the small (17 ha) Nashua, New Hampshire landfill, which did not have gas recovery, this study included a combination of measured emissions using chamber and tracer techniques with supporting laboratory studies to develop soil temperature & moisture-related CH_4 oxidation rates for the landfill cover soil (Czepiel et al., 1996a). After using the laboratory-derived oxidation rates in a climate model, they derived an annual value of 10% for CH_4 oxidation. Thus, through a combination of field measurements, laboratory incubations, and modeling studies, this study concluded that the CH_4 actually being emitted at this New England landfill during an annual cycle had been reduced to 90% of what it would have been without aerobic

oxidation by indigenous methanotrophic microorganisms in the landfill cover soils. The timing of this study coincided with the finalization of the IPCC (1996) guidelines—thus a 10% value for oxidation at well-managed sites was adopted at that time. This 10% value was retained in the subsequent IPCC (2006) guidelines. However, published literature since 1996 has demonstrated that oxidation can vary from negligible to >100% and field measurement of emissions can vary from negative (atmospheric uptake) to >1000 g m^{-2} d^{-1} (Bogner et al., 1997a; Bogner et al., 1997b; Bogner et al., 1997c; Chanton and Liptay, 2000; Hegde et al., 2003; Scheutz et al., 2009; Babilotte et al., 2010; Fredenslund et al., 2010; Chiemchaisri et al., 2011). In general, large differences in seasonal oxidation at specific sites contribute to the high variability in U.S. and international measurements of landfill CH_4 emissions ranging over 6-7 orders of magnitude.

Finally, we address the use of first order models in approved methodologies for carbon credits offset projects and carbon tax initiatives. During the first Kyoto commitment period through 2012, it was possible for entities in Kyoto-signatory countries with Kyoto obligations to offset those obligations through various "enabling mechanisms", including the purchase of offset credits from GHG emission reduction projects in developing countries via the Clean Development Mechanism (CDM). The CDM enabled purchase of offset credits as Certified Emission Reductions (CERs; units of metric tons CO_2 eq.) from landfill gas recovery projects in developing countries, including LFG recovery projects (Willumsen and Terraza, 2007). Currently, there is one approved methodology under the Kyoto Executive Board (ACM0001) for registered LFG CDM projects. This methodology requires the baseline estimation of CERs using a first order model, typically IPCC (2006). However, CERs are only approved based on rigorous monitoring protocols for actual CH_4 recovered. In practice, projects have reported a large shortfall between initial LFG recovery estimates and actual verified CERs [GHG reductions] (Sutter and Parreño, 2007).

In addition, the FOD model has been applied to "avoided landfill" CDM projects and carbon tax initiatives, as discussed below and in Table 1. Both of these risk further overextension of first order models to additional applications which cannot be supported as either good science or good policy. For landfill gas CDM projects, the applicable methodology (ACM-0001) only uses the IPCC or similar models for baseline calculations, not as the basis for monetized credits. Thus credits are created only via rigorous monitoring of LFG flow rates and CH_4 concentrations in the recovered LFG. However, other CDM methodologies for "avoided CH_4 to landfill" enable the monetization of credits for organic waste materials which are aerobically or anaerobically treated, but not landfilled, based only on application of the IPCC or similar models for landfilled waste (Möllersten and Grönkvist, 2007; Siebel et al., 2013).

Regarding carbon taxes, Australia has implemented a carbon tax of $25/ton for landfill CH_4, based on the IPCC (2006) FOD model with Australia-specific inputs, subtraction of recovered CH_4, an allowance for 10% oxidation, and the assumption that the remainder is emitted and thus subject to the tax. However, due to the strong dependence of FOD model results on the mass of waste, it is not possible for large landfill sites to reduce their emissions below a certain threshold. This has proven to be a strong financial disincentive

for landfill gas recovery and utilization projects, quite the opposite of the intended purpose of this tax (Australia, 2012a, b; Dreyfus, 2012). Recently (late 2013), there has been a political change in the Australian government, so the future of the carbon tax is uncertain (Black, 2012).

Therefore, consistent with a growing body of international literature suggesting that a new approach is needed, it is time to critically review the FOD-based approach for modeling surface emissions (Amini et al., 2013), as well as the 10% oxidation value (Chanton et al., 2009). Moreover, consistent with the evolving scientific understanding regarding rates and controls for landfill processes, it is now possible to develop a process-based, field-validated model specifically for ***emissions***. As the development, validation, and application of models is an evolutionary process, the underlying scientific understanding for measuring and modeling landfill CH_4 emissions has sufficiently evolved over the last decade to permit the development of a more rigorous modeling strategy. As discussed above, landfill CH_4 emission and oxidation rates, similar to rates in other soil settings, can vary over several orders of magnitude when measured at small scale (m^2). As also discussed above and in Table 1, instantaneously-measured rates are related to the composition and thickness of site-specific cover materials, the implementation of engineered gas recovery, and seasonal variability in oxidation in specific cover soils as a function of soil microclimate. Importantly, the IPCC acknowledges and encourages the development of more advanced "Tier 3" models in their documentation for the most recent GHG inventory guidelines (IPCC, 2006). Specifically, an "inventory compiler may use country-specific methods that are of equal or higher quality", favoring "a validated country-specific method." (p. 3.7, IPCC, 2006). Also, "when…Tier 3 approaches are used, countries can…create their own models" (p. 3.11, IPCC, 2006). We suggest that the CALMIM model meets these criteria.

2.3. NEW CALIFORNIA DATASET: EXAMINING THE APPLICABILITY OF THE FIRST ORDER DECAY (FOD) MODEL FOR LFG GENERATION AND RECOVERY.

The discussion in this section is enabled by a recently-available dataset (Walker, 2012) on permitted California landfills from the California Dept. of Resources Recovery and Recycling (CalRecycle), the agency responsible for regulation of California landfills. The Walker (2012) dataset is the update from the September 2011, presented at the CalRecycle Monthly Public Meeting[3]. This Excel spreadsheet was compiled from regulatory information supplied directly to CalRecycle, followed by extensive internal data review and validation. When this dataset became publically available in late 2012, we further analyzed some of the data contained therein to examine relationships between the 2010 mass of waste-in-place at specific sites, landfill cover areas, landfill gas recovery, and the CH_4 content of the recovered gas.

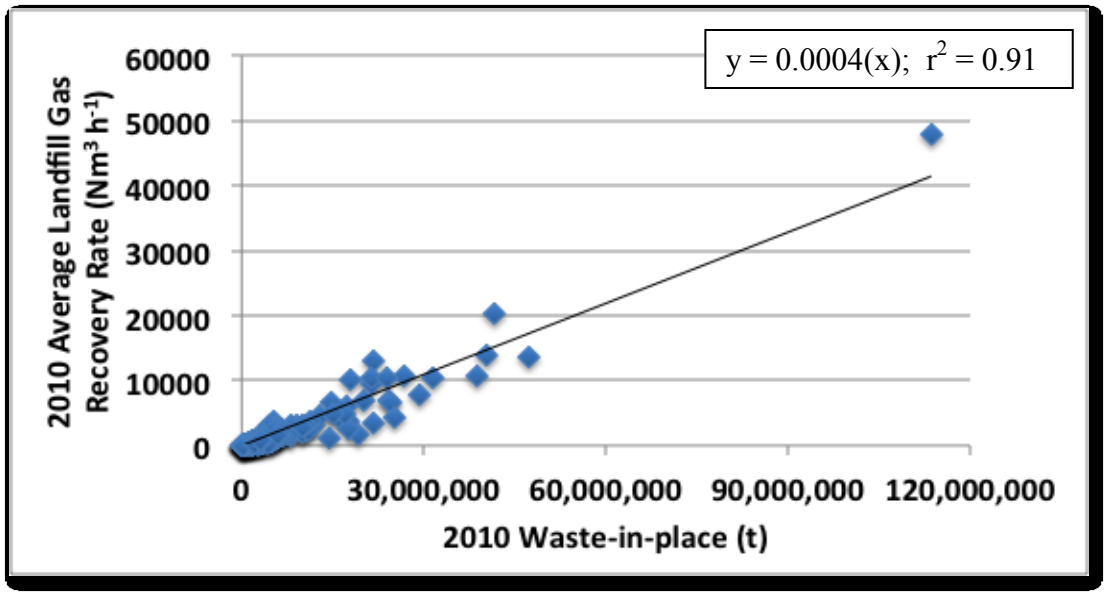
Through this data compilation, CalRecycle has determined that ***94% of the total waste-in-place in permitted California landfills is under active LFG extraction***. Thus, it is important to note that for California virtually all the waste landfilled is under active landfill gas recovery, or representing "welled" waste in place.

Using this dataset, we ask a very basic question: Is there a better alternative to first order kinetic equations for relating LFG generation and recovery to waste mass?
Figure 2A relates LFG recovery to the mass of waste-in-place at 129 well-managed California sites with full-scale LFG extraction systems. Figure 2B is the same plot without the high outlier (Puente Hills Landfill, Whittier, CA). Figure 3 presents the same data as Figure 2B, but with the y-axis values converted to a CH_4 basis, rather than total LFG.

Note the surprisingly robust linear relationship in all three of these plots. In all three cases the regression equation is forced through the origin with high r^2 values ranging from 0.81-0.91. Moreover, this relationship based on field data indicates that, contrary to a first order kinetic equation, these data suggest that LFG generation **proceeds at a fairly constant rate during the entire lifetime of a landfill site**. This conclusion is justified due to the fact that this database has a wide range of landfill ages and sizes. However, LFG recovery data suggests a similar production rate that is correlated to the waste in place (Figures 2 & 3). Even with the very large Puente Hills site [the high outlier], this relationship is consistent with the regression for the other 128 sites, indicating a relatively constant rate of LFG production, which is **0.003 to 0.004 m^3 LFG hr^{-1} (ton of landfilled waste)$^{-1}$** for all landfills in California.

[3] See http://www.calrecycle.ca.gov/Actions/PublicNoticeDetail.aspx?id=498&aiid=483.

(A)



(B)

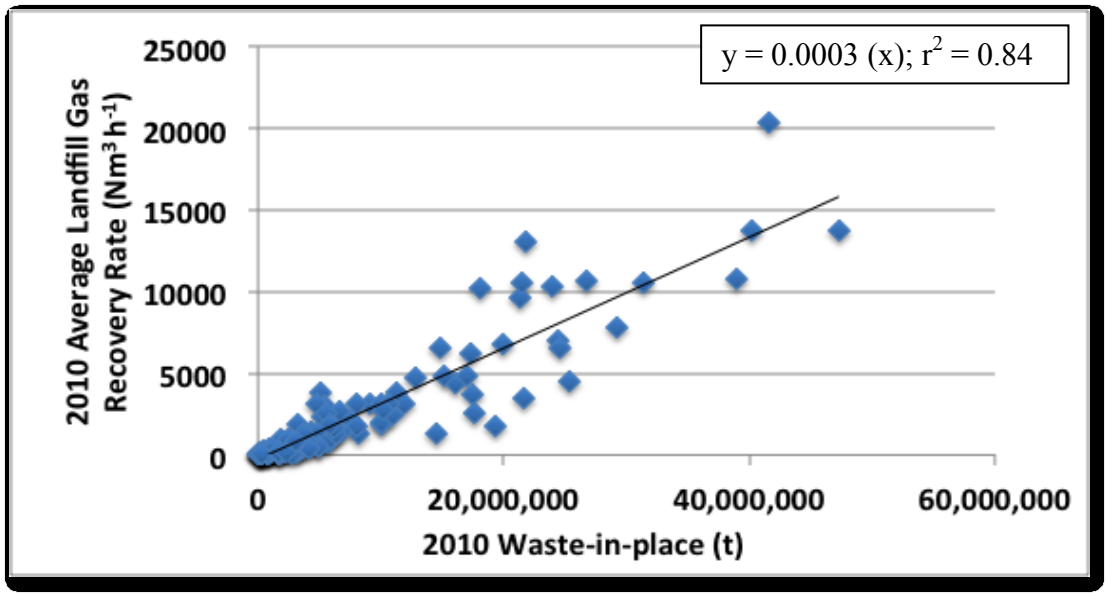


Figure 2. Relationship between waste in place (1 t = 1000 kg = 1 Mg) and average annual total landfill gas recovery rate (A) all for 129 Californian sites using data from CALRecycle (Walker, 2012) and (B) same data with Puente Hills landfill data point omitted (high outlier).

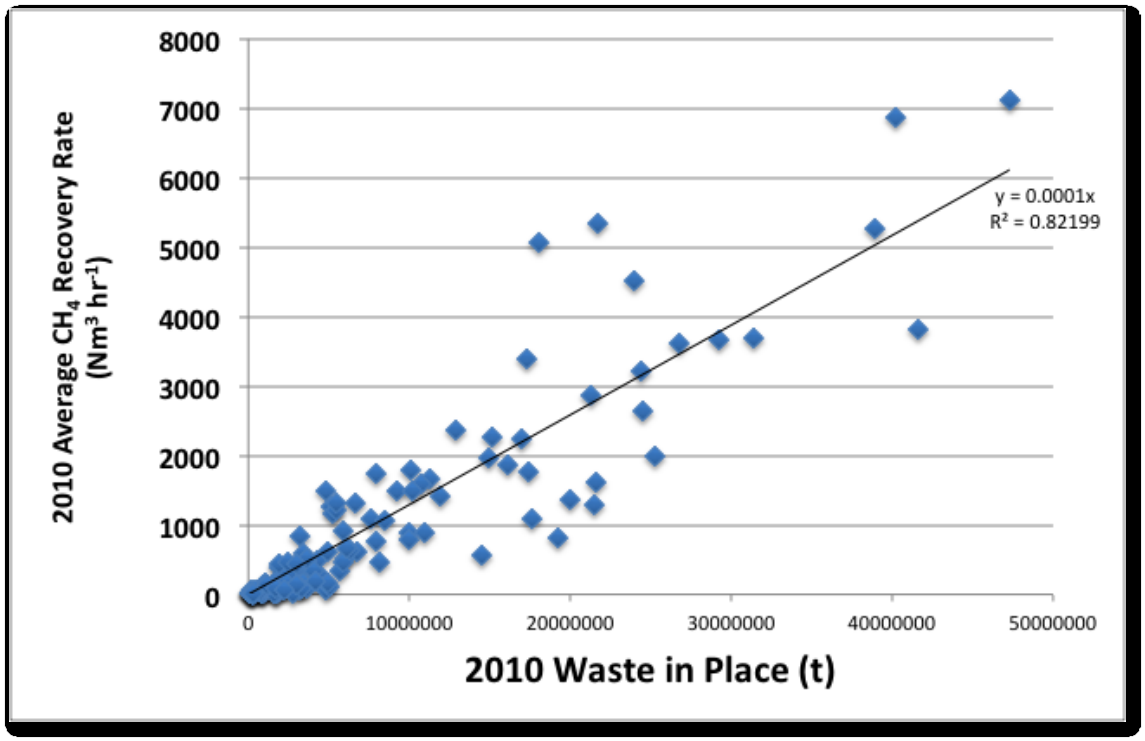


Figure 3. Relationship between waste in place (1 t = 1000 kg = 1 Mg) and total landfill methane recovery rate for only the sites in the California database (Walker, 2012) *where the CH_4 concentration was given (values between: 5-57%) and with the Puente Hills data point removed.*

These relationships call into question the FOD-based approach even for gas generation modeling, since this would suggest that a much simpler alternative to a first order kinetic equation is appropriate for estimating LFG recovery. This new LFG empirical relationship has the added advantage of field validation for 129 full-scale California landfills, the largest collection of internally consistent data known to be presently available. In a later section of this report, we will extend this discussion for California emissions to measured and modeled 2010 landfill CH_4 emissions based on the current California inventory (CARB, 2012) and develop a new California inventory using CALMIM.

2.4. JUSTIFICATION FOR CALMIM MODEL DEVELOPMENT AND IMPLEMENTATION

The development of CALMIM, a process-based model for site-specific landfill CH_4 emissions inclusive of seasonal oxidation has been extensively discussed in previous publications (Bogner et al., 2011; Spokas et al., 2011; Spokas and Bogner, 2011). CALMIM is an evolving, freely-available process-based model which represents an improvement over previous FOD-based strategies by directly modeling emissions. In general, when modeled emissions using IPCC (2006) are compared to field measurements of emissions at specific sites completed over the last two decades, the models cannot be relied upon to reasonably replicate those results (Schuetz et al., 2003; Scheutz et al., 2009; Spokas et al., 2011). Empirical data have indicated that it is not uncommon for well-designed and well-managed LFG recovery projects to recover double or more the estimated rate of recovery using LANDGEM or IPCC models [see discussion in Bogner et al. (2011) regarding original CALMIM field validation sites]. On the other hand, after the Kyoto Protocol entered into force in 2005 and LFG recovery projects in developing countries were eligible to provide offset carbon credits under the Clean Development Mechanism (CDM) to entities in developed countries with Kyoto obligations, many CDM projects have recovered only a fraction of the original baseline estimates using IPCC (2006) and similar models. This is often a function of several factors: overly optimistic models, lacking or unreliable waste input data, and non-optimized management practices. Nevertheless, there is recent historical precedent for high rates of both under prediction and over prediction using the first order models (Kumar et al., 2004; Chiemchaisri et al., 2011; McBean, 2011).

Although the literature contains several process-based models which rigorously address the seasonality of gaseous carbon and nitrogen fluxes in other managed and natural ecosystems [e.g., CENTURY (Parton, 1996); CASTANEA (Davi et al., 2006); and LPJmL (Müller et al., 2006)], similar seasonal models have not been previously developed for landfill settings (Boeckx et al., 1996; De Visscher and Van Cleemput, 2003; Molins et al., 2008; Abichou et al., 2011). Therefore, consistent with recent literature emphasizing strong seasonal dependencies for CH_4 transport, oxidation, and emissions in other managed and pristine soil ecosystems (Cao et al., 1995; Wille et al., 2008), a major goal for the current project was to further improve and internationally field validate a functional, process-based landfill CH_4 emissions model. Recent literature has emphasized the dependency of emissions of cover soil thickness and texture, as well as microbial oxidation rates which vary spatially and temporally with seasonal climatic trends (Jones and Nedwell, 1990; Kightley et al., 1995; Scheutz et al., 2009).

For landfill modeling purposes, the major controls are:

1. Engineered gas recovery which lowers CH_4 concentrations at the base of the cover, in turn reducing the driving force for diffusive flux of CH_4 to the atmosphere (Bogner et al., 1997a; Mosher et al., 1999; Park and Shin, 2001; Zhang et al., 2008), and

2. Soil gas transport and methanotrophic oxidation processes, which rely on the site-specific properties of the cover materials as well as seasonally-variable CH_4 transport and microbial oxidation (Maurice and Lagerkvist, 2003; Chanton et al., 2009; Abichou et al., 2011; Gebert et al., 2011).

In summary, the magnitude of landfill CH_4 emissions at a particular site are dependent on the thickness and properties of the various cover materials, site operational issues which includes the presence of engineered gas recovery, and the site location on the surface of the earth (which determines daily climate- and soil microclimate-related CH_4 oxidation rates in cover materials). However, these controls related to soil type and climate are not properly accounted for in current GHG inventory methods for landfill CH_4.

3. Methods

This section and the subsequent section (IV. Results and Discussion) of this report are each divided into 6 sub-sections. Each sub-section addresses a different aspect of the project. These sub-sections include:

1. CALMIM overview and programming improvements during EREF Project.

2. Direct comparison of CALMIM model results to field measurements of landfill CH_4 emissions from U.S. and international research groups.

3. Latitudinal gradient for landfill CH_4 emissions using CALMIM simulations for standardized cover soils.

4. CALMIM simulations for landfill CH_4 emissions under future climate change scenarios for selected global cities (SRES scenarios A2 and B1 for 2020, 2050, and 2100).

5. Field project, Indiana Landfill: May and August, 2012 field campaigns to quantify CH_4 and O_2 soil gas concentration gradients and variability for daily and intermediate cover soils for comparison of emissions prediction using default and custom boundary conditions. Custom boundary conditions are the preferred method for using CALMIM where data exist.

6. New 2010 California GHG inventory using CALMIM and site-specific comparisons to California field measurements of emissions.

3.1. CALMIM OVERVIEW AND IMPROVEMENTS DURING EREF PROJECT

3.1.1. Model Structure and Components

CALMIM is written entirely in JAVA. CALMIM currently consists of 531 Java Classes and is written in the NetBeans Integrated Developer Environment (IDE). NetBeans IDE and NetBeans Platform are based on software from netbeans.org, which has been dual licensed under the Common Development and Distribution License (CDDL) and the GNU General Public License Version 2 with Classpath exception. For more information, please visit www.netbeans.org.

CALMIM uses a total of 21 integrated libraries, with the most significant ones being:

- **jFreeChart** – Provides the graphical display of the generated data - see http://www.jfree.org/
- **Liquid-Look-n-Fee**l – Overall look-n-feel of the program
- **PTPLOT 5.6** – plotting program to display data - http://ptolemy.eecs.berkeley.edu/java/ptplot/
- **NanoXML** – Embedded XML parser for the CMM preference files http://nanoxml.sourceforge.net/orig/
- **XStream** – simple library to aid in saving and loading XML class library files (CMM preference file) - http://xstream.codehaus.org/
- **MigLayout** – layout manager for GUI windows http://miglayout.com/

CALMIM is a 1-dimensional finite difference model for the simultaneous simulation of heat, water, and gas transport through the landfill soil cover. Table 2 provides an overview of the model structure, components and default boundary conditions. CALMIM (https://www.ars.usda.gov/services/software/download.htm? softwareid = 300) is a freely available JAVA program which integrates site-specific data (location and cover design) with climatic simulation and one-dimensional soil microclimate and gas diffusion models for daily, intermediate, and final cover areas inclusive of CH_4 oxidation over a typical annual cycle.

CALMIM includes: (1) the effect of engineered gas extraction; (2) the physical effect of daily, intermediate, and final cover materials to retard emissions; and (3) seasonal moisture and temperature effects on both gaseous transport and methanotrophic CH_4 oxidation in cover soils. See Appendix A (User Manual) and Appendix B (Reprint of Spokas et al., 2011b).

The empirical relationship for oxidation used in the CALMIM model is derived from a series of over 900 laboratory incubations of landfill cover soils to determine relationships between methanotrophic activity and soil temperature (Figure 4) and moisture (Figure 5).

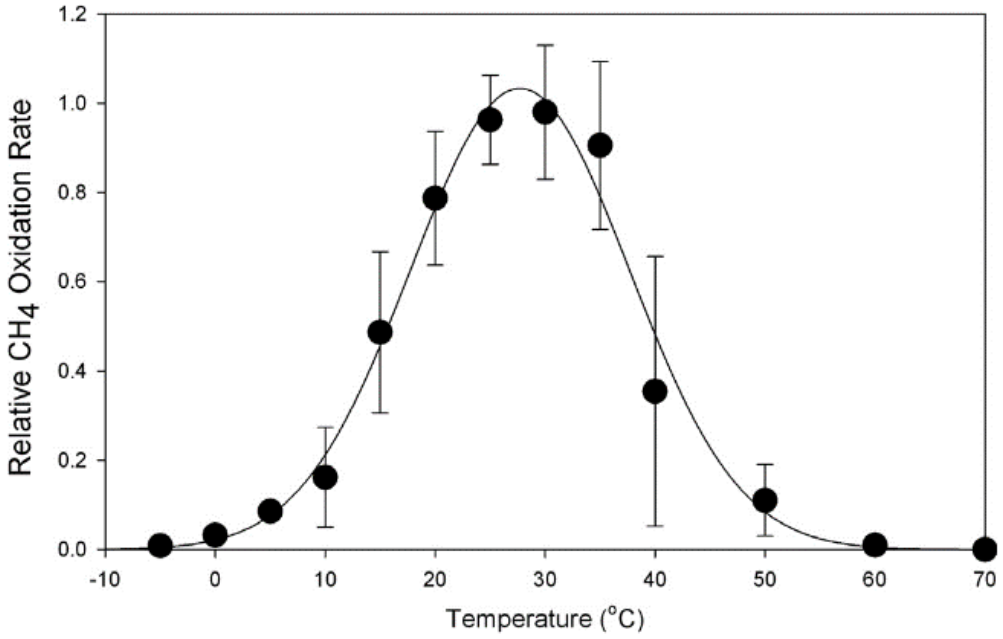


Figure 4. Effects of soil temperature on relative rates of CH4 oxidation [Figure taken from Spokas and Bogner (2011)].

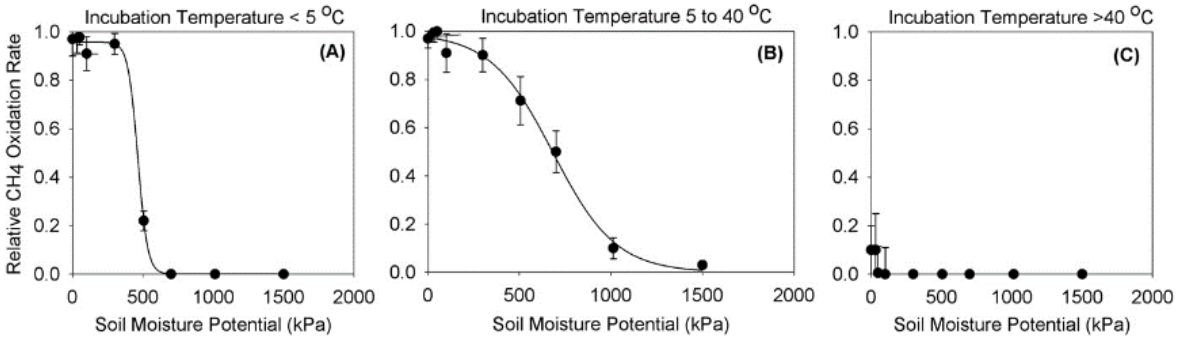


Figure 5. Effect of soil moisture content on relative rates of CH_4 oxidation as a function of soil temperature (A) <5°C, (B) 5-40°C, and (C) >40°C. [Figure taken from Spokas and Bogner (2011)].

Table 2. Overview of CALMIM input parameters, bundled models, and outputs.

					Description	**Value/Units/Reference**
Model Inputs	Site				Latitude	Decimal degrees (+N , -S)
					Longitude	Decimal degrees (-W, +E)
					Waste Footprint	Acres
	Cover Characteristics				Coverage	0-100% of waste footprint
					Organic Matter	Low-high (0-5%)
					Vegetation Presence	0-100% cover (slider bar)
						Modifies incoming solar radiation [Si = (1-Veg%)*Si]
					Gas Recovery System	0-100% coverage (slider bar) Reduces the lower methane concentration in default cover scenarios
		Cover Type Selection				
			Daily	Temperature	Upper	Air temperature simulation
					Lower	25 ºC
				CH_4	Upper	2 ppmv
					Lower	0.3 % (v/v)
				Oxygen	Upper	20 % (v/v)
					Lower	5 % (v/v)
				CH_4 oxidation rate		400 µg CH_4 $g_{soil}^{-1}d^{-1}$
			Intermediate	Temperature	Upper	Air temperature simulation
					Lower	35 ºC
				CH_4	Upper	2 ppmv
					Lower	45 % (v/v)
				Oxygen	Upper	20 % (v/v)
					Lower	1 % (v/v)
				CH_4 oxidation rate		400 µg CH_4 $g_{soil}^{-1}d^{-1}$
			Final	Temperature	Upper	Air temperature simulation
					Lower	40 ºC
				CH_4	Upper	2 ppmv
					Lower	55 % (v/v)
				Oxygen	Upper	20 % (v/v)
					Lower	0 % (v/v)
				CH_4 oxidation rate		400 µg CH_4 $g_{soil}^{-1}d^{-1}$
			Custom	User selectable boundary conditions		
		Layer Characteristics			Material	Various materials (Table 2)
					Thickness	Variable: 2.5 cm to 2.5 m (1 to 100")

Table 2. (Conitnued)

				Description	Value/Units/Reference
Bundled Models	GlobalTempSIM			Air temperature simulation	Spokas and Forcella, 2009
	GlobalRainSIM			Precipitation simulation	Spokas and Forcella, 2009
	SolarCalc			Solar radiation simulation	Spokas and Forcella, 2006
	STM^2			Soil temperature and moisture model	Spokas and Forcella, 2009
	Gas Diffusion			Oxygen and methane diffusion	Campbell, 1985
Model Outputs	*Model outputs are written directly to Excel compatible files for each cover type*				
	Daily Surface CH_4 emissions			With oxidation	g CH_4 $m^{-2}d^{-1}$
				Without oxidation	g CH_4 $m^{-2}d^{-1}$
	Soil Nodes (2.5 cm layer in cover)			Soil Temperature	^oC
				Soil Moisture	Volumetric (cm^3 cm^{-3})
				Air-filled porosity	cm^3 cm^{-3}
				Oxygen Concentration	% O_2
		CH_4 Concentration		With oxidation	% CH_4
				Without oxidation	% CH_4
				CH_4 oxidation rate	g CH_4 $m^{-2}d^{-1}$
				CH_4 oxidation percentage	%
				Bulk density	g cm^{-3}
				Fraction of time oxidizing	0 to 100% (0-1)
	Simulated Weather Data			Maximum air temperature	^{o}C
				Minimum air temperature	^{o}C
				Precipitation	mm

The major driving force for emissions is the CH_4 concentration gradient through user-selectable cover materials, which is, in turn, related to the presence of engineered gas extraction systems and the efficiency of CH_4 oxidation in any particular cover soil. Both transport and oxidation are rigorously linked to seasonal climatic and soil microclimate variability through modified versions of existing, globally validated models: Global TEMPSIM, Global RAINSIM, SOLARCALC, STM2 (Spokas and Forcella, 2006, 2009). Thus, CALMIM estimates annual CH_4 emissions while accounting for climate-induced variability on transport and microbial oxidation.

Although more complex models exist for predicting the flow of LFG as a function of diffusion and advection (Findikakis and Leckie, 1979; Young, 1989; El-Fadel et al., 1996; El-Fadel et al., 1997; De Visscher and Van Cleemput, 2003; Kindlein et al., 2006; Wang et al., 2011; Karanjekar, 2012), a number of the assumptions in these models are often violated in field settings (e.g., homogeneity of waste mass; uniform characteristics; static CH_4 generation rates). Moreover, required model input parameters are often unknown, highly variable or cannot be directly measured in field settings (e.g., gas flux to the base of soil cover). Thus, the theoretical complexity of existing models linked to various uncertainties relative to field settings hinders our ability to arrive at a robust tool that can be field-validated for prediction of surface CH_4 emissions.

Therefore, for CALMIM, we relied on a 1-D gaseous diffusion model, since this approach focuses directly on the factors that control surface emissions (e.g., cover soil characteristics, microbial CH_4 oxidation, climate, and CH_4 concentration gradient through the cover materials). Many components have both default settings as well as settings which can be customized by the user based on field measurements or site management practices (Table 2). The inclusion of site-specific practices including various cover materials and engineered gas recovery are extremely important for landfill settings which, compared to other CH_4-emitting settings such as wetlands or rice production systems, represent a highly managed endpoint (Bogner et al., 2000).

3.1.2. Overview of Model Structure and Site-Specific Inputs

Required CALMIM inputs include the site location (latitude and longitude), cover description (material type and layer thickness), and corresponding CH_4 concentration gradient. The site information is collected from the user through data input screens. Each daily, intermediate, and final cover material, up to a total of 10 different covers, is modeled separately with the results summed for an estimate of annual total site emissions. The user can choose between typical California cover designs or a customized sequence using the "cover designer" where any layered soil sequence can be entered (see Appendix A).

For a particular cover, the minimum thickness for any layer is 2.5 cm with a maximum total thickness of about 2.5 m, which is related to limits for typical PC memory resources. USDA standard soil texture classes, alternative daily cover (ADC) and other non-soil materials (e.g., composts, biosolids, tire chips, geomembranes) are also available with their corresponding transport properties taken from published literature.

A number of structural improvements to the JAVA code, additional modeling capabilities, and cosmetic upgrades have been added to CALMIM. In addition, some programming bugs were fixed. These improvements will be discussed in the "Results and Discussion" Section (Section IV-A).

3.2. DIRECT COMPARISON OF CALMIM MODEL RESULTS TO FIELD MEASUREMENTS OF LANDFILL CH_4 EMISSIONS FROM U.S. AND INTERNATIONAL RESEARCH GROUPS

We cooperated with U.S. and international research groups, individuals, and institutions with recent research results on landfill CH_4 emissions. We also consulted previously-published literature. A variety of field techniques have been historically used for landfill CH_4 emissions, including static chambers, vertical radial plume mapping, tracer correlation techniques, micrometeorological techniques, and aircraft-based mass balance techniques. As discussed previously in Bogner and Spokas (2010), there is no single field technique which is universally appropriate for all field campaigns. The choice of a technique depends on the research questions/purpose of a specific field campaign as well as the spatial/temporal scale of the measurements. For example, static chambers remain the best choice for small-scale process-based studies at the m^2 scale (e.g. temporal variations in areal emissions for a specific cover type as g CH_4 m^{-2} d^{-1}). In general, the combination of static chambers with an "above ground" technique is a useful approach to provide statistically significant data for whole sites partitioned into various subareas (e.g., different cover types, topography, construction techniques, and/or gas management strategies). Therefore, a combination of techniques can provide meaningful data for larger areas and whole site determinations (Mg CH_4 d^{-1} or Mg CH_4 y^{-1}).

For the current project, available field data were directly compared to CALMIM using 2 strategies:

- *CALMIM default runs*: using regulatory "minimum" standards for cover thicknesses and composition. This is consistent with CALMIM use for site-specific GHG emissions inventory reporting or compliance, as a replacement for the current FOD model-based approach. For example, in the U.S., state regulatory agencies operating under U.S. EPA Subtitle D municipal solid waste landfill regulations typically specify that daily cover shall be a minimum of 6 in and intermediate cover a minimum of 12 in. soil with low hydraulic conductivity. In most states, final covers are specified as geomembrane composite designs overlain by a soil layer for site vegetation growth. However, in some states, notably California and other western states, equivalent water balance or other types of monolithic or layered earthen soil covers are also permitted for final covers.

  "Default" runs give conservative results because:

a) For the landfill sites investigated in this report as well as other documented landfill field excavations to determine cover thicknesses; landfill covers have been observed to be thicker than regulatory or reported thicknesses. For example, 1 to 5 m variability was observed for intermediate cover thickness at a California hazardous waste landfill (Zornberg et al., 2003), 1-2 m variability in a final cover at a New Hampshire landfill site (Czepiel et al., 1996a), and 1-3 m variability for

soil cover thickness at a San Francisco landfill (Whalen et al., 1990). Daily and intermediate covers are typically thicker than the regulatory minimum of 6 inches or 12 inches, respectively. This results from the difficulty in placing a uniform 6" or 12" cover to adequately cover the irregular surface of the compacted refuse, whether this is after the working day (overnight) for daily cover or for extended periods of time (years) for intermediate cover. At some sites, moreover, thicker intermediate covers may also constitute long-term stockpiles for cover soil. Unfortunately, there is no existing database for actual cover thicknesses in the U.S. or internationally. A thicker daily covers retards onsite and offsite odors, reducing neighborhood complaints. For intermediate covers, a "typical" thickness would be 24 to 36+ inches or even greater (Peyton and Schroeder, 1988). Landfill sites which have topped out at high elevations (e.g., southern California canyon fills) routinely use thicknesses of 50-60+ inches for better odor control in the context of local meteorological conditions. In this report for CALMIM "default" runs for intermediate covers, we routinely compared 12 inch "minimum" to 36 inch intermediate covers.

b) CALMIM uses agricultural soil databases imbedded within the JAVA code so that, for a given soil type (e.g., sandy loam) transport rates will be over-predicted in comparison to more compacted landfill cover soils. As discussed in Spokas et al. (2011), comparable databases for landfill cover soils have not yet been developed.

- <u>*CALMIM custom runs*</u>: Using site-specific cover materials, thicknesses, soil gas profiles (CH_4, O_2), and weather data, as available. Available data from projects yielding "custom" data depended on the specific research questions, goals, and experimental designs of the individual field campaigns.

The 32 sites used in this validation are listed in Table 3 with locations shown in Figure 6. For each site, we summarized the site-specific information including, as applicable, reference to published sources. Then we directly compared field data to CALMIM modeled results for "CH_4 emissions with oxidation" and "CH_4 emissions without oxidation" in units of g CH_4 m^{-2} d^{-1}. The model results are based on 10-min. time-steps and 2.5 cm (1 in.) depth increments for a "typical annual cycle" of 365 days at a specified latitude/longitude location, cover thickness and composition, specified soil gas profile, modeled annual air temperature and precipitation, and modeled soil moisture/temperature. All of the detailed site summaries are presented in Appendix B.

These graphical summaries permit direct visual comparison of modeled vs. measured emissions, including the field measurements plotted correctly with respect to their date(s) within an annual cycle (x-axis = 365 days). The oxidation rate [also in g CH_4 m^{-2} d^{-1}] is calculated using the ratio of the current oxidation rate to the maximum rate for a particular instantaneous soil moisture and temperature. In this way, the magnitude and

variability of daily emissions, both with and without oxidation, can be readily visualized over the annual cycle.

In addition, to illustrate the drivers for the calculated emissions with and without oxidation, we also include standard modeled plots, again as a "typical annual cycle" for air temperature & soil temperature, precipitation & soil moisture, gas-filled porosity, and modeled soil gas CH_4 and O_2 profiles. Finally, as feasible, depending on the site, the annual results (kg CH_4 y^{-1} per cover type and per site) are also modeled and reported by CALMIM.

Table 3. Listing of US and International landfill sites that were used for the CALMIM validation

	Location	City/State	Country	Latitude (^{o}N)	Longitude (^{o}W)
1.	Taylors Road Landfill	Lyndhurst, VIC	Australia	-38.040	145.240
2.	St. Polten		Austria	48.197	15.592
3.	Grand'Landes		France	46.821	-1.650
4.	Lapouyade		France	45.085	-0.288
5.	Montreuil-sur-barse		France	48.226	4.295
6.	Landfill A	Johannesburg	South Africa	-26.200	28.500
7.	Landfill B	Johannesburg	South Africa	-26.300	27.800
8.	Landfill C	Johannesburg	South Africa	-26.200	27.600
9.	Landfill D	Johannesburg	South Africa	-26.200	28.000
10.	IN-1	IN	USA Midwest	39.742	-86.500
11.	Mallard Lake	Hanover Park, IL	USA Midwest	42.000	-88.000
12.	Newton County	IN	USA Midwest	40.917	-87.350
13.	Southside	Indianapolis, IN	USA Midwest	39.717	-86.200
14.	Randolph	IN	USA Midwest	40.083	-85.117
15.	Caldwell	IN	USA Midwest	39.691	-85.726
16.	Marina	Monterey, CA	USA Northern California	36.710	-121.762
17.	CA-4	CA	USA Northern California	37.760	-121.650
18.	CA-2	CA	USA Northern California	37.180	-121.670
19.	CA-1	CA	USA Northern California	38.165	-122.563
20.	CA-3	CA	USA Northern California	37.494	-121.995
21.	Scholl Canyon	Glendale, CA	USA Southern California	34.158	-118.196
22.	CA-5	CA	USA Southern California	34.742	-118.118
23.	Calabasas	Agoura, CA	USA Southern California	**34.151**	**-118.720**
24.	Puente Hills	Industry, CA	USA Southern California	**34.020**	**-118.006**
25.	Högbytorp	Stockholm	Sweden	59.200	18.000
26.	Malmö	Malmö	Sweden	55.400	13.000
27.	Helsongborg	Helsingborg	Sweden	56.000	12.400
28.	Emerald Park Landfill	Muskego, WI	USA Midwest	42.850	-88.060
29.	WI-1	WI	USA Midwest	42.850	-88.070
30.	Leon County Landfill	Tallahassee, FL	USA Southeast	30.420	-84.150
31.	Shan-Chu-Ku Landfill	Taipei City	Taiwan	25.033	120.533
32.	Muribeca Landfill	Muribeca, PE	Brazil	-10.430	-36.960

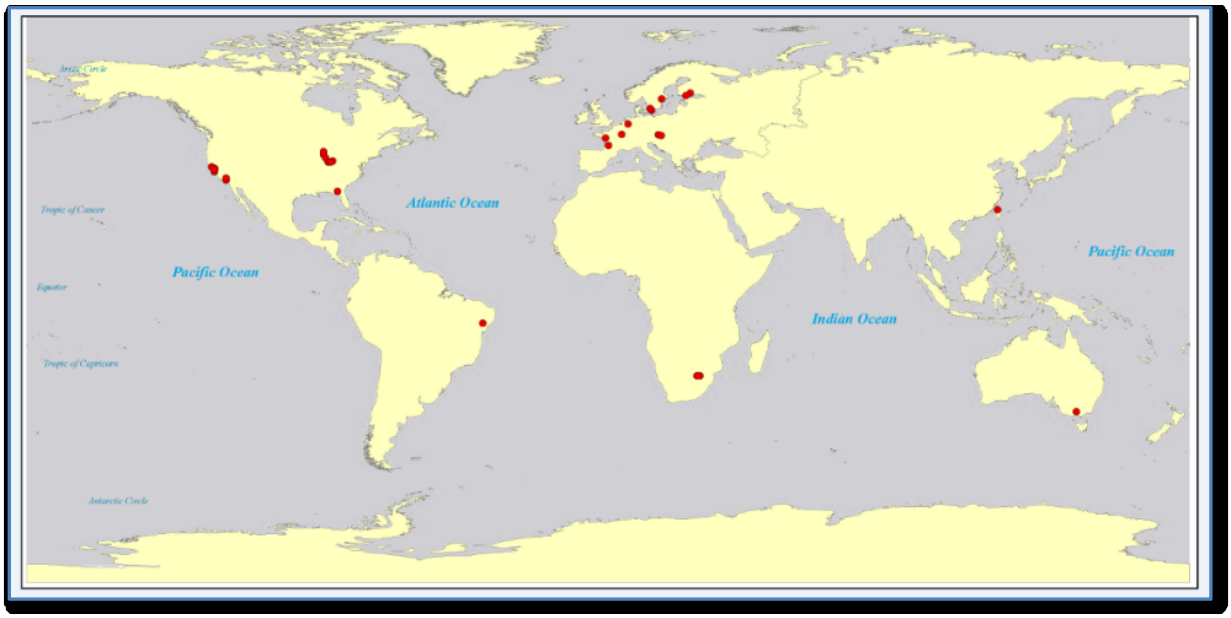
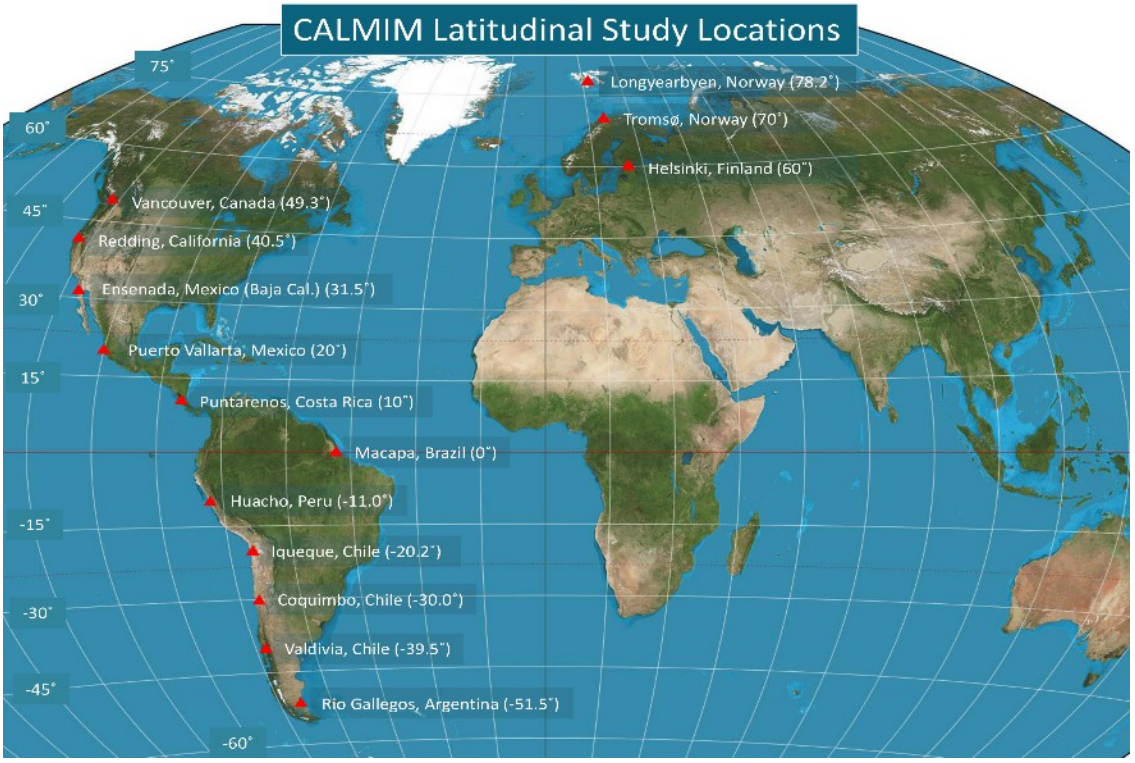


Figure 6. Location of the global sites used in the CALMIM validation study.

3.3. LATITUDINAL GRADIENT FOR LANDFILL CH_4 EMISSIONS USING CALMIM SIMULATIONS FOR STANDARDIZED COVER SOILS.

To compare CALMIM output for various cover types over a range of thicknesses, a series of generic runs for soil triangle end members and midpoint (sand, silt, clay, loam) were completed for selected global locations encompassing a latitudinal gradient from high northern to high southern latitudes. With the exception of the 3 most northerly latitudes, which were in Europe, all of the other cities were in the Western Hemisphere (Canada, U.S., Mexico, Central, and South America). This latitudinal variability permitted comparison of typical annual cycles, annual emissions, and oxidation for a variety of global locations. The cities are shown in Figure 7.

For this project, we selected a series of 13 global locations ranging from 70 ^{o}N (Norway) to 50 ^{o}S latitude (Argentina) and examined predicted landfill CH_4 emissions with soil oxidation for a 0.5 m sand cover, no vegetation, and full gas recovery. Although the transect locations include a mix of developed and developing countries, we suggest that a 0.5 m sand cover could perhaps be considered a global minimum for sites in developing countries.



1) Longyearbyen, Norway 78.2 deg. N
2) Tromsø, Norway 70 deg. N
3) Helsinki, Finland 60 deg. N
4) Vancouver, BC, Canada 49.3 deg. N
5) Redding, California, USA 40.4 deg. N
6) Ensenada, Mexico (Baja) 31.5 deg. N
7) Puerto Vallarta, Mexico 20 deg. N
8) Puntareno, Costa Rica 10 deg. N
9) Macapa, Brazil 0 deg. N
10) Huacho, Peru -11 deg. S
11) Iquque, Chile -20.2 deg. S
12) Coquimbo, Chile -30 deg. S
13) Valdivia, Chile -39.5 deg. S
14) Rio Gallegos, Argentina -51.5 deg. S

Figure 7. Latitudinal study using CALMIM

3.4. CALMIM SIMULATIONS FOR LANDFILL CH_4 EMISSIONS UNDER FUTURE CLIMATE CHANGE SCENARIOS FOR SELECTED GLOBAL CITIES (SRES SCENARIOS A2 AND B1 FOR 2020, 2050, AND 2100).

One facet that has not been addressed to date is the impact of climate change on the CH_4 oxidation capacity of landfill cover soils and what this means for landfills as a GHG source in light of future climate variability. Importantly, other CH_4 environments have been previously assessed for their sensitivity to climate change, particularly wetlands (Shindell et al., 2004) and peat lands (Moore et al., 1998). Here we utilized CALMIM as a validated landfill CH_4 emissions model to examine the potential implications of global climate change on future landfill CH_4 emissions.

The availability of site-specific climate predictions for daily precipitation and daily minimum/maximum air temperatures for selected global cities permitted us to model future landfill CH_4 emissions in 2050 and 2100 inclusive of oxidation. Two contrasting scenarios (A2 and B1) from the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000) were selected. In total, there were four major "SRES" scenarios which, taken together, encompassed a range of trajectories for future development, population growth, energy strategies, and international cooperation (see Figure 8). For purposes of the current CALMIM project, the selected A2 and B1 scenarios describe contrasting global conditions over the remainder of the 21st century, as follows (Banuri et al., 2001):

> **Scenario A2.** The A2 storyline and scenario family describe a heterogeneous world in which the underlying theme is self-reliance and preservation of local identities. The population is continuously increasing with fertility patterns across regions converging very slowly. Economic development is regionally oriented with per capita economic growth and technological change more fragmented and slower than in the other scenarios.
>
> **Scenario B1.** The B1 storyline and scenario family describe a convergent world with global population which peaks in mid-century and declines thereafter with rapid change in economic structures towards a service and information economy, reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions for issues of economic, social, and environmental sustainability but without additional climate initiatives (e.g. Kyoto Protocol).

For this analysis, we were limited to global locations for which detailed daily projections for temperature and precipitation were available. Datasets for A2 and B2 scenarios for projected daily air temperature (high, low) and daily precipitation for 2020, 2050 and 2100 were accessed from the National Center for Atmospheric Research (NCAR) (NCAR, 2012b, a). These modeled climatic datasets were then used in CALMIM projections for landfill CH_4 emissions for those years for standardized cover materials (sand, silt, clay, loam) for the following global cities:

a. Lulea, Sweden (high northern latitude, temperate: 65.6 deg N, 22.2 deg. E)
b. Cairo, Egypt (mid-northern latitude, dry, 30.1 deg N, 22.2 deg. E)
c. Macapa, Brazil (equatorial, tropical: 0.03 deg N, -31.2 deg. W)
d. Capetown, S.Africa (mid-southern latitude, coastal: -33.6 deg S,18.3 deg. E)

The landfill emissions projections discussed in the next section of this report compare "CH_4 emissions with oxidation" to "CH_4 emissions without oxidation" to indicate how climate change alone can alter landfill CH_4 emissions in contrasting global regions. Emission units for all cover types are standardized on an area basis (g CH_4 m^{-2} d^{-1}).

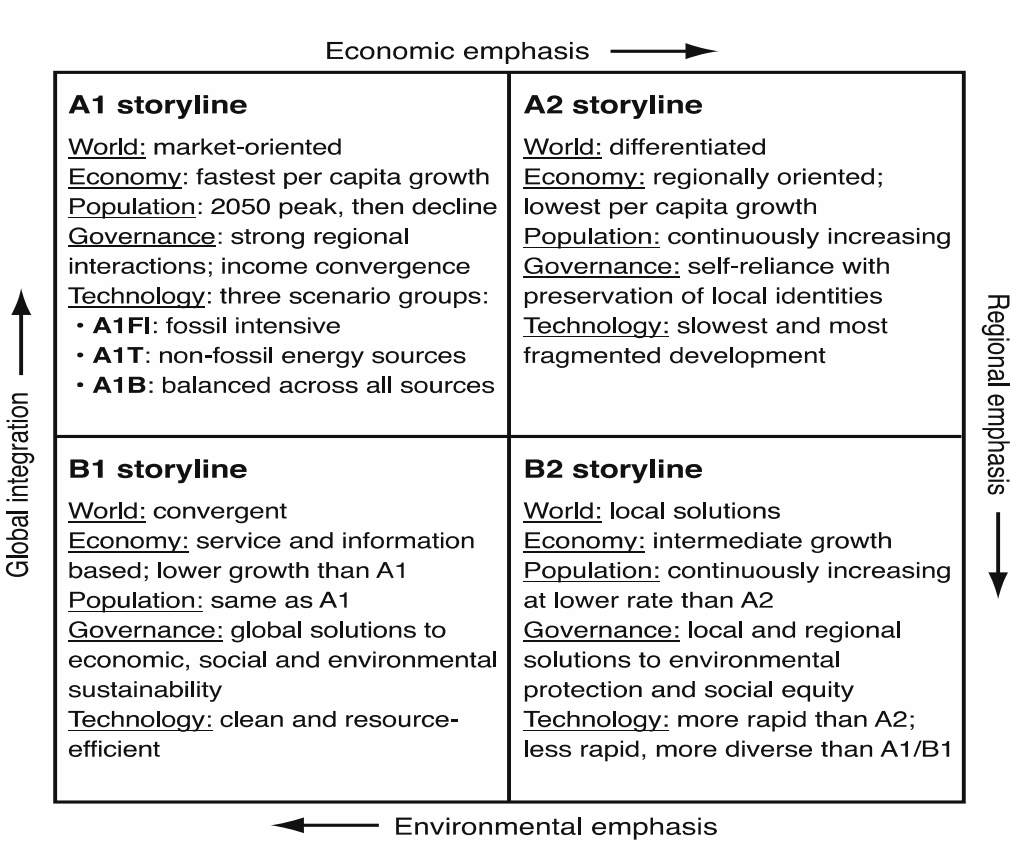


Figure 8. Summary of SRES scenarios [Image taken from Technical Summary, IPCC 3rd Assessment Report, Working Group III: Mitigation (Banuri et al., 2001)].

3.5. FIELD PROJECT, INDIANA LANDFILL.

UIC conducted two field campaigns (May & August, 2012) at a central Indiana landfill operated by Waste Management, Inc. This project consisted of a 3-way collaboration between UIC, Waste Management, Inc., and Purdue University with 2 major objectives:

1) For the current CALMIM project: development of guidance for CALMIM users regarding a "minimum" site-specific field campaign for input of site-specific "custom" data into CALMIM for soil gas profiles, as opposed to use of CALMIM default data for a given cover type.

2) More generally: a comparison of landfill CH_4 emissions at field scale using 4 different methods over a variety of scales. The responsible organization for each method is given in brackets. The methods included:

    - Small static chambers with supporting soil gas probes to measure soil gas concentration profiles [UIC/EREF],
    - Intermediate-scale Vertical Radial Plume Mapping (VRPM) (Goldsmith Jr et al., 2012) [Waste Management, Inc.],
    - Dynamic tracer correlation approach (TCA) using C_2H_2 (Czepiel et al., 1996b; Chanton et al., 1999; Hensen and Scharff, 2001) [Waste Management, Inc.], and
    - Larger-scale aircraft-based mass balance method relying on vertical CH_4 concentration and wind speed gradients (Garman et al., 2006; Mays et al., 2009; Zhang et al., 2009) [Purdue University].
    - As of December 2013, the field data from the collaborators were incomplete and are not discussed in this report.

This report will focus on the UIC studies. The UIC studies included field measurement of CH_4 emissions, soil gas profiles, and CH_4 oxidation rates for intermediate (May 2012) and daily cover soils (August 2012). Included were soil gas CH_4, CO_2, O_2, and N_2 concentrations at the base of the cover, soil gas concentration profiles, and direct measurement of CH_4, N_2O, and CO_2 fluxes to the atmosphere using a static closed chamber technique (previously described in Spokas et al., 2011; Bogner et al., 2011).

During May, 2012, at "near-well" and "between-well" locations, we completed static chamber fluxes and concurrent soil gas profiles on an intermediate cover area with vertical gas extraction wells, using a stratified random sampling design. A portable soil gas probe (USGS Branch of Isotope Geology) was used for soil gas profiles. Samples were withdrawn using a 10 mL syringe at successive depths (after purging at each depth). Samples were extracted through a septum port installed in a ¼ in. stainless steel Ultra-Torr fitting (Swagelok^{TM}) on top of the probe—this fitting was removed during successive probe installations at deeper depths. The stainless steel static chambers consisted of 2 parts: 1) a cylindrical base with a beveled lower edge to push into the cover soil and a thin trough welded to the top which is filled with distilled water during measurement periods; 2) a hemispheric chamber which exactly fits into the water-filled

top trough and is further secured with four hand clamps (Figure 9). During short monitoring periods (<30 min), 6 timed samples of 5 mL each are withdrawn from a septum port at the top of each chamber using a 10 mL syringe. Each gas sample is immediately placed into a headspace vial (Agilent) flushed with He.

Figure 9. Photo of stainless steel flux chamber used for Indiana Field Project

The May 2012 field campaign focused on a long term intermediate cover area with full gas recovery, while the August 2012 study focused on a smaller "extended" daily cover area without gas recovery wells which, over the last 1-2 years, has been the focus of multiple Waste Management campaigns monitoring CH_4 emissions using VRPM and, more recently, the TCA technique. For the May 2012 field campaign on intermediate cover, UIC quantified "proximal" fluxes and soil gas soil profiles at constant 4 m distances from existing gas wells with "distal" fluxes and soil gas profiles at greater randomized distances from gas wells. For the August 2012 field campaign on the "extended" daily cover area, each of 6 randomized soil gas profiles were paired with 3 static chamber fluxes. Additional randomized soil gas profiles to the base of the cover were also completed on this area. Also, three of the static chambers were replicated four times over an 18-hour period.

Sample Analysis:

All samples were sent to K. Spokas at the USDA/ARS laboratories in St. Paul, MN for analysis using GC and GC/MS instrumentation (Figure 10) as described in previous publications (Spokas and Bogner, 2011; Bogner et al., 2011; Spokas et al., 2011). The minimum detectable fluxes were 12 mg m^{-2} d^{-1} for CH_4, 0.322 mg m^{-2} d^{-1} for CO_2, and 0.7 mg m^{-2} d^{s} for N_2O. In addition, a separate set of samples were also sent to J. Chanton at Florida State University, Tallahassee, for stable carbon isotopic analysis ($\delta^{13}C$ on CH_4 and CO_2).

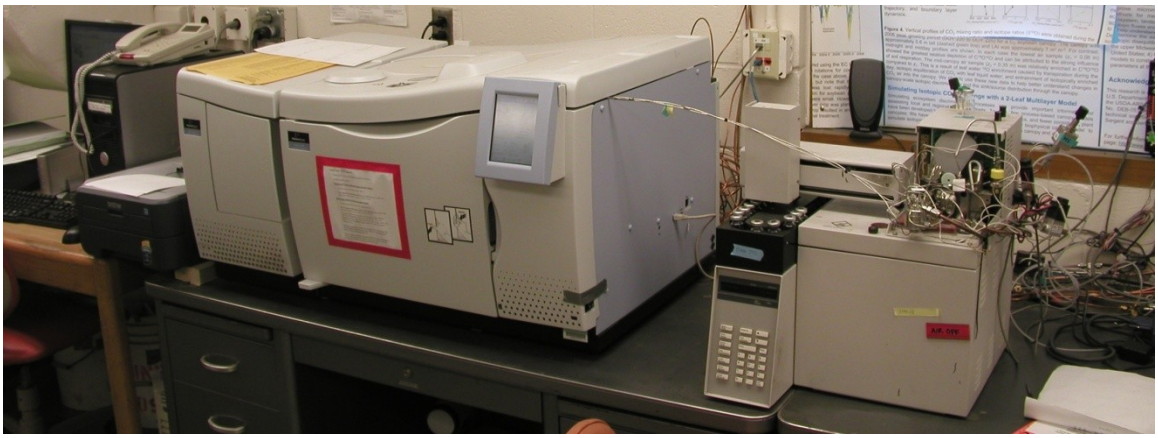


Figure 10. Photo of the GC-MS system (Perkin-Elmer Model 600T Gas Chromatograph-Mass Spectrometer) used to analyze the Indiana field gas samples in the USDA-ARS laboratory in St. Paul, MN.

This report will focus specifically on the UIC results relative to the current CALMIM project. A journal article is in progress with Purdue University and Waste Management, Inc. summarizing the multi-technique comparisons at field scale. However, this draft manuscript will not be available until after the deadline of the EREF project.

3.6. NEW 2010 CALIFORNIA GHG INVENTORY USING CALMIM AND SITE-SPECIFIC COMPARISONS TO CALIFORNIA FIELD MEASUREMENTS.

There have been a number of recent studies addressing the improved mathematical prediction of landfill CH_4 emissions. As discussed previously, there is a wide-spread realization that landfill emissions are spatially and temporally heterogeneous and that soil texture, temperature and moisture control soil methanotrophic activity (Czepiel et al., 1996a; Bogner et al., 1997c; Chanton and Liptay, 2000; Pawłowska et al., 2003; Albanna et al., 2007; Lee et al., 2009; Pratt et al., 2013). Despite this linkage, the first grouping of recent studies focuses on improved FOD modeling of landfill CH_4 generation through modification of the L_o and k factors to arrive at an improved estimation of the CH_4 generation rate (i.e., Amini et al., 2012; Karanjekar, 2012; Sormunen et al., 2013). On the other hand, there have also been recent efforts to develop a more mechanistic model simulating gas diffusion and/or advection processes in landfill cover soils (De Visscher and Van Cleemput, 2003; Abichou et al., 2006a; Abichou et al., 2006b; Abichou et al., 2011). However, a major issue with previous modeling efforts is the complexity of input requirements and concurrent difficulty with model validation at field scale. Some recent model advancements have turned to the use of artificial neural networks (ANN), due to the overall complexity of soils and the inability of mechanistic models to account for interrelated factors (discussed by Young et al., 2001). For example, Abushammala et al. (2013a) utilized an artificial neural network to predict the percentage of oxidation for a particular landfill. Although not used directly as a replacement for model input parameters, this ANN was assumed to account for a variety of climatic and soil properties to arrive at an improved prediction of the percent of methane that was oxidized at a particular site. The authors then utilized this improved percentage in the IPCC guidelines, modifying the FOD prediction from the gas generation model (Abushammala et al., 2013b). However, a disadvantage is that ANN models would require separate training (calibration) for different soil textures, climates, and cover geometries.

Therefore, to improve estimates of landfill emissions it is clear that the seasonality of the mitigating potential of the landfill cover soil must be accounted for. This was accomplished in this study by using a customized batch-processing utility developed for CALMIM, which permitted us to estimate the entire 2010 California GHG inventory for landfill CH_4 emissions for all 372 California landfill sites.

For 2010 input data, we relied on the Walker (2012) database discussed above, which had the most complete data for 2010 for all California landfill sites. Inputs included the site-specific waste footprint, final cover area, and [daily + intermediate] cover area (all in acres). For sites that were still active, we assumed a 10 acre working face that would be covered with daily cover at end of each day. Consistent with the most common types of California cover materials in the Walter (2012) database, we also made the following assumptions:

- **Daily cover: 6 in. composted/ground garden waste**. This is a conservative value as many sites use 12 in. or more daily cover, and many sites use fine-grained soils rather than recycled source-separated organic matter.
- **Intermediate cover**: sandy loam over a range of thicknesses from 12 in to greater than 72 in. The regulatory minimum is 12 inches; however, it is standard practice to use thicker intermediate cover materials, and more clayey soils where available, up to a maximum thickness of 60 in. or more. Therefore, we used **36 inches sandy loam**, which can be considered a typical but conservative value.
- **Final cover:** We used the California 27 CCR specified minimum cover, consisting of **12 in loam, 12 in clay, and 24 in silty clay loam**. Earthen soil covers are more common than composite geomembrane covers in California. The CA 27 CCR and similar earthen covers are the most common specified 2010 final covers in the Walker (2012) database. As with the intermediate covers, many sites use soil covers thicker than the specified minimum, so this 48 in. cover can also be considered a conservative value.
- For all covers, we assumed low organic matter, and no surface vegetation.
- **LFG Recovery:** This was selected as indicated in the database, if the site had gas recovery then CALMIM was run with the LFG recovery option selected with the default concentration profiles. If there was no LFG recovery system, then this option was not selected.

We then compared total California landfill CH_4 emissions, as well as the spatial and temporal distribution of emissions inclusive of CH_4 oxidation, to the existing 2010 inventory (Hunsaker, 2012). The major research questions were:

a. Which sites and cover materials were responsible for the highest emissions and largest % of landfill CH_4 emissions?
b. Statewide, how did monthly % oxidation vary over an annual cycle?
c. How do "net" emissions with oxidation relate to the important climatic variables affecting oxidation rates (temperature, precipitation)?

Finally, for 10 California sites where landfill CH_4 emissions have been measured at field scale by various research groups using a variety of methods (from small-scale chambers to aircraft-based methods), we compared field measurements to both the CALMIM 5.4 modeled values and values from the CARB (California Air Resources Board) 2010 GHG inventory for landfill CH_4 emissions calculated using the FOD methodology (IPCC, 2006).

4. Results and Discussion

4.1. SPECIFIC CALMIM IMPROVEMENTS DURING EREF PROJECT TIMELINE (2011-2013).

Numerous structural/cosmetic improvements, additional computation capabilities, graphical interfaces, and other upgrades have been added to CALMIM during this project. Below is a listing of the most significant improvements:

4.1.1. Overall Program Enhancements:

- Improved main menu graphics and menu structures as shown in Figure 11.

Figure 11. Improvements in CALMIM main menu screens.

- Improved model performance through decreased run times. A major emphasis of this project was to reduce run-times. This has been accomplished: Currently, a 1.5 m cover takes about 6 minutes on a typical dual core (Intel i3 – 1.8GHz) processor.

- Corrected minor bugs in the calculation modules to reduce memory leaks during program execution.

- Improved multi-platform capability (PC, MAC O/S, UNIX)

- Download section on ARS website now includes a specific MAC version with standard Mac O/S Installer

- Expanded ability to run 10 different covers concurrently for one site using 30 available materials (standard soil textures and alternative cover materials) for layered cover soils specified by user. Total cover thickness is limited by local computer resources (e.g., cover thickness >2.5 m requires 4+ GB memory)

4.1.2. Specific Program Improvements

These include improved graphical interfaces, expanded automatic generation of output files and graphs, and more user-friendly features. Also included is the modernization of the GUI interface to the new JAVA standards.

For example, the improved on-line map feature for site selection is shown in Figure 12.

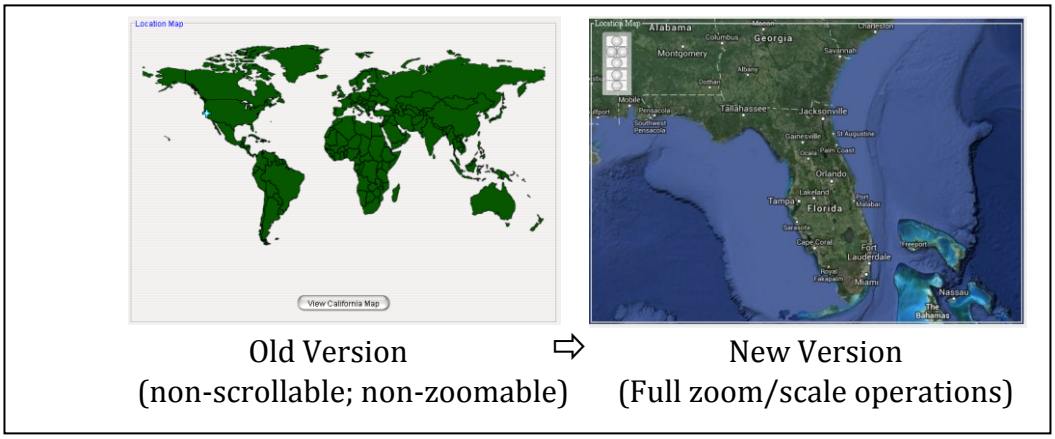


Figure 12. Improvements in CALMIM site selection screens

Satellite imagery is also provided through Google Hybrid Maps and OpenMapStreet sources for improving landfill site selection (Figure 13) .

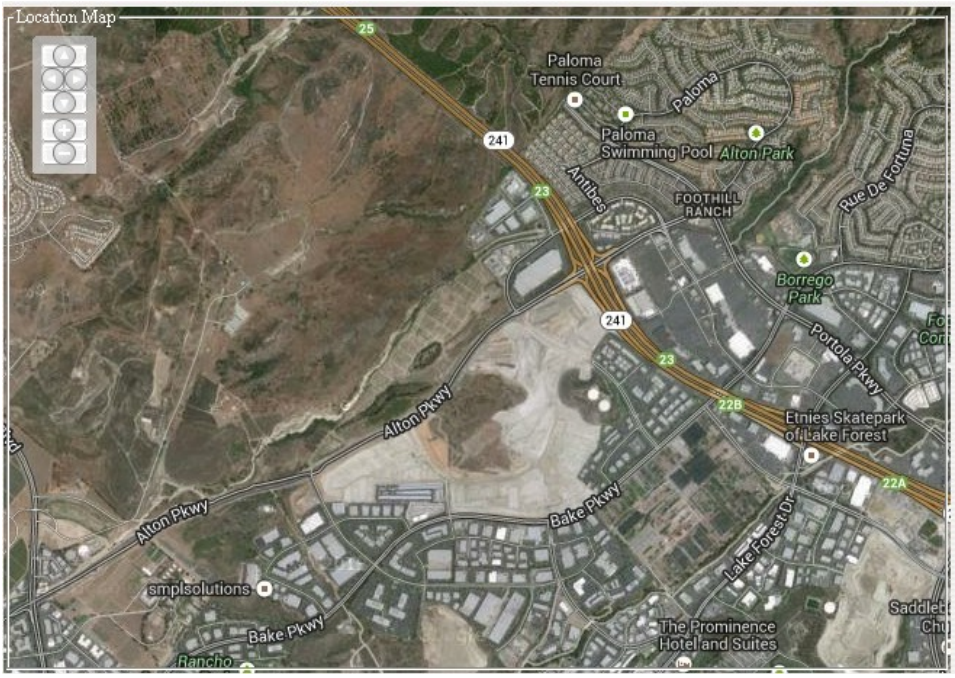


Figure 13. Overlaying of satellite imagery to improve landfill site selection.

Other map tile server possibilities were also added to the program (Figure 14), to give the user additional options for the level of detail in the displayed map.

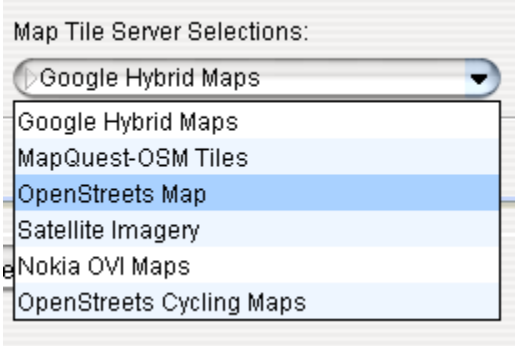


Figure 14. Selection box for new map tile servers now available in CALMIM.

With the exception of the Google Hybrid Maps, these map tile features are based on OpenStreetMap.

OpenStreetMap is *open data*, licensed under the Open Data Commons Open Database License (ODbL). The cartography in our map tiles, and our documentation, are licensed under the Creative Commons Attribution-ShareAlike 2.0 license (CC BY-SA). OpenStreetMap is "© OpenStreetMap contributors". Map data is available under the Open Database License, and if using our map tiles, that the cartography is licensed as CC BY-SA. (see this copyright page). Although OpenStreetMap is open data, we cannot provide a free-of-charge map API for third-party developers. See their API Usage Policy, Tile Usage Policy and Nominatim Usage Policy. Contributors to OpenStreetMap include thousands of individuals.

We also include openly-licensed data from national mapping agencies and other sources, including:

- **Austria**: Contains data from Stadt Wien (under CC BY), Land Vorarlberg and Land Tirol (under CC BY AT with amendments).
- **Canada**: Contains data from GeoBase®, GeoGratis (© Department of Natural Resources Canada), CanVec (© Department of Natural Resources Canada), and StatCan (Geography Division, Statistics Canada).
- **France**: Contains data sourced from Direction Générale des Impôts.
- **Netherlands**: Contains © AND data, 2007 (www.and.com)
- **New Zealand**: Contains data sourced from Land Information New Zealand. Crown Copyright reserved.
- **South Africa**: Contains data sourced from Chief Directorate: National Geo-Spatial Information, State copyright reserved.
- **United Kingdom**: Contains Ordnance Survey data © Crown copyright and database right 2010-12.

For further details of these, and other sources that have been used to help improve OpenStreetMap, please see the Contributors page on the OpenStreetMap Wiki. Inclusion of data

in OpenStreetMap does not imply that the original data provider endorses OpenStreetMap, CALMIM or provides any warranty, or accepts any liability.

Other new features include the following:

- Added embedded unit conversions for metric system (i.e., site area in hectares).
- Improved graphical buttons for quick positioning within the site wizard screens as shown in Figure 15.

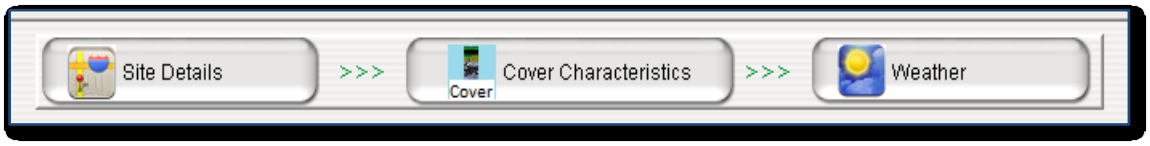


Figure 15. Improvements in CALMIM wizard progress buttons.

- Improved data output directly into Microsoft Excel® compatible workbooks.
    - Output directory format established to ensure ease of user data retrieval.
    - Added generation of an "Overview" Excel file, which contains the pertinent information for each model run (Figure 16).

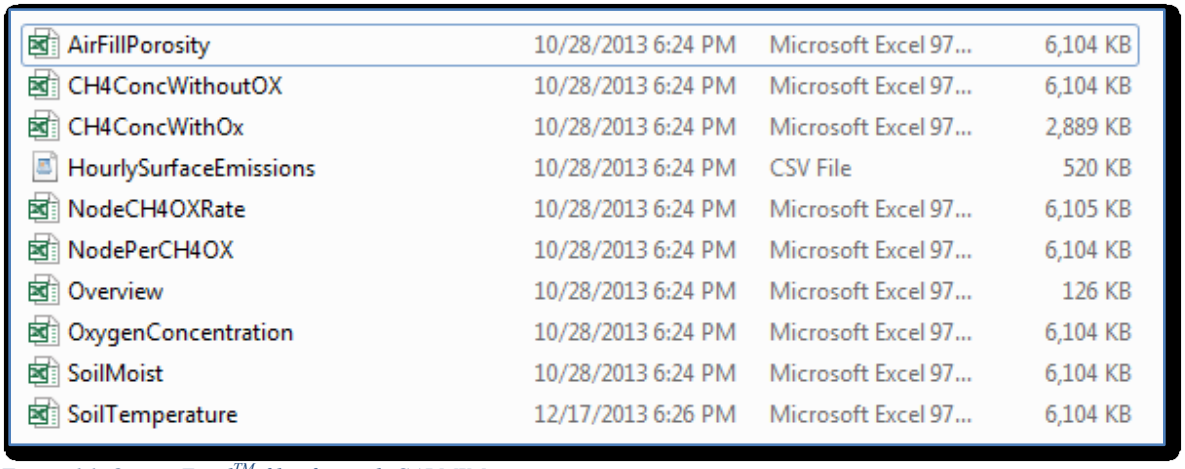


Figure 16. Output Excel™ files for each CALMIM run.

- Added on-line help (Microsoft based HELP file), which allows searches and improved linking with the program interface as shown in Figure 17.

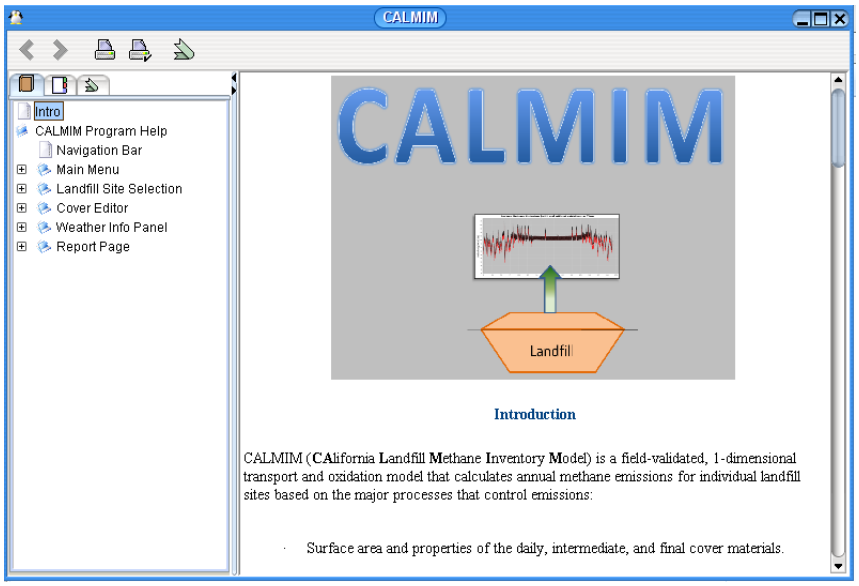


Figure 17. Illustration of CALMIM on-line help system.

- Improved soil profile initialization step to minimize numeric error due to model initialization.

  For numerical modeling, particularly for seasonal climatic effects, consistent initialization of differential algebraic equations (DAEs) is often very difficult to obtain (Ascher and Petzold, 1998). This stems from the fact that the model starts out uninitialized (in other words all variables are 0 [zero]). However, our starting conditions do vary from year-to-year as well as site-to-site. Adding further complication is the requirement that there are fixed algebraic constraints in the numeric solutions for the DAEs that are often difficult to satisfy with unknown initial starting values. In order to keep the number of required model input parameters to a minimum, a solution was needed for model initialization.

  However, discrete initialization steps can and do have drawbacks. Initialization steps in a numeric model can place a large burden on the computation time, often limiting the real-time simulation that can be performed (Tummescheit and Eborn, 2002). In order to prevent the doubling of computation time, a pre-initialization run of the CALMIM model is performed where the model uses hourly time steps (60 minutes) to simulate the soil temperature, moisture, and gas transport through the various soil covers over a typical annual cycle. This initialization run then retains the ending values to re-initialize the model for the "real" calculations using the model conditions at the end of the initialization year as the starting values for the new start of the year.

  This initialization method saved computation time, while improving initialization of the numeric model with minimal data for initial conditions (e.g., temperature and soil moisture profile data). When we expanded CALMIM applications after

2010 to landfill sites outside of California for the current EREF project, initialization errors were a particular issue for (northern latitude) cold climatic regions with freezing soil temperatures.

- Improved modeling of site-specific boundary conditions.

  We fixed a bug which ignored user-entered boundary conditions if the stability criterion for the numerical modeling was violated. The remedy for this issue was also aided by the pre-initialization runs discussed above.

- Fixed bug in oxygen transport routines, which instead of allowing bidirectional transport, was formerly only allowing downward diffusion of oxygen and not upward oxygen diffusion. This has been fixed in Version 5.4.

4.2. Direct Comparison Of CALMIM Model Results To Field Measurements of Landfill CH_4 Emissions From U.S. and International Research Groups.

4.2.1. Overview of measured vs. modeled results.

This section focuses on detailed comparisons between field measurements at specific sites and CALMIM (version 5.4) modeled results. Table 3 previously provided a list of the 32 sites where site data were compared to CALMIM modeling. This section provides a summary for all sites in this table with the exception of the California sites, which will be discussed in a later section focusing specifically on California and a new statewide California landfill CH_4 emissions inventory using CALMIM. [see California Inventory]

For individual cover materials, all landfill CH_4 emissions (measured and modeled) were normalized on an area basis [g CH_4 m^{-2} d^{-1}]. For some sites, where area information was available, annual emissions [kg CH_4 y^{-1}] were also calculated for the various cover types and for the site as a whole. For all sites, in order to visualize the comparison between measured and modeled emissions, the field data were overlain on CALMIM output plots for "CH_4 emissions with oxidation" and "CH_4 emissions without oxidation" for a typical annual cycle (365 d) (See Figure 18 as an example). Field measurements were plotted according to their correct time of year, also permitting direct visualization of individual field results compared to the expected daily and seasonal variability in emissions. Please note that the seasonal variability alone for an individual cover material at a specific site can extend over 2-3 orders of magnitude. This is typical for diffusional soil gas processes and consistent with observed variability in field measurements at individual sites. It is also consistent with variability of orders of magnitude for the global database for measured landfill CH_4 emissions [expressed as g CH_4 m^{-2} d^{-1}] as discussed previously and in more detail below.

In this section, we will first address the overall comparisons between measured and modeled results and then discuss the individual site comparisons according to a standardized format. As discussed previously, the measured emissions at an individual site are a function of the properties and thickness of individual cover materials, site-specific operational practices (especially gas recovery), and seasonal CH_4 oxidation, which depends on the date, time, and specific location of the measurements on the surface of the earth. In all cases, field measurements only provide a snapshot of emissions for a given place at a given time. Thus, because CALMIM relies on 30-year average weather data (daily minimum/maximum air temperatures, daily precipitation) for inventory purposes, as discussed in Spokas et al. (2011), the CALMIM modeled values may differ from individual field measurements.

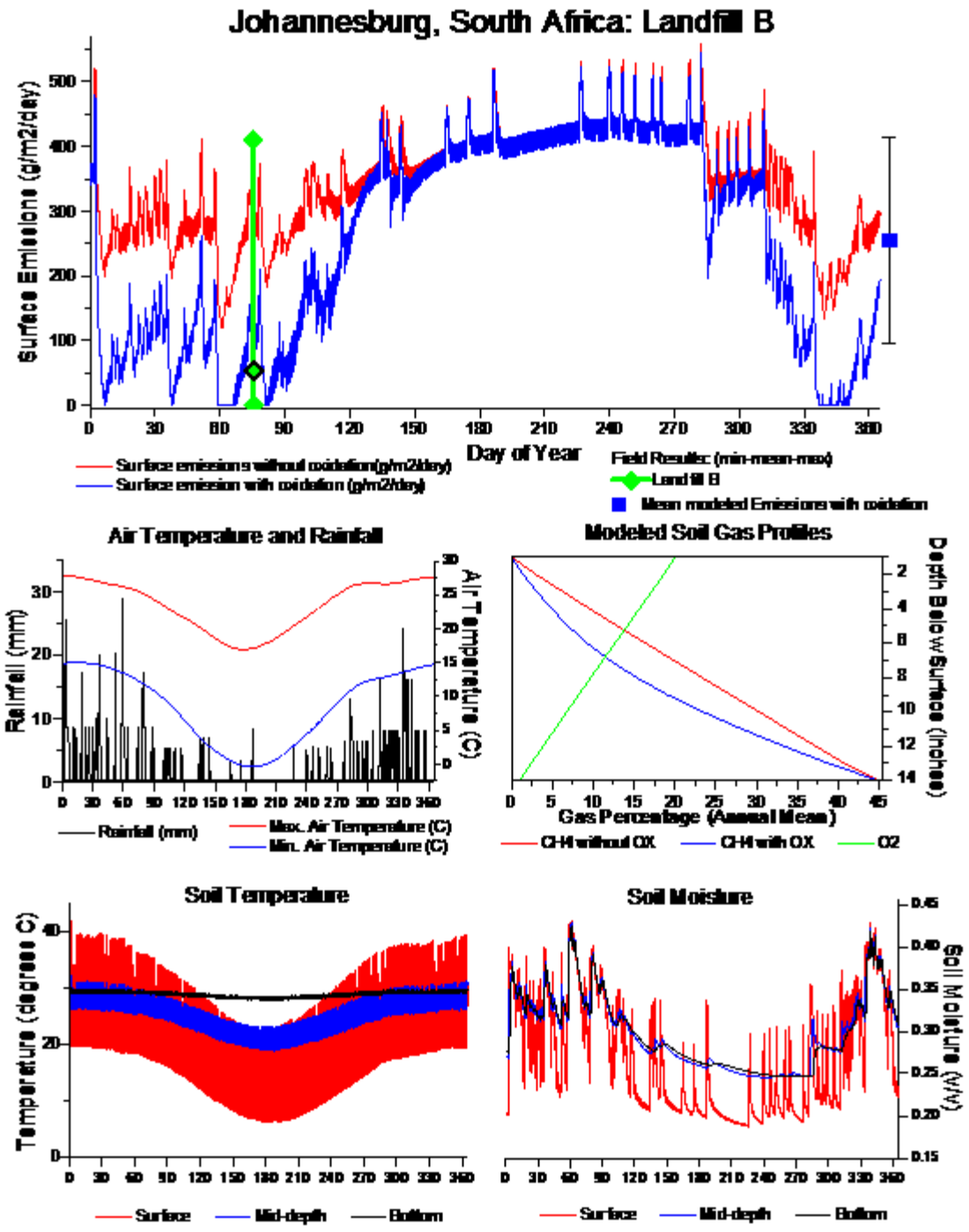


Figure 18. Example illustration overlaying measured field data on predicted CALMIM results for an intermediate cover area at a South African landfill, along with the annual cycles for air temperature, precipitation, and predicted diffusive CH4 emissions with and without oxidation.

We support the use of CALMIM "default" [30-year] weather for GHG inventory purposes, as it provides an integrative scenario for typical annual emissions which is unaffected by annual and seasonal variability. The magnitude of this variability, of course, differs from site to site. If, however, site-specific weather data are available for a specific year, additional CALMIM runs using those data for a particular year can indicate how, due to weather alone, annual emissions can deviate from longer-term trends. To some extent, the modeled values are preferable for inventory purposes as more representative of longer-term conditions, provided the other model inputs adequately reproduce field conditions. In subsequent sections of this report, we also address latitudinal variability in landfill CH_4 emissions, as well as expected future emissions under selected climate change scenarios.

In general, CALMIM includes a number of embedded features which, taken together, will tend to elevate (positive bias) the modeled results, thus making CALMIM "conservative" for inventory purposes. As discussed in Spokas et al. (2011), these include:

- Constraining the CALMIM model to zero emissions when, realistically, it might yield negative emissions (e.g., no negative emissions are allowed).

- CALMIM uses standard soil databases for soil gas transport characteristics of cover soils—these yield higher gaseous transport rates than correspondingly more dense, compacted landfill soils (Hauser et al., 2001; Wickramarachchi et al., 2011). Due to the fact that there are typically power (exponential) relationships between bulk density and gas flow characteristics (Wickramarachchi et al., 2011), even small changes (e.g. 1-5%) can have an order of magnitude or more effect on diffusive gas flux. However, field experience indicates that, over periods of years, vegetated landfill cover soils can become largely indistinguishable from non-landfill soils with respect to gaseous transport processes.

These conservative CALMIM-specific features may also contribute to differences between field measurements and CALMIM simulations.

4.2.2. Overview of techniques and historic results for field measurement of landfill CH_4 emissions.

Existing worldwide data for field measurements of landfill CH_4 emissions rely on multiple and diverse above-ground, ground-level, and below-ground techniques deployed over a wide range of spatial and temporal scales. As discussed below, due to the limitations and inherent variability of each technique over a wide range of co-existing cover types, terrains, climatology, and multiple CH_4 sources, there is no "perfect" technique for universal use. Moreover, the field measurements to date have typically been conducted by U.S. and international research groups addressing specific research questions and not for direct application to GHG inventory reporting. Results from small-scale static chambers, the most common technique in the global literature to date, indicates that emissions can vary over more than 7 orders of magnitude, from <0.001 to >1000 g CH_4 m^{-2} d^{-1} (Scheutz et al., 2009; Bogner and Spokas, 2010). As previously discussed, CALMIM assumes that the primary transport mechanism is diffusion with this large variability typical for soil gas transport processes which are predominately diffusional (see Supporting Information, Spokas et al., 2011). Because CALMIM is a process-based technique, the original CALMIM field validation for California relied on static chambers, which are capable of providing process-level data at the appropriate m^2 scale (see Spokas et al., 2011; Bogner et al., 2011). In contrast, it is important to note that this observed variability is absent from current GHG inventory estimates, which rely on a first order model based on the mass of waste in place (e.g., IPCC, 2006). Moreover, at a specific site, CH_4 emissions from a particular cover may vary over 3-4 orders of magnitude during a single field campaign (e.g., see Bogner et al., 2011). Static chambers are also the only technique which quantifies negative fluxes or the uptake of atmospheric CH_4 by methanotrophic microorganisms in landfill cover soils (Bogner et al., 1997).

However, static chambers are not suitable for quantifying fugitive CH_4 emissions from surface cracks, piping leakages, or perimeter gas losses (edge of waste footprint at liner interface). Current regulations in the U.S. require quarterly surface scans of landfill sites using a field instrument capable of ppm v/v determinations for CH_4 in air at the landfill surface. Any locations where elevated surface CH_4 concentrations are observed must be quickly remediated as part of normal operations and maintenance activities. Thus, it is reasonable to exclude such fugitive emissions from annual inventory reporting, as is done within CALMIM, focusing instead on longer term "soil" emissions.

When comparing CALMIM modeled results to field measurements, it is important to take into account the orders-of-magnitude spatial and temporal variability of measured landfill CH_4 emissions in light of the variety of different techniques which have been deployed at landfills at various scales, ranging from the small-scale static chambers discussed above to a variety of above-ground techniques (static and dynamic tracer techniques, micrometeorological techniques, vertical radial plume mapping, aircraft-based mass balance techniques), as well as the use of soil gas profiles to estimate diffusive flux. Results from all of these techniques have differing sources of error, plus the magnitude of the error can differ between sites deploying the same technique, depending on site

characteristics (e.g. topography, wind), the technique configuration, and other details of the site-specific experimental design.

For this project, we have compared CALMIM simulations to field results from a wide variety of techniques, some of which have not been extensively deployed to date for landfill CH_4 emissions measurements. An overview of field techniques was previously provided in Spokas and Bogner (2010), with the exception of more recent aircraft-based mass balance techniques and associated modeling (Garman et al., 2006; Mays et al., 2009; Peischl et al., 2013). The most common "above ground" techniques which have been deployed for landfill CH_4 emissions include static and dynamic tracer techniques (using SF_6, N_2O, or C_2H_2 tracers), vertical radial plume mapping using a tunable laser diode instrument, micrometeorological techniques (eddy correlation; eddy covariance), and aircraft-based mass balance techniques. Large uncertainties still remain with respect to the "best" technique to be deployed at scales larger than static chambers (Scharff and Jacobs, 2006). Many of the above-ground techniques have an uncertainty of 30-50% or even greater, depending on the site-specific and technique-specific factors discussed above, and have not been extensively deployed over multiple seasons at large numbers of landfill sites. Other difficulties to consider include local landfill topography in light of complex atmospheric boundary layer dynamics with resulting problems of interpretation, representativeness of gap filling, footprint analysis, averaging of data, and other sources of error (Wille et al., 2008; Mays et al., 2009; Aubinet et al., 2012; Foken et al., 2012; Rannik et al., 2012; Zitouna-Chebbi et al., 2012). In general, static chambers remain the recommended technique for small-scale process-level measurements of gaseous emissions. As discussed above, chambers are also consistent with the process- and climate-based approach of the CALMIM model which considers diffusive flux combined with modeled CH_4 oxidation rates scaled to maximum rates at optimum soil temperature and moisture conditions over all soil types (see Spokas et al., 2011 and Spokas and Bogner, 2011 for further discussion).

For most landfill field settings, the combination of static chambers, soil gas profiles, and an "above ground" technique is recommended to provide a more comprehensive view of site emissions. This is because the parallel deployment of an "above ground" method can quantify the combination of diffusive soil emissions and fugitive emissions from surface inhomogeneities, edge leakages (especially the liner/soil interface), and possible points of leakage in the gas and leachate system infrastructure (Fredenslund et al., 2010; Di Trapani et al., 2013). To date, there have been a limited number of field campaigns using multiple techniques (Tregoures et al., 1999; Diot et al., 2001; Babilotte et al., 2010; Goldsmith Jr et al., 2012). Importantly, cold season measurements from sites in temperature climates are especially sparse in the literature. Taken together, technique uncertainties combined with the year-to-year meteorological variability can result in substantial differences between the results of individual field campaigns using multiple methods and CALMIM modeled results. For the future, though, in large part due to advances in instrumentation (i.e., transportable cavity ring down laser spectrometer instruments), the science and technology for emissions measurement is evolving rapidly.

One issue that remains largely unaddressed by techniques at any scale is daytime vs. nighttime emissions. We particularly want to raise the issue of potentially high daytime emissions from the relatively-small working face area. Many large landfill sites in the U.S. are filled using multiple layers of cells, and many sites have been permitted for vertical expansions. At these sites, it is standard practice to strip the intermediate cover on the underlying cell before new waste is placed in the overlying cell. Thus an active tipping face can overlie older waste which is fully methanogenic with potentially high rates of daytime CH_4 emissions from that relatively small area. As most of the "above ground" techniques have not been or cannot be deployed at night, the differences between daytime emissions from the working face and nighttime emissions after placement of daily cover are unknown. We suggest that this might be a significant, but currently non-quantified, source of diurnal variability in landfill CH_4 emissions. If so, such a strong source from a small area would also contrast sharply with larger adjacent areas of final or long-term intermediate cover with significantly lower emissions on a unit area basis.

4.2.3. Site-specific results

In this section we directly compare field measurements to CALMIM modeled results for the 32 sites listed in Table 3. The results are summarized in Table 4, with the average mean error ($\bar{y}_{field} - \bar{y}_{CALMIM}$) and Pearson's correlation (R) for all comparisons at the location. Specific sites are located on many continents (Europe, Africa, Asia, South America, and North America) where available literature or data could be used by this project. In many cases, in addition to consulting published literature we contacted individual research groups for expanded project details and background information about the measurements cited. We are grateful to many individuals who generously shared information to make this project possible (Acknowledgments).

Figure 19 is a simple scatter plot for measured vs. modeled CH_4 emissions for all of the sites in Table 4. This figure is subdivided into CALMIM simulations using default values for CALMIM input (Figs. 19A&B) and simulations where it was possible to use site-specific input for soil gas profiles (Figs. 19C & D), a much smaller subset of sites. For the default comparison, a total of 174 individual comparisons between CALMIM and measured field data are shown. In addition, we separately plotted modeled CH_4 emissions with oxidation (Figs. 19A & 19C) and without oxidation (Figs. 19B & 19D) to visually indicate the difference in modeled emissions due solely to predicted microbial soil CH_4 oxidation. In Figure 19A, note that both the measured and modeled CH_4 emissions with oxidation cluster over about 5 orders of magnitude with the modeled CH_4 emissions slightly higher than the measured, consistent with the conservative features of CALMIM as discussed above. In Figure 19B, where modeled results without oxidation are plotted on the y-axis, note that the minimum modeled values are elevated to higher unit values of >50 g CH_4 m^{-2} d^{-1}. Figure 19C includes a limited subset of sites with site-specific soil gas profiles, this amounted to a total of 36 individual comparisons. However, even though the number of sites is limited there is an improved correlation between the measured and modeled results which largely disappears in Figure 19D which excludes oxidation.

What can we conclude about the model validation?

- CALMIM actually performed very well in determining the order of magnitude emissions (see Figure 20). Even though the annual average data did a very good job of matching measured values, this would have been improved by having a greater density of site-specific weather data.

- We also calculated the Willmott Index of Agreement (d-index) (Willmott, 1981; Legates and Willmott, 1990), where:

$$d = 1 - [(\sum((obs - sim)^2)] / \sum((abs(sim - mean(obs)) + abs(obs - mean(obs)))^2) \qquad \textit{Equation 3}$$

  This d-index is a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all (Willmott, 1981).

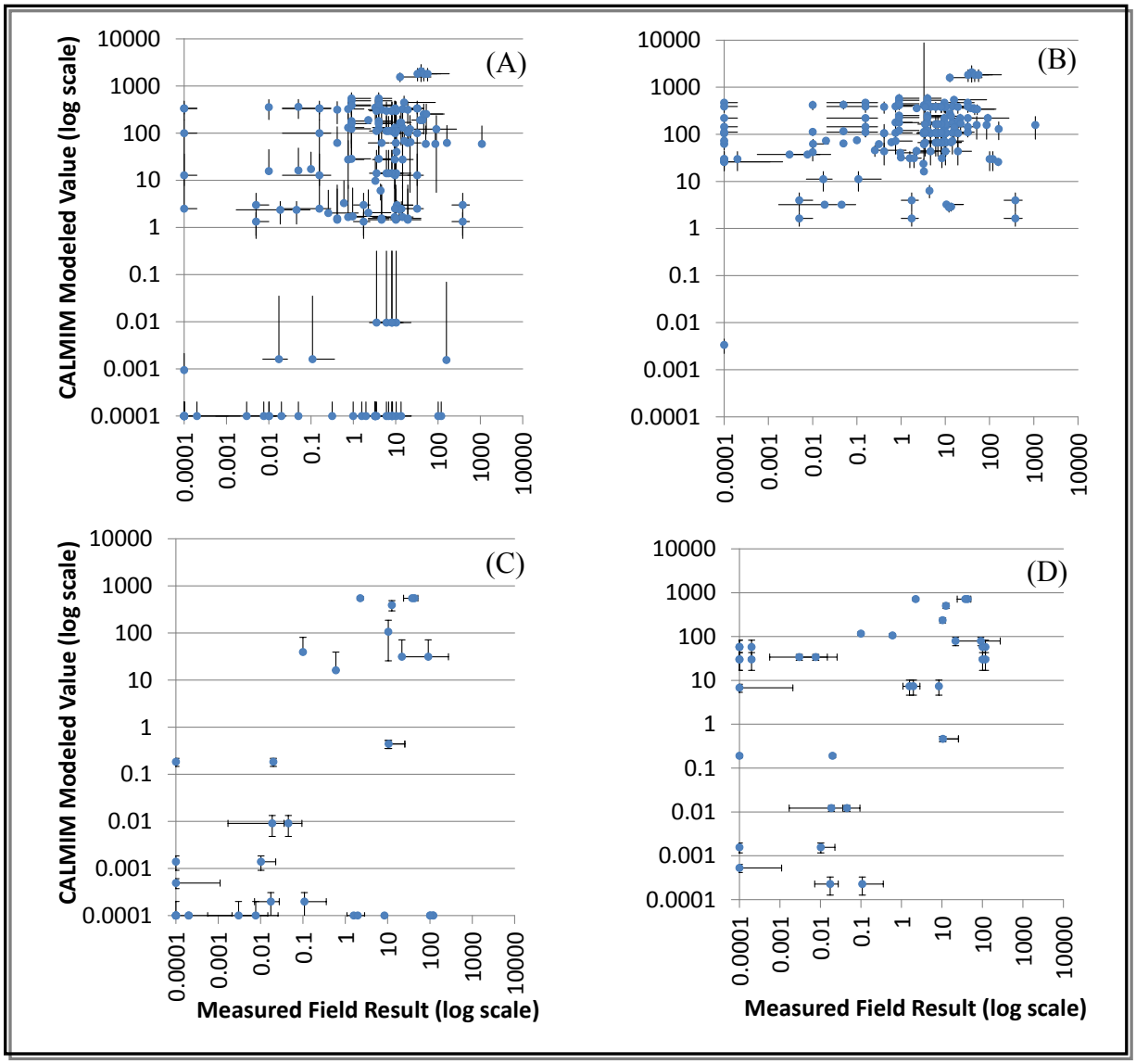
  For the default comparisons, we have an overall d-index of **0.045** and when site-specific data are used, a d-index of **0.7354**. Therefore, the use of site-specific data drastically improves the predictions compared to "default" values.

Table 4. Results of US and International landfill sites that were used for the CALMIM validation

Landfill	Average Mean Error ($g\ m^{-2}\ day^{-1}$)	Pearson's Correlation (R)	Details of Comparison/Notes
Taylors Road Landfill (Australia)	-1.03	0.99	A very good match with CALMIM with the LFG system on. Overall, a very good match with the CALMIM prediction; when LFG system was off field flux values were higher, but still within the CALMIM prediction.
St. Polten	509 (with no cover simulation) [7.3 without]	0.99	CALMIM predicted the order of magnitude of the field data. TC-5 was an attempt at simulating an "open" landfill face with no soil cover, in CALMIM a 3" cover was used for this simulation (poor match). This resulted in a significantly higher flux value than was observed in the field.
Grand'Landes	-42	0.99	CALMIM bracketed 4 out of 6 field flux measurements in default and when custom gas profile entered for the two outlier flux values CALMIM adequately predicted those as non-oxidized surface emissions. This site was an example of the importance of custom soil gas boundary conditions to account for hotspots.
Lapouyade	-184	0.88	CALMIM custom boundary entry adequately predicted range of flux values observed in field data. One test cell was severely over predicted by CALMIM
Landfill A	-1170.0	1.0	Very high flux predicted from CALMIM; CALMIM over-predicted field data point (4" cover thickness – possible reason)
Landfill B	45	1.0	A very good match for the range of field flux values and the observed field flux values.(14" cover)
Landfill C	1290	0.80	6" cover – not as good average values from CALMIM
Landfill D	304	0.95	15" cover very good match with field data
IN-1 (Indiana Field Project)			Overall, CALMIM predicted the range of measured emissions – customized boundary conditions improved comparison.
Mallard Lake	0.007	-0.2	Very good match with oxidized flux prediction on final cover
WI1	30	0.99	Poor match on 6" daily cover – However, still within order of magnitude. CALMIM over-predicted the observed field data. Improved match on intermediate cover – very good match to bracket range of field values
Marina	-25	0.6	Re-evaluation of the field data from Marina – CALMIM model updated and changed significantly since the last validation (2011). Daily cover within the same order of magnitude, but CALMIM did over predict. Intermediate cover good match during wet season, dry season field measurements higher, but within same order of magnitude.

Table 4 (continued)

Landfill	Average Mean Error (g m^{-2} day^{-1})	Pearson's Correlation (R)	Details of Comparison/Notes
CA-1	-4.7	1.0	CALMIM prediction for the intermediate cover areas nicely bracketed oxidized to non-oxidized flux values measured in the field – CALMIM adequately indicated the range of possible field values.
CA-2	2.5	1.0	Very good match with intermediate cover areas – bracketed oxidized to non-oxidized flux values predicted from CALMIM – potential indication of the lack of oxidation in cracks? – CALMIM adequately indicated the range of possible field values.
CA-3	-1.9	-1.0	Very good match with intermediate cover areas – bracketed oxidized to non-oxidized flux values predicted from CALMIM – potential indication of the lack of oxidation in cracks? – CALMIM adequately indicated the range of possible field values.
CA-4	-5.9	0.93	Excellent match with intermediate cover areas – bracketed oxidized to non-oxidized flux values predicted from CALMIM. CALMIM adequately indicated the range of possible field values.
CA-5	9.53	0.9	Fairly good match, potential issue with using simulated weather, since the timing of the precipitation could be critical for timing of oxidation activity [arid site].
Scholl Canyon	7.26	0.4	CALMIM excellent match – very thick covers
Calabasas	-0.15	1.0	12" daily cover – very good match; intermediate cover – good match;
Puente Hills	2.6	-1.0	Overall a very good match to field data – The CALMIM bracketed the field measurements between oxidized and non-oxidized very well.
Högbytorp (Stockholm)	0.4	1.0	Final cover – very good match with field data for oxidized flux prediction.
Malmö	0.7	1.0	Final cover – very low fluxes – perfect match with oxidized flux
Helsongborg	1.0	1.0	Final cover – very low fluxes – perfect match with oxidized flux
Lahti	2.5	1.0	Final cover – very low fluxes – perfect match with oxidized flux
Lohja	0.6	1.0	Final cover – very low fluxes – perfect match with oxidized flux
Emerald Park Landfill	-74.3	-0.46	Poor match with daily cover on slope (huge variability was also seen in the field measurements (10-200 g/m2/day); CALMIM comparison on intermediate cover is very good.
Leon County Landfill	135	1.0	CALMIM over predicted the flux results from biocover test cells. This could be an indication that biocovers might require special handling due to the enhanced CH_4 oxidation that is possible. Further work is needed in this area.
Shan-Chu-Ku Landfill	-1.37	0.99	Over 1m cover – low measured emissions – CALMIM bracketed all field measurements between non-oxidized and oxidized flux predictions. 2 of 3 are well predicted.
Muribeca Landfill	-1.11	-0.82	Only landfill where the field measurements were higher than the CALMIM results. 2 of 3 covers matched.



Notes: All values are g CH_4 m^{-2} d^{-1}. Error bars for field measurements are the standard deviation for average values. Error bars for CALMIM5.4 modeled results are the standard deviation of the annual average emissions (using the variability in surface emissions from the 10-minute time steps). Values of 0.0001 on either axis indicate negligible to zero emissions (or negative emissions on "measured" axis).

Figure 19. Direct comparison of CALMIM model results to field measurements for (A) default model parameters versus measured emissions for modeled emissions with oxidation, (B) default model parameters for emissions without oxidation flux versus measured emissions, (C) site-specific site soil gas profile for emissions with oxidation versus measured emissions, and (D) site-specific soil gas profile for modeled emissions versus measured emissions.

From this validation, we conclude that the comparison between CALMIM modeled values and measured values, both spanning many orders of magnitude, gives credibility to the CALMIM model for application to landfill CH_4 emissions inventory calculations for specific sites. When we examine the comparison by cover type, we see that CALMIM statistically matches the field measurements across all cover types at all locations (Figure 20).

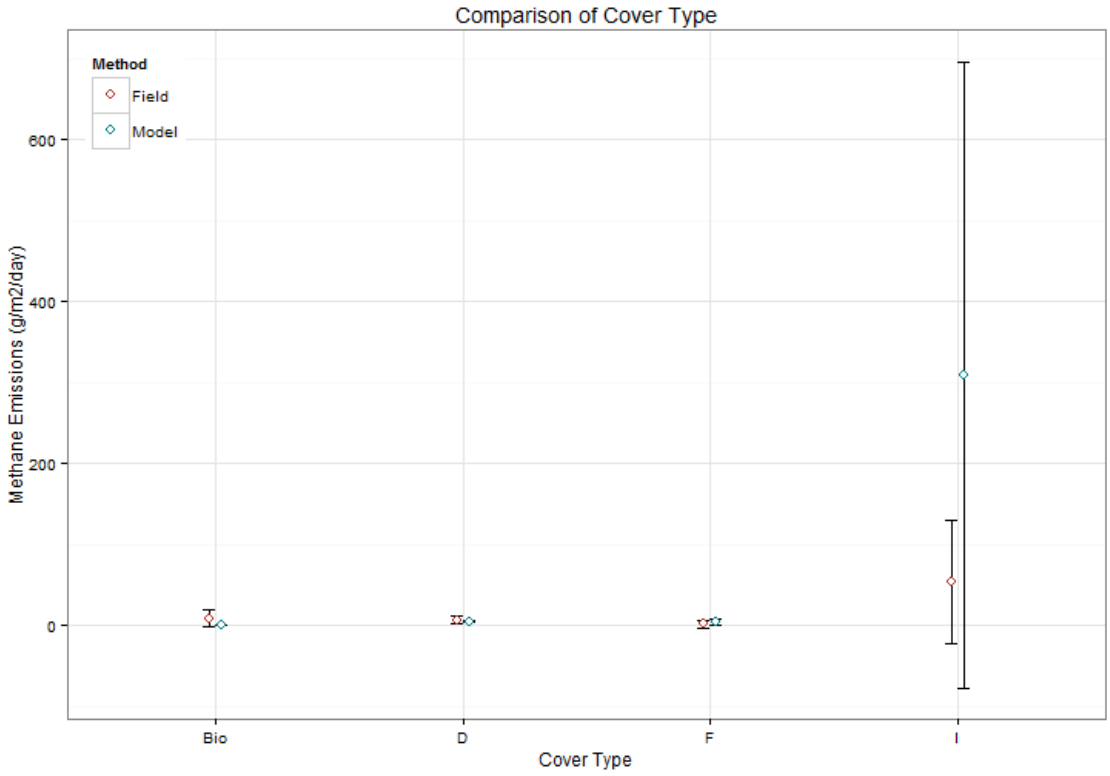


Figure 20.Overall mean and standard deviations for all the site comparisons conducted in this report (See Appendix A). Overall, there was no statistical difference between the field and model averages by cover type across all the sites (n=104). For the intermediate cover, the over-prediction of CALMIM is related to the inclusion of very thin and "no cover" simulations in the comparison data sets.

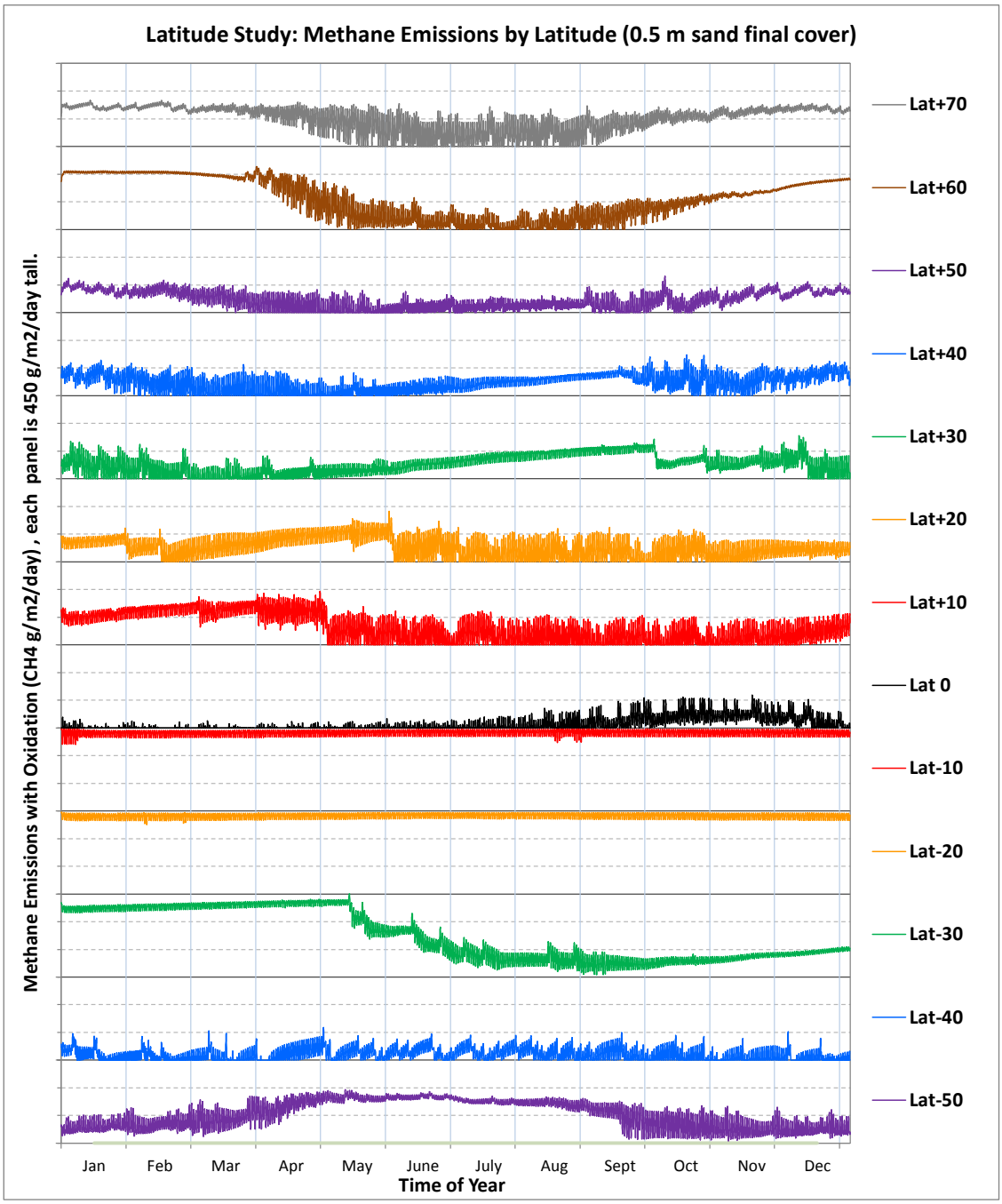
In general, these comparisons indicate that CALMIM provides a conservative order-of-magnitude estimate for *typical annual emissions* from site-specific landfill cover materials. Comparisons are improved using site-specific "custom" data for soil gas profiles and annual weather, where those data exist. Importantly, based on 30-year average climate data, CALMIM replicates the typical annual variability of emissions with respect to gaseous transport in site-specific soils and temperature/moisture-dependent CH_4 oxidation rates. Thus CALMIM can provide an improved estimate of annual emissions based on the major processes which directly control CH_4 emission rates—namely, the thickness and physical properties of various cover materials, their surface areas, the presence of engineered gas extraction, and seasonally-variable CH_4 oxidation rates in each cover. CALMIM simulations yield longer term spatially-explicit information regarding the expected magnitude and variability of emissions from specific sites and are thus suitable for GHG inventory calculations.

The detailed graphical comparison and discussions for all the individual sites are given in Appendix (Appendix C). There we compare the site-specific field measurements to CALMIM modeled results for a typical annual cycle. Also, we give background information on the site, the research project, and additional CALMIM output so that the emissions data can be understood in the context of the major properties which control landfill CH_4 transport, oxidation, and "net" emissions to the atmosphere. For intermediate covers at U.S. sites, we also typically compare "minimum permitted" intermediate covers of 12 in. thickness to more typical field installed thicknesses of 24 or 36 inches (e.g., 2X or 3X thickness). In a later section of this report, we will specifically address CALMIM comparisons for the 10 California sites and provide a new 2010 California GHG emissions inventory for landfill CH_4 emissions using CALMIM, which was made possible as a result of the Walker (2012) CalRecycle database discussed earlier. This database gives basic area, cover, and LFG recovery information for all permitted California landfills. We will also compare the site-specific magnitude of emissions and the areal distribution of emissions to the current 2010 inventory (CARB, 2012).

4.3. Latitudinal gradient for landfill CH_4 emissions using CALMIM simulations for standardized cover soils.

We completed a series of latitudinal runs using CALMIM for a standardized cover in order to answer the question: Over a typical annual cycle, how would landfill CH_4 emissions differ from high northern to high southern latitudes following placement of a "minimum" final cover? In other words, how does climate alone affect oxidation and "net" emissions for the same final cover over a latitudinal gradient?

The global locations are shown on Figure 7 (Section III). With the exception of the most northerly latitudes (Norway, Finland), all of the other locations are in the Western Hemisphere from Canada to California, Mexico, Central America, and South America. Table 5 summarizes the different climatic attributes for each site, along with the average annual predicted emission rate (g CH_4 m^{-2} d^{-1}). Figure 21 shows the results for "emissions with oxidation" for all of the sites using a constant scale for the y-axis. One of the locations for the latitudinal transect (the equatorial location of Macapa, Brazil) also overlaps with available locations for the climate change simulations discussed in the next section (2020, 2050, and 2100 for SRES scenarios A2 and B1). At the equatorial position (0 N), the climate supports CH_4 oxidation during the full year when there is adequate soil moisture. However, other latitudinal trends are not immediately clear, due to the complicating aspects of precipitation differences at intermediate positions. By comparing the +70 N (top graph) and the -50 S (bottom graph), one can see the seasonal reversal of optimum CH_4 oxidation between the northern and southern hemispheres. A period of higher soil methanotrophic activity would correspond to lower total CH_4 emissions. For the Northern hemisphere, oxidation is dominant during *April through September*, whereas in the Southern hemisphere methane oxidation is dominant *September through April* (Figure 21).



Note: Landfill CH_4 emissions inclusive of CH_4 oxidation for 50 cm sand "minimum" final cover. For all sites, the y-axis is scaled linearly from 0 to 450 g CH_4 m^{-2} d^{-1}.

Figure 21. Methane emissions for a global latitudinal comparison using CALMIM.

Table 5. Average climatic and surface emission rate prediction for the various sites

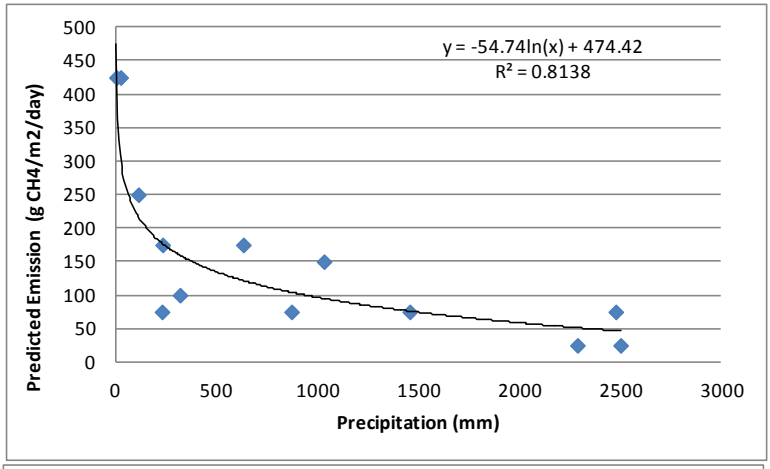
Location	Latitude (^{O})	Annual Air Temperature (^{o}C)	Annual Precipitation Amount (mm)	Average Predicted Surface Emission (g CH_4/m^2/day)	% Cover CH_4 Oxidation
1) Tromsø, Norway	70	-1.1	1030	150	45
2) Helsinki, Finland	60	5	630	175	50
3) Vancouver, BC, Canada	49.3	4	2476	75	70
4) Redding, California, USA	40.4	17	869	75	75
5) Ensenada, Mexico (Baja)	31.5	17	227	75	79
6) Puerto Vallarta, Mexico	20	25	1455	75	77
7) Puntareno, Costa Rica	10	27	316	100	68
8) Macapa, Brazil	0	27	2286	25	91
9) Huacho, Peru	-11	20	22	425	0
10) Iquque, Chile	-20.2	19	1	425	0
11) Coquimbo, Chile	-30	14	110	250	36
12) Valdivia, Chile	-39.5	11	2500	25	92
13) Rio Gallegos, Argentina	-51.5	8	230	175	50

Note: Shaded cells in light blue indicate sites with very low annual precipitation.

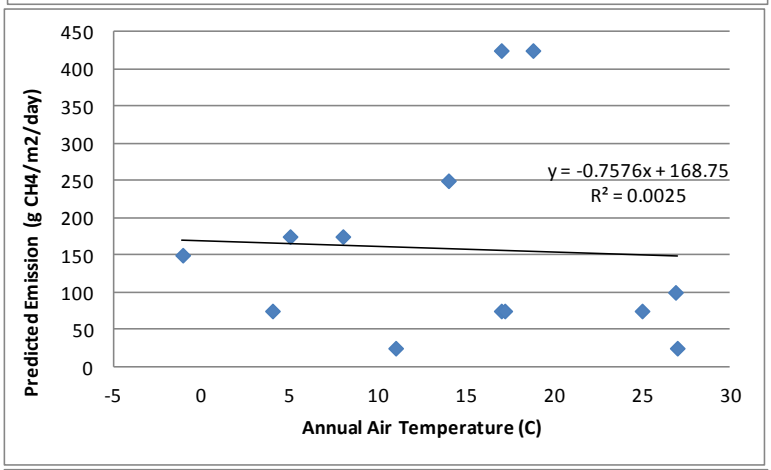
When we examine the relationship between annual air temperature and precipitation at the sites, we see that there is a clear function with precipitation (Figure 22A). However, there is not a significant relationship with temperature (Figure 22B). There is the suggestion of decreasing air temperature resulting in higher emissions (Figure 22C), when the three driest sites are eliminated from the comparison. However, the relationship is very weak (R^2=0.3).

This section has demonstrated that landfill CH_4 emissions for the same cover soil for a particular latitudinal location are a function of the CH_4 oxidation efficiency for that location. This oxidation efficiency is, in turn, related to the timing and magnitude of precipitation events which dynamically affect soil moisture, as well as soil temperature changes responding to atmospheric temperature changes during daily, seasonal, and annual cycles. Sites that receive >1000 mm of precipitation, typically have a predicted cover methane oxidation percentage exceeding 50%.

(A)



(B)



(C)

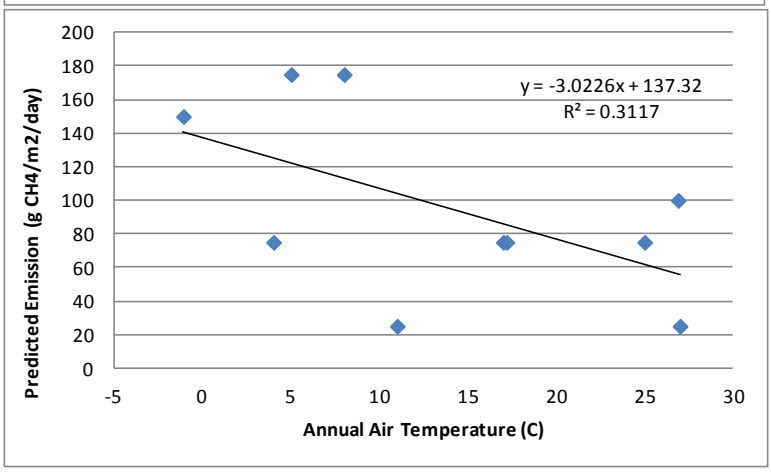


Figure 22.Relationship between average annual CH_4 emissions with oxidation for global latitudinal sites and (A) average annual precipitation, (B) average annual air temperature including the 3 driest sites, and (C) average annual temperature excluding the 3 driest locations.

Figure 23 through 35 show selected meteorological and soil plots corresponding to the locations in Figure 6. Comparing Figure 23 to Figure 35, emissions for sites in the high northern latitudes above 50 ^{o}N (e.g., Finland, Norway) are drastically reduced by soil oxidation during the warmer months of April-September. At latitude 50 ^{o}N (Finland), the April-September emissions are reduced even further. This can be largely attributed to the 6 ^{o}C higher annual temperatures (Table 4). Moving further south, oxidation is much reduced during late summer hot, dry periods (& lower annual precipitation) at Latitudes 30 ^{o}N and 40 ^{o}N (California and Baja, Mexico), resulting in higher predicted emissions. For latitude 20 ^{o}N on the western coast of Mexico (Puerto Vallerta) and latitude 10 ^{o}N in Costa Rica, the higher emissions during the first 4-5 months of the year are related to low soil moisture (below the optimum for oxidation) and high daytime soil temperatures (generally above the optimum for CH_4 oxidation). For Macapa, Brazil, located on the equator, those same effects are responsible for higher emissions during the dry portion of the year (Sept-Dec). Further south, even though temperatures are favorable, the consistently high emissions for latitude 10 ^{o}S (Peru) and 20 ^{o}S (Iqueque, Chile) are due to very dry soils over most of the year, which is due to the virtual lack of moisture (<25 mm; Table 4). These conditions result in soil that is well below the optimum moisture range for oxidation and, indeed, microbial activity in general. For 30 ^{o}S (Coquimbo, Chile), high emissions during the first months begin to drastically reduce in May to minimum values in late August, which parallel increases in soil moisture from the beginning of the rainy season. Further south at approximately 40 ^{o}S (Valdivia, Chile), the relatively even distribution of annual precipitation (2500 mm per year) permits soil CH_4 oxidation over much of the year, which reduces emissions. Finally, at 50 ^{o}S (Rio Gallegos, Argentina), the relatively higher emissions during the mid-year period are due to the combination of lower soil temperature and lower soil moisture (250 mm per year; 10% of the annual precipitation at Valdivia, Chile).

In general, climate impacts landfill emission rates by altering the soil temperature and moisture contents, which directly impact microbial CH_4 oxidation rates (Börjesson and Svensson, 1997; Spokas and Bogner, 2011). Through this study we observed that precipitation was more significant than air temperature for CH_4 oxidation, and in turn, directly affected the magnitude of the predicted surface emissions.

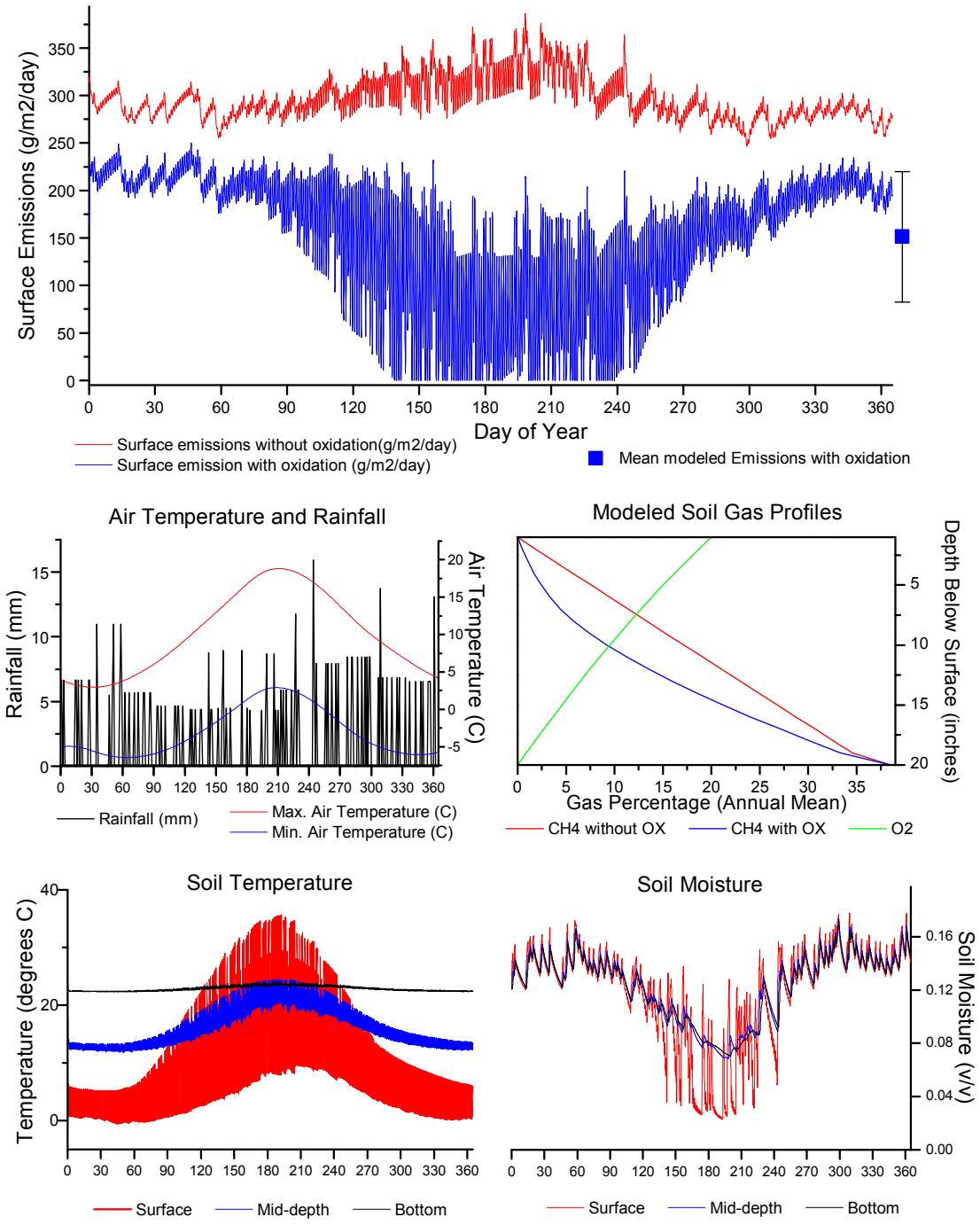


Figure 23. Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +70 ºN (Norway).

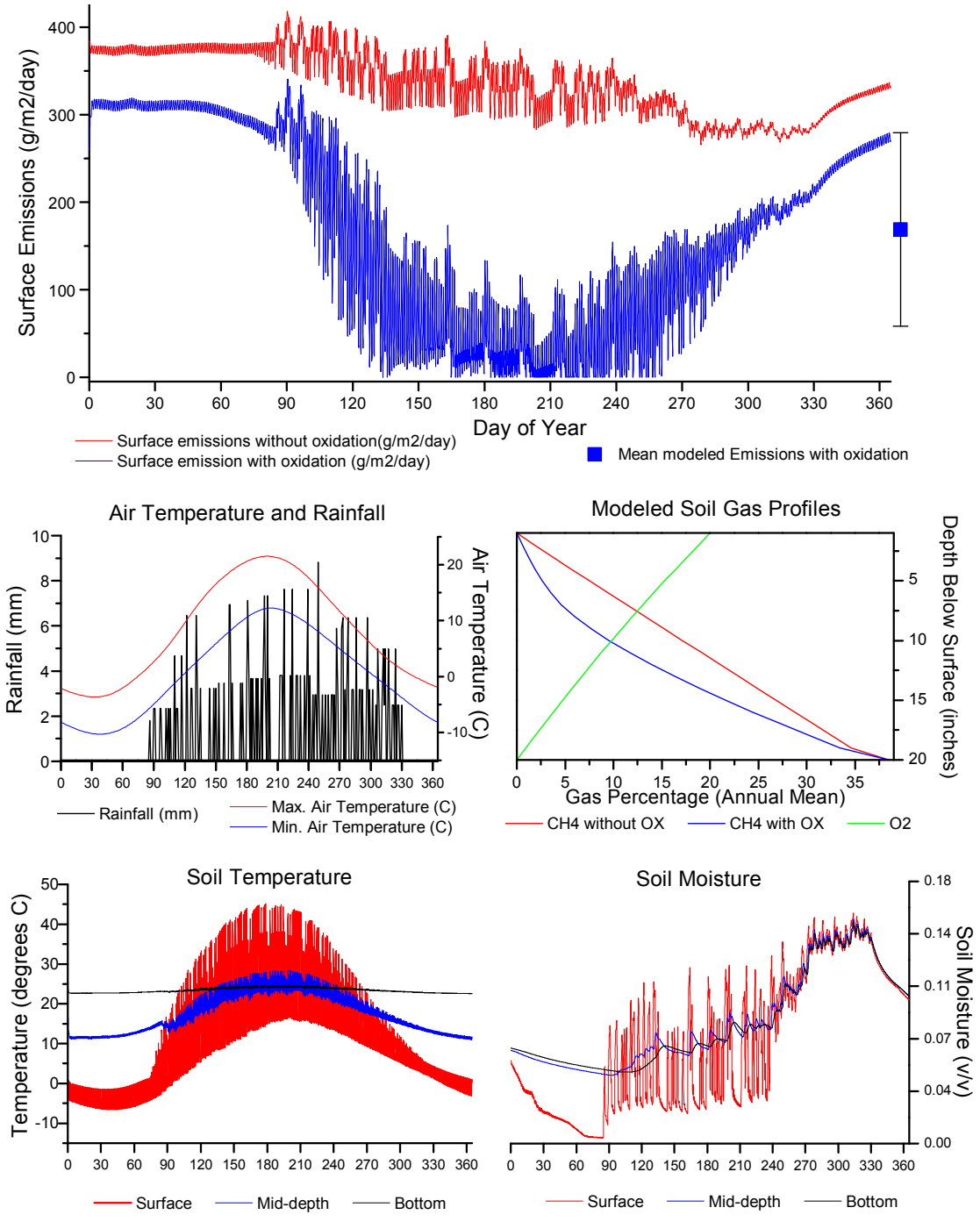


Figure 24. Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +60 ºN (Finland).

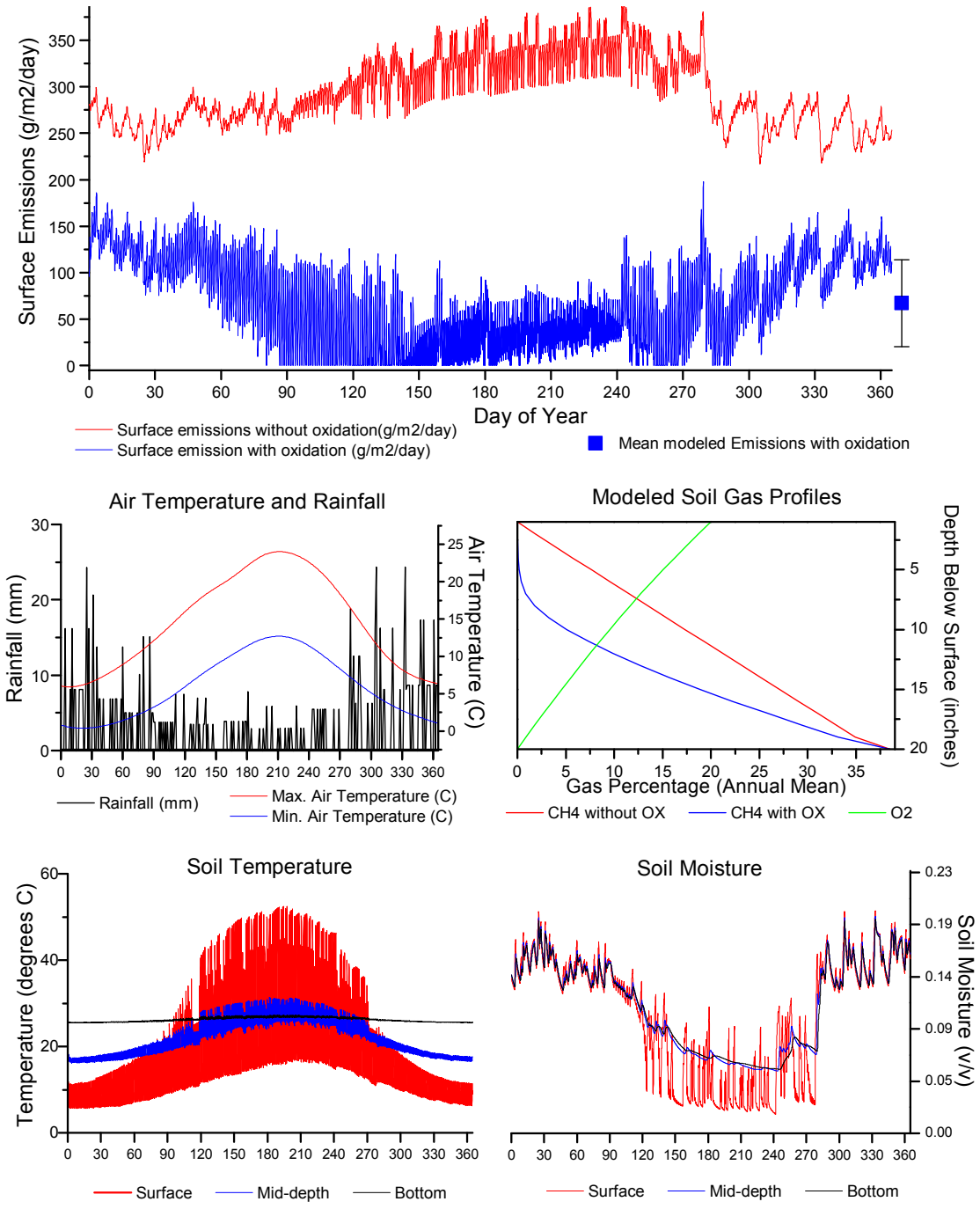


Figure 25.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +50 ^{o}N (Vancouver, Canada).

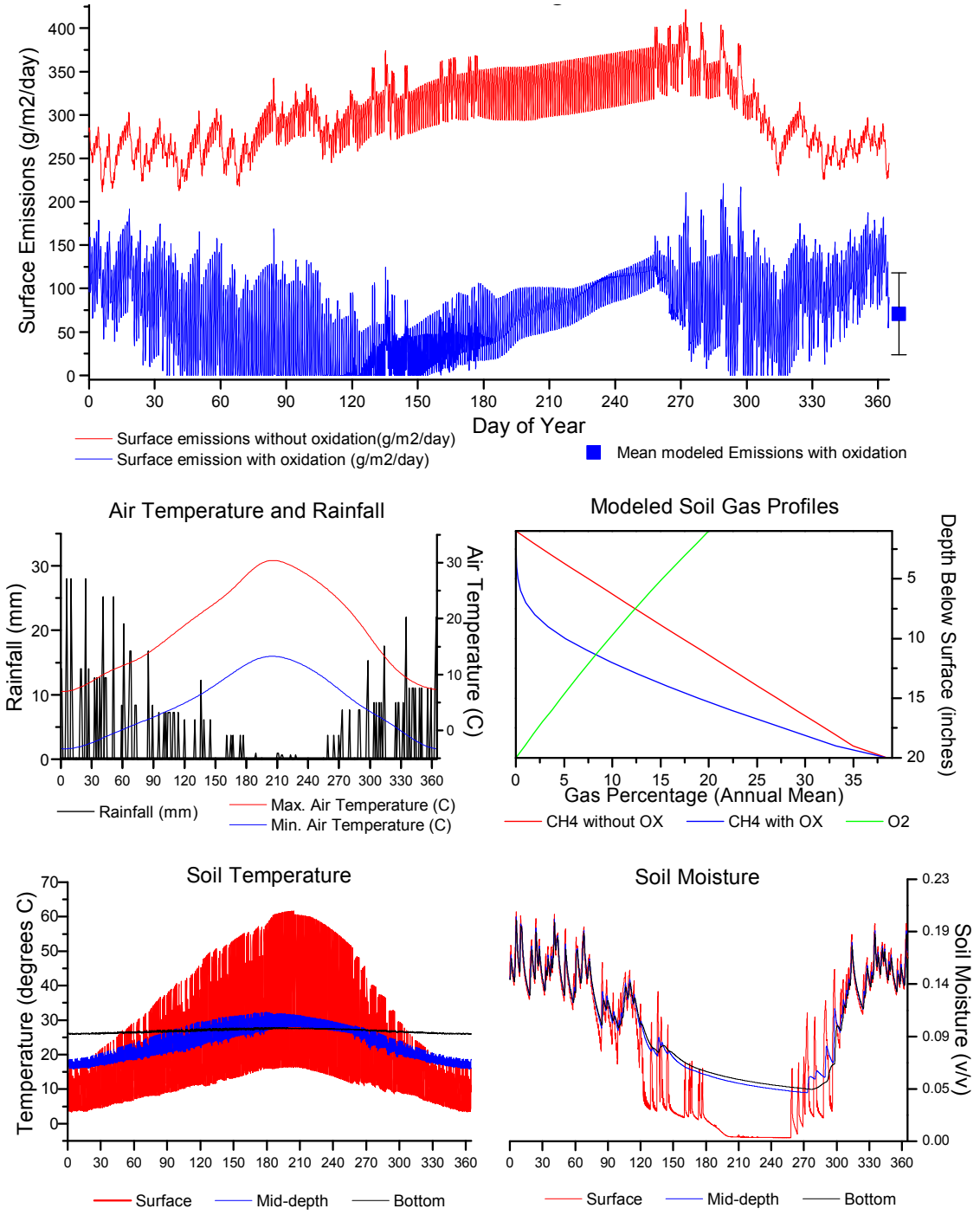


Figure 26.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +40 ^{o}N (Redding, California).

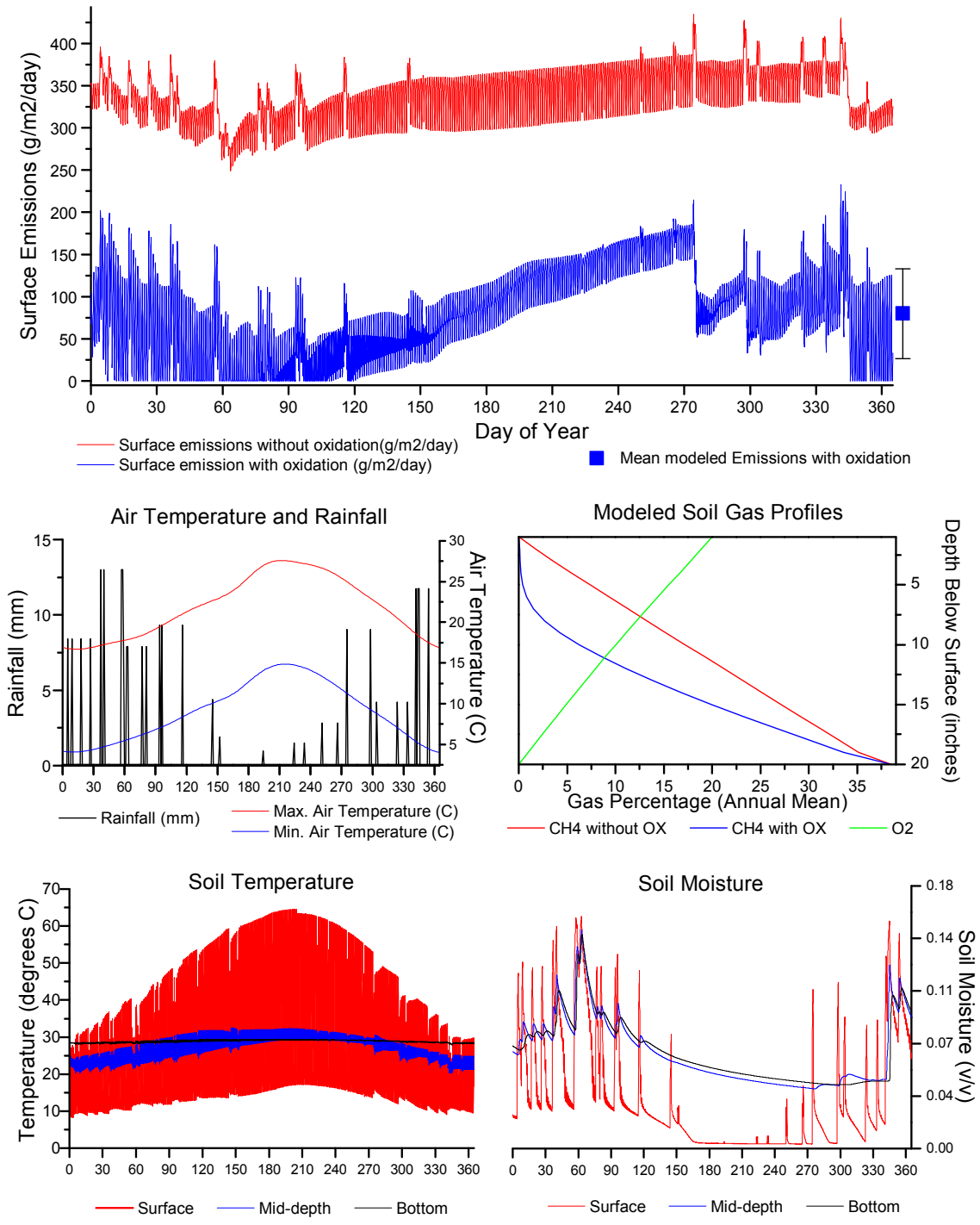


Figure 27. Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +30 °N (Ensenada, Mexico).

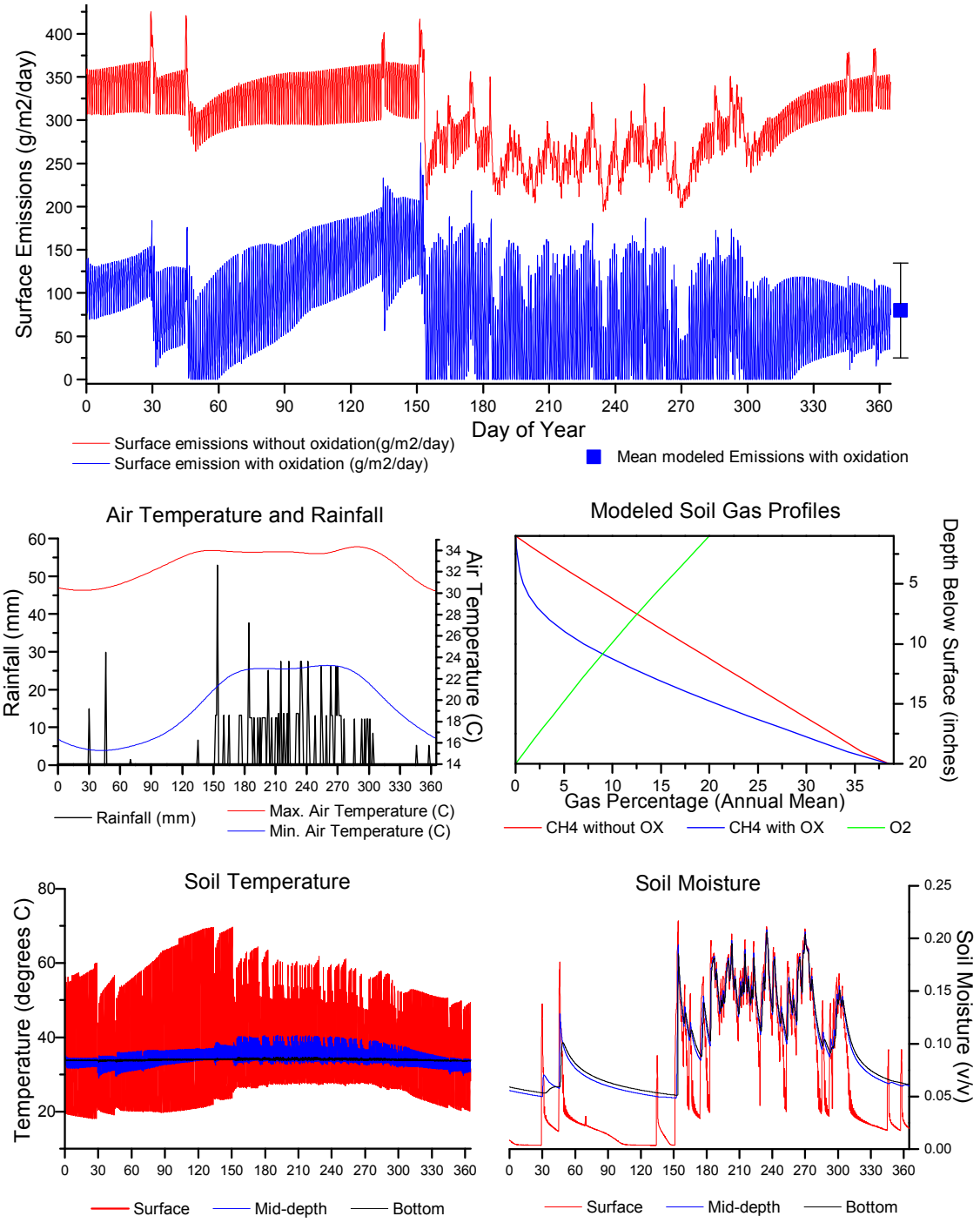


Figure 28.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +20 ^{o}N (Puerto Vallarta, Mexico).

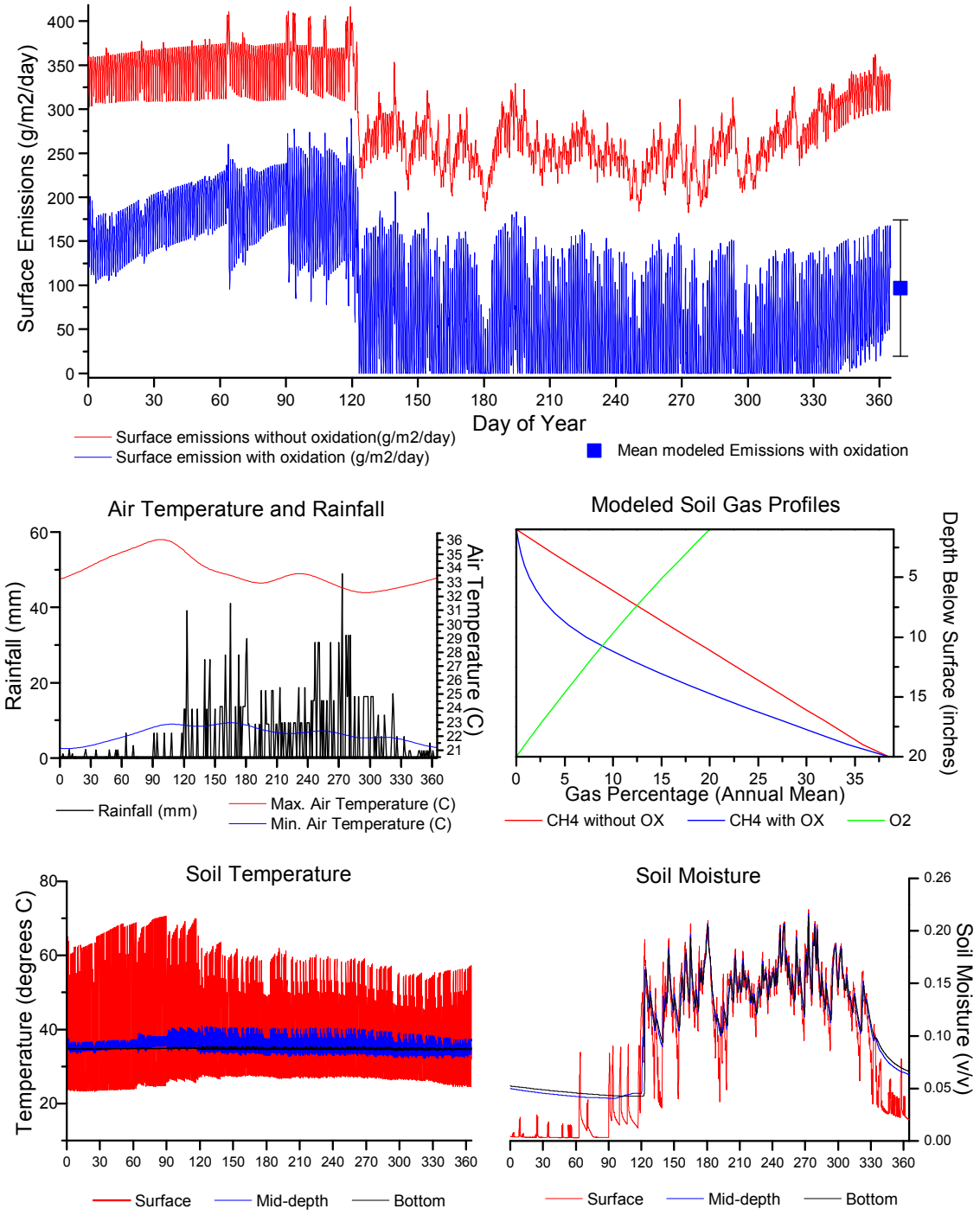


Figure 29.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +10 °N (Puntareno, Costa Rica).

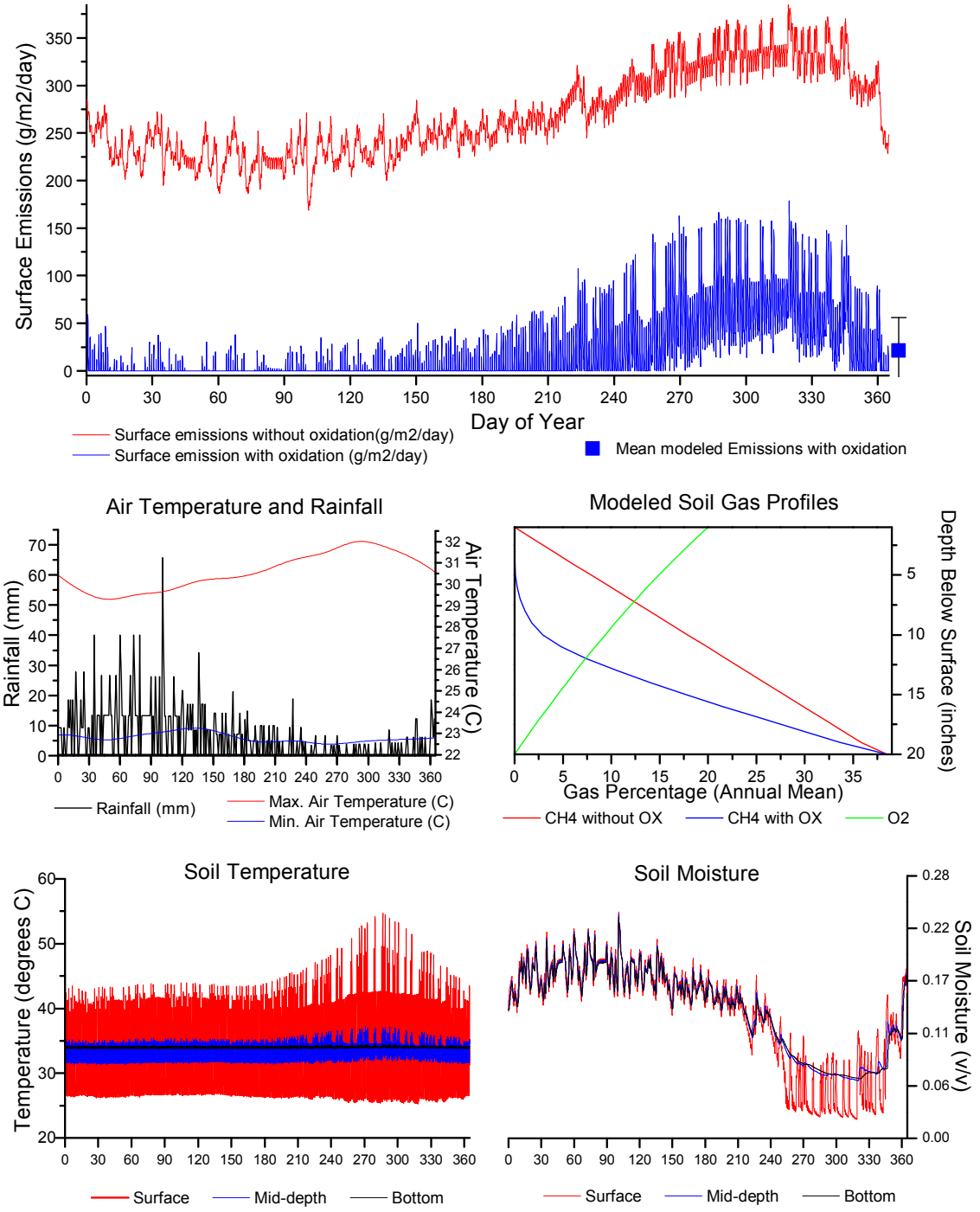


Figure 30.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at +0 °N (Macapa, Brazil).

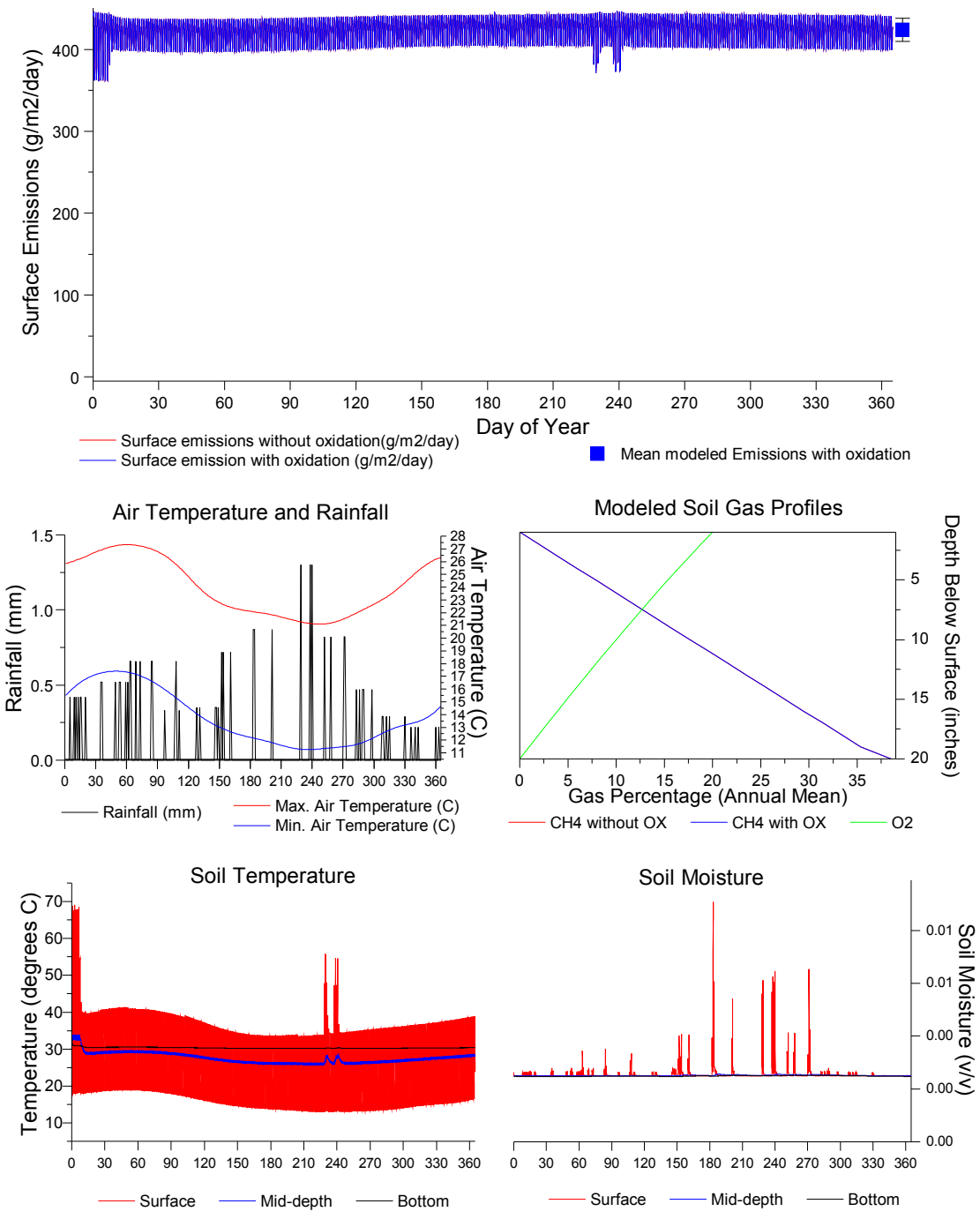


Figure 31.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at -10 °N (Huacho, Peru).

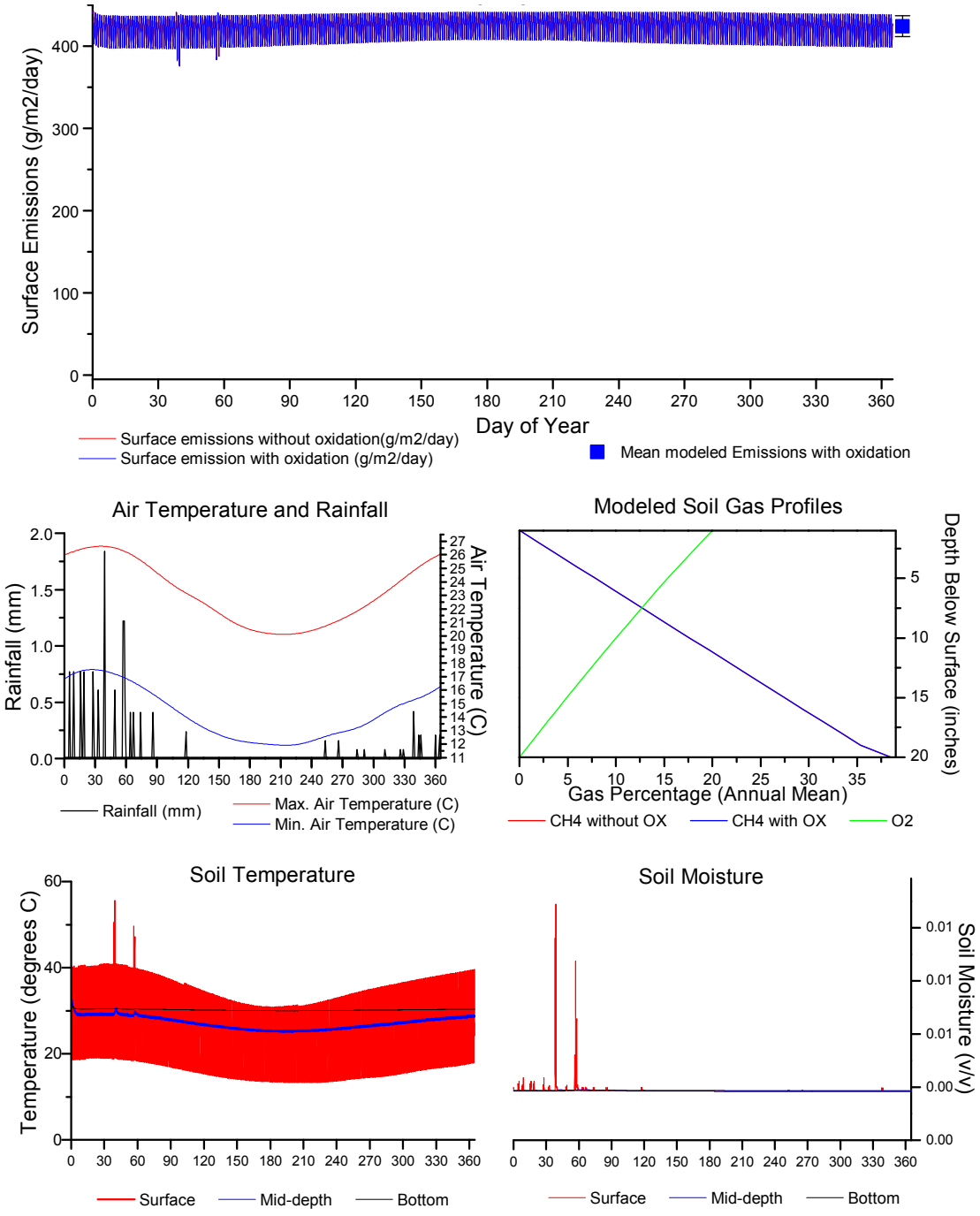


Figure 32. Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at -20 °N (Iquque, Chile).

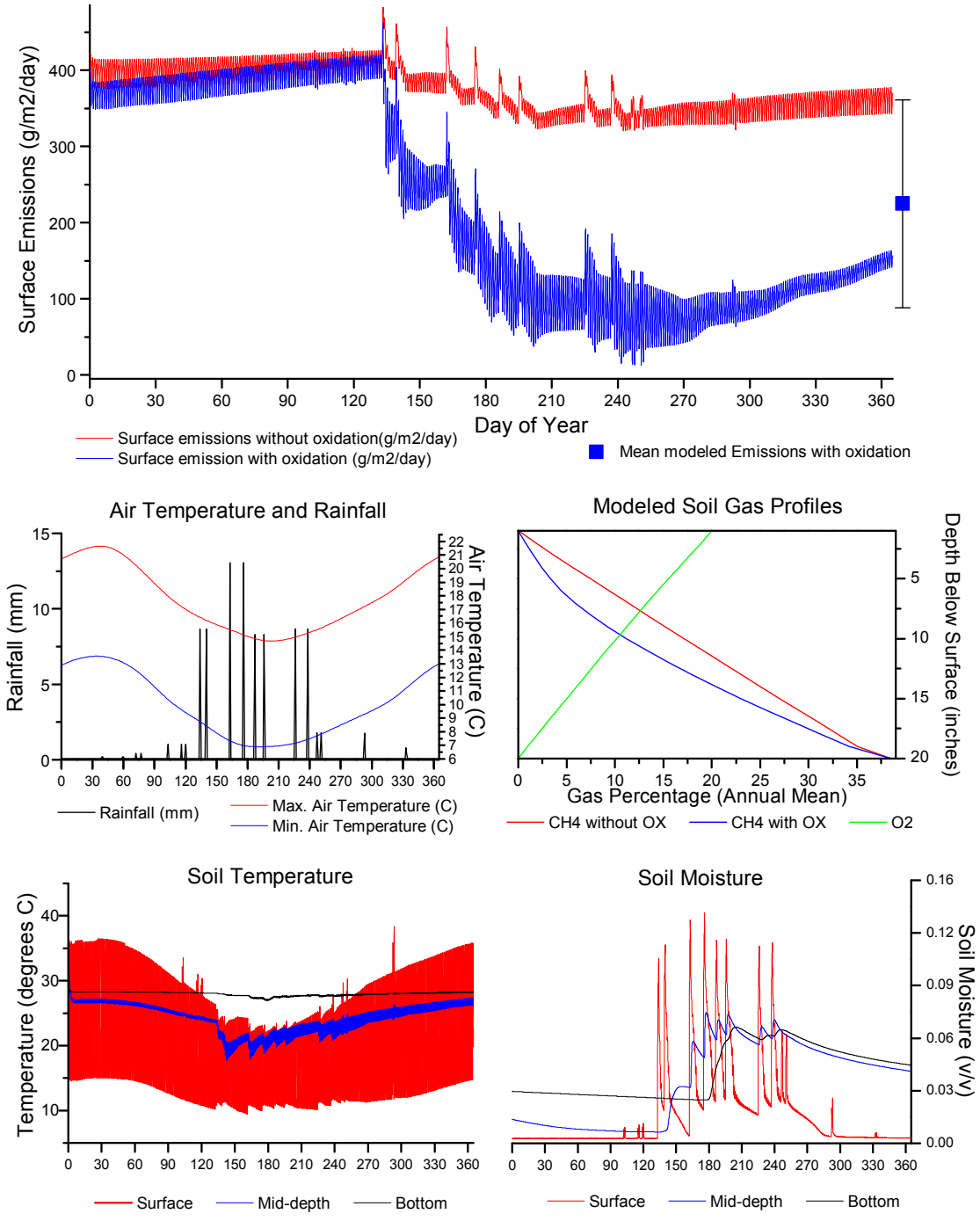


Figure 33.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at -30 °N (Coquimbo, Chile).

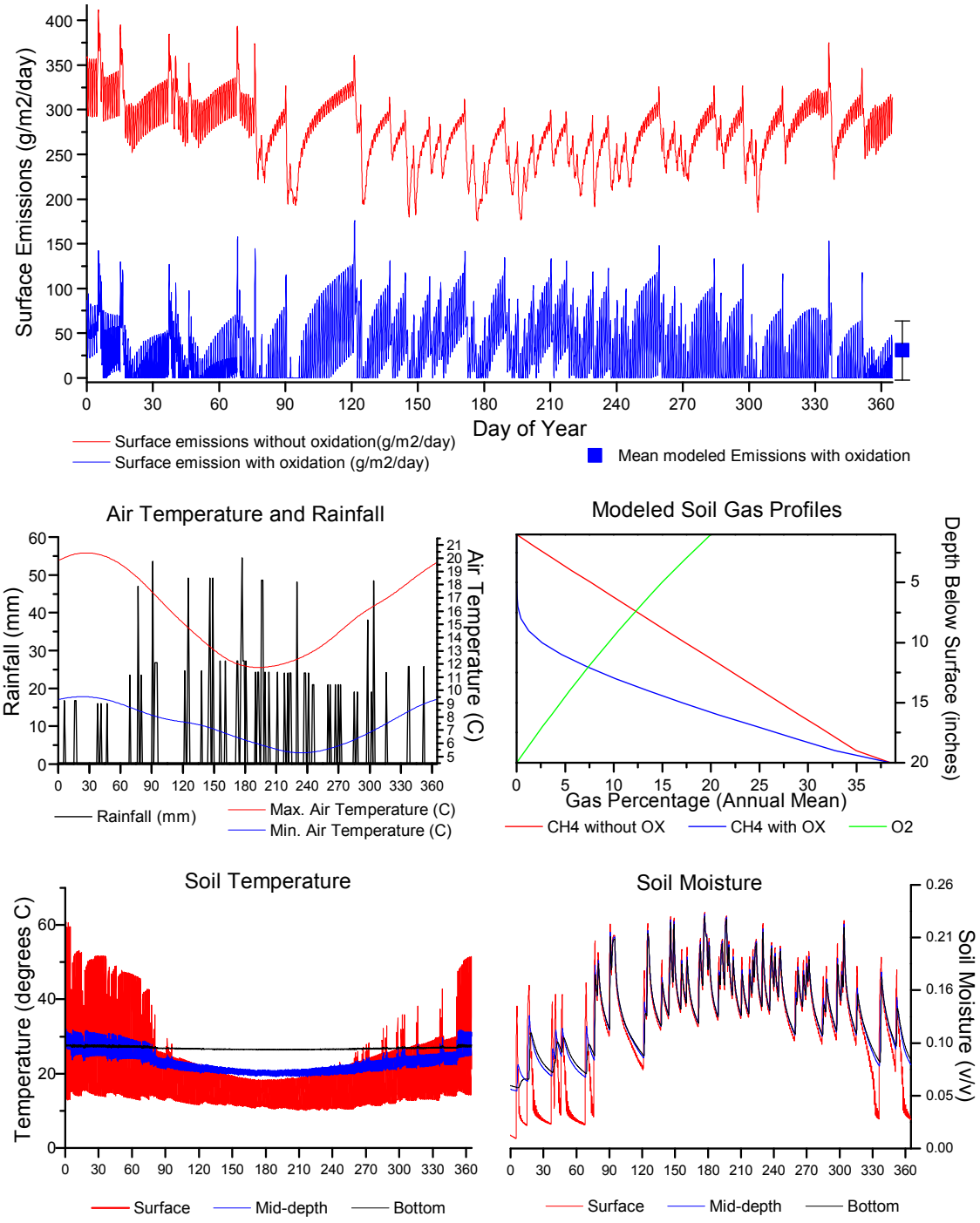


Figure 34. Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at -40 °N (Valdivia, Chile).

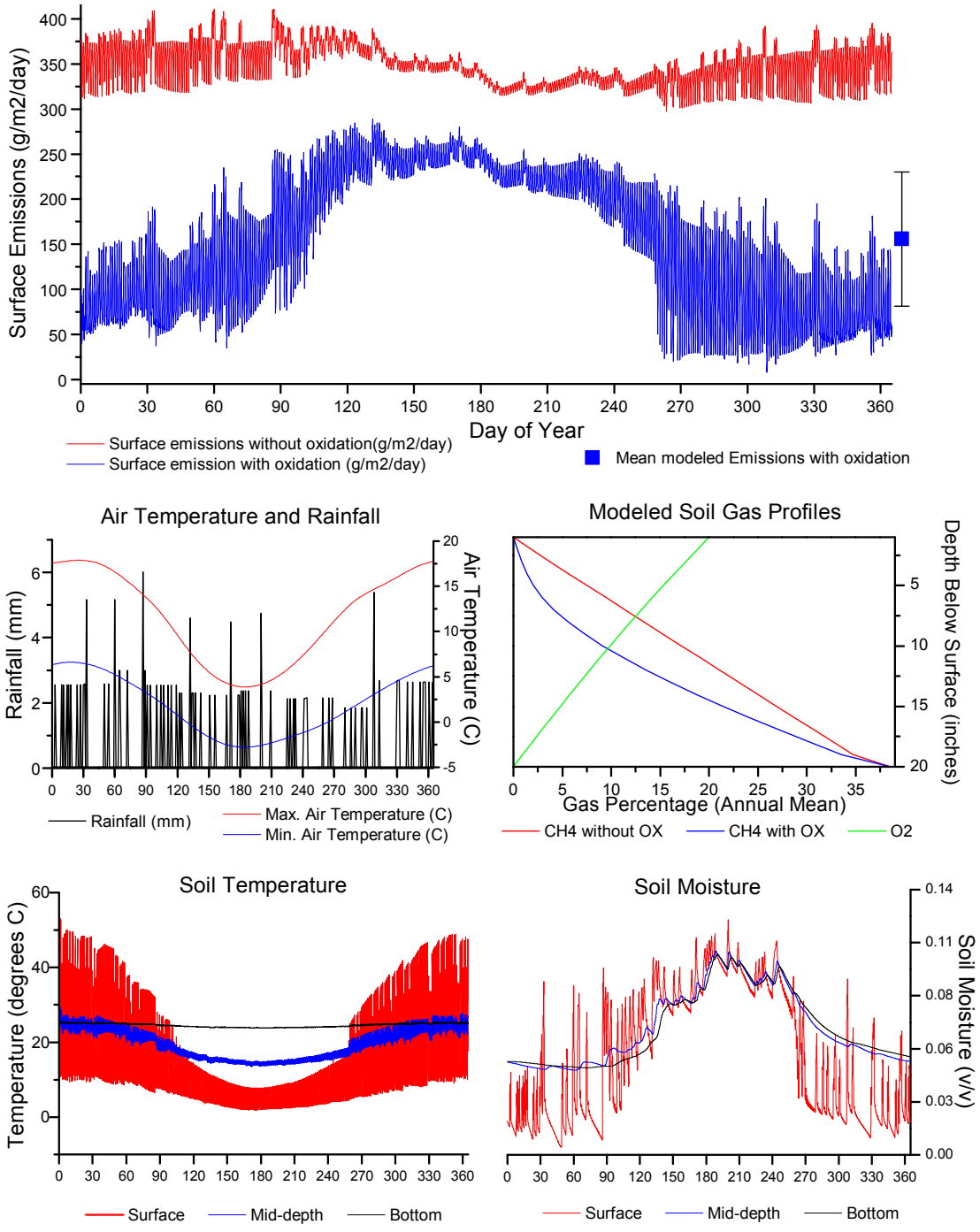


Figure 35.Typical annual cycle for emissions, precipitation, air temperature, soil gas profile, soil moisture, and soil temperature for the location at -50 ^{o}N (Rio Gallegos, Argentina).

4.4. CALMIM simulations for landfill CH_4 emissions under future climate change scenarios for selected global cities

As discussed above under methods, using publically-available climate projections for SRES scenarios A2 and B1 for 2020, 2050, and 2100 (NCAR, 2012b), landfill CH_4 emissions were projected with CALMIM for selected intermediate cover materials (clay, silty clay loam, sand, and sandy loam soils) with selected thicknesses (0.25 m, 0.50 m, and 1.0 m). Intermediate cover materials were chosen because these typically have the largest surface area at landfill sites and are predicted to be the largest contributor to the overall site emissions (see Section IV-E). In this section we discuss how landfill CH_4 emissions with and without oxidation could change under the two scenarios A2 and B1 for four cites: Lulea, Sweden; Cairo, Egypt; Macapa, Brazil; and Cape Town, South Africa (see Method Section III-D).

Figures 36 through 40 indicate projected emissions with oxidation for the four cover types and three depths for the two scenarios for 2020, 2050, and 2100 for the four locations examined here. Please note the log scale for the y-axis (emissions with oxidation, unit area basis, g CH_4 m^{-2} d^{-1}) in figure panels A and C. The orders-of-magnitude range for the projected emissions is similar to the range of emissions from worldwide field data as discussed in the Introduction. For all scenarios at all 4 locations there were orders-of-magnitude decrease in emissions associated with thicker cover materials of a given soil texture. Thus, both for future scenarios, as well as for currently-available field measurements, one must consider the large variability in emissions associated with variability in cover texture and thickness. Figure panels B and D display the net percent oxidation to corresponding to the A and C panels respectively, for the A2 and B1 scenarios. In all cases, as calculated by CALMIM, this is the average annual value for (emissions without oxidation – emissions with oxidation)/emissions without oxidation plotted as a percentage. Each site will be discussed individually below.

For Lulea, located in the north of Sweden, surface emissions were reduced by approximately two orders of magnitude by increasing the cover thickness from 0.25 to 1.00 m, as shown in Figure 36. Although the clay, sandy loam, and silty clay loam covers have similar "order-of-magnitude" values for emissions at the various depths, low emissions were typically associated with the silty clay loam cover. However, the minimum emissions were associated with the A2 2099 sandy loam cover. As shown in Figure 36B, this was the only cover which achieved 100% oxidation in any Lulea scenario simulation. We hypothesize that this was due to increased soil temperature and more optimum soil moisture at depth, combined with lower oxygen diffusion into the clay and silty clay loam soils. Thus, there was more efficient oxidation in the deepest sandy loam cover. This phenomenon has been observed in the real world as well, with texture playing a critical role in the efficiency of methanotrophic activity (Gebert et al., 2011). The combined effect of soil texture, soil temperature, and soil moisture variations on CH_4 transport and oxidation is an important strength of process-based models, such as CALMIM. This permits the use of the model to examine specific combinations of different soil types and their theoretical impact on diffusive methane transport at a specific global location.

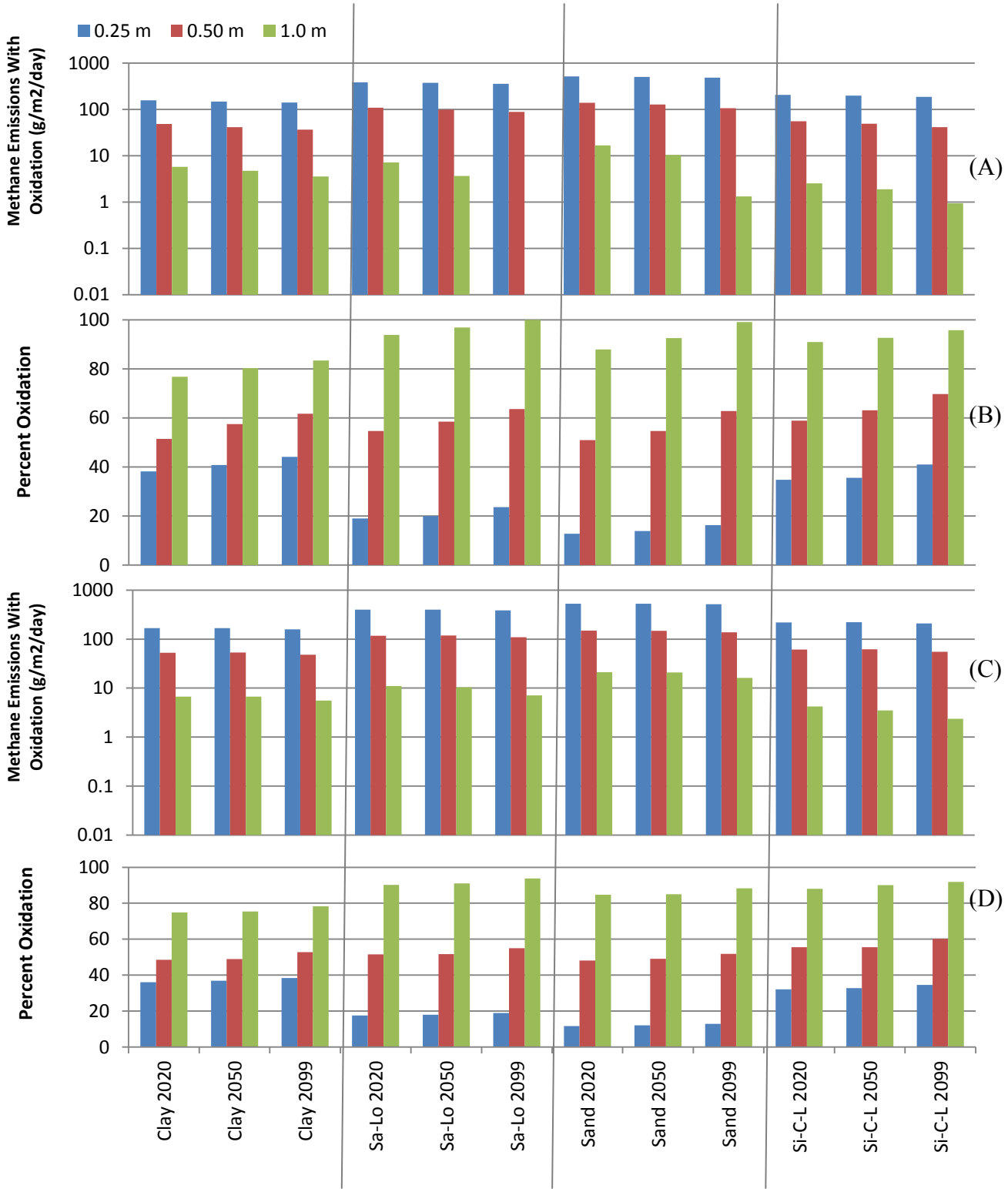


Figure 36.Lulea, Sweden. (A) Impact of climate change A2 scenario on landfill methane emissions with oxidation, (B) the corresponding percent CH_4 oxidation for the A2 scenario, (C) impact of scenario B1 on landfill emissions with oxidation and the (D) corresponding percent CH_4 oxidation.

Overall for Lulea, Sweden, climate change appears to have little or positive impact (reduced emissions) for the largest impact scenario A2. The largest reductions correspond to the thickest covers.

For Cairo, Figure 37 shows that, with the exception of the sand cover, all of the other covers indicate higher emissions for all cover thicknesses than for Lulea. This is due to increased temperatures (above the optimum for oxidation) and decreased moisture (below oxidation optimum). Even for the thickest 1 m covers (except for sand), modeled emissions approach or attain very high values of 100 or >100 g CH_4 m^{-2} d^{-1}. Figure 37 shows low fractional oxidation for almost all the Cairo covers, except for the high oxidation associated with the 1 m sand and moderate oxidation associated with the 0.5 m sand.

Figure 38 shows soil moisture and temperature over an annual cycle at the intermediate depth for all soil thicknesses for the Cairo sand simulations. The intermediate depth soil temperature for the 1 m sand, and to a lesser extent, the 0.5 m. sand are in the optimum range for oxidation (moisture content is higher than the wilting point) (Spokas and Bogner, 2011). For soil moisture, even though all of the mid-depth soil moisture values are low during the annual cycle, the highest values are associated with the 1 m cover.

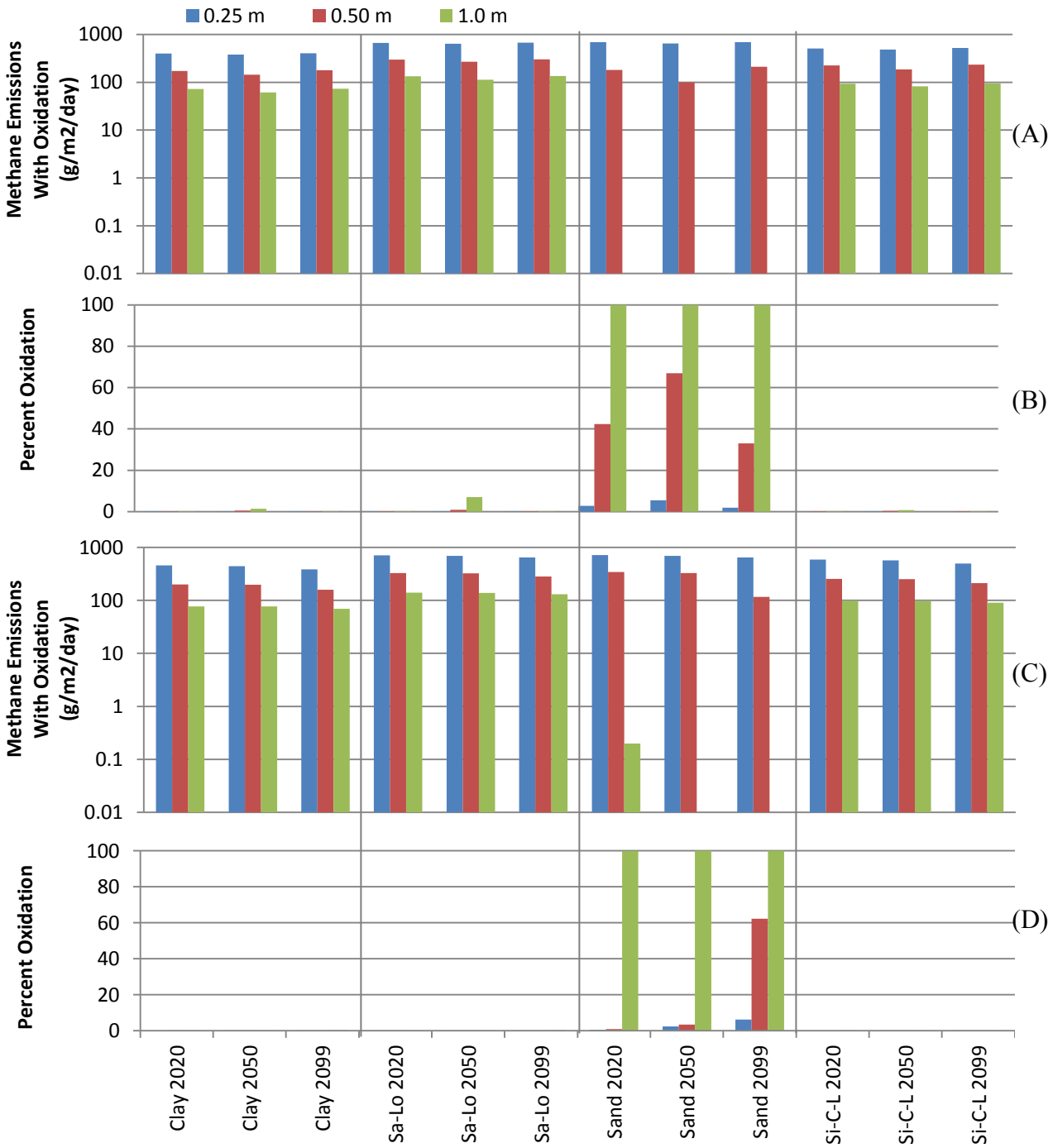


Figure 37.Cairo, Egypt. (A) Impact of climate change A2 scenario on landfill methane emissions with oxidation, (B) the corresponding percent CH_4 oxidation for the A2 scenario, (C) impact of scenario B1 on landfill emissions with oxidation and the (D) corresponding percent CH_4 oxidation.

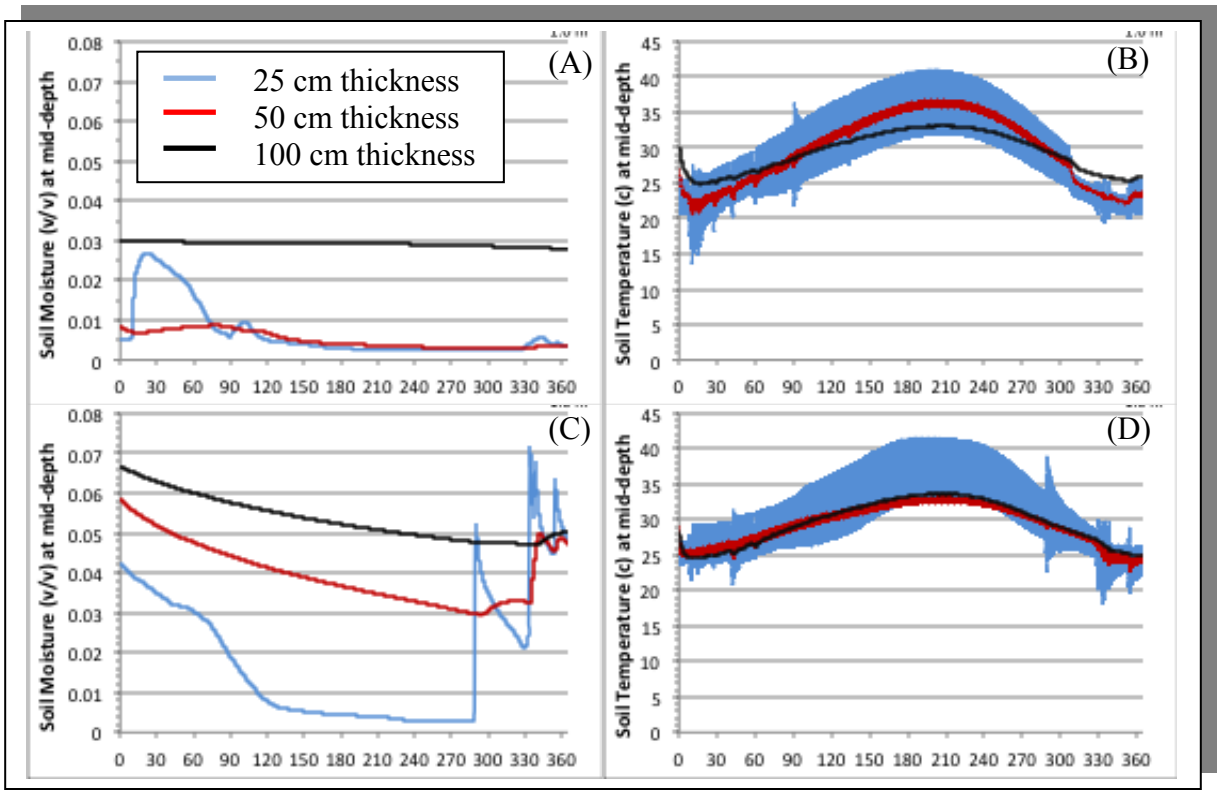


Figure 38.Results of climate scenario A2 mid-depth soil moisture (v/v) and soil temperature [C] over the annual cycle for Cairo sand simulations for SRES scenarios A2 (A and B) and B1 (C and D).

For Macapa, in the tropical northeastern part of Brazil, Figure 39 indicates that all of the thin 0.25 m cover soils for both scenarios result in very large emissions greater than 100 g CH_4 m^{-2} d^{-1}. The thicker 0.50 m cover for all soils results in moderately lower emissions in the range of 50-100 g CH_4 m^{-2} d^{-1}. However, the thickest 1 m cover for all soils is necessary to achieve emissions below 10 g CH_4 m^{-2} d^{-1}. Looking at the % oxidation in Figure 39C & 39D, the highest values for oxidation are paired with the lowest emissions in Figure 39, especially for the thicker soils. As for Cairo, the lowest emissions are paired with the coarser texture soils, the sand and sandy loam soils.

There is another interesting effect observed in the Macapa, Brazil climate change scenarios, which theoretically is identical to the effect observed in Cairo, Egypt with decreasing precipitation. As we move from 2020 to 2099, decreased moisture in the Macapa clay soil is linked to a future climate with lower precipitation. As we move from 2020 to 2099, in both scenarios for this location, there is a projected increase in CH_4 emissions in the clay soil resulting from drier soils. However, the relative impact on emissions is a function of both cover thicknesses and soil textures. For thicker clay covers (1 m), emissions increase an order of magnitude (from 0.05 to 0.5 g CH_4 m^{-2} d^{-1} under B1 and 0.3 to 3.7 g CH_4 m^{-2} d^{-1} under A2), whereas with the 25 cm clay cover the increases are only 21% under the A2 and 8% increase in the B1 scenario. The other finer-textured soil results (silt loam and clay-silt loam) are similar. On the other hand, emissions from the sand cover did not increase and were unaffected by the predicted climate change.

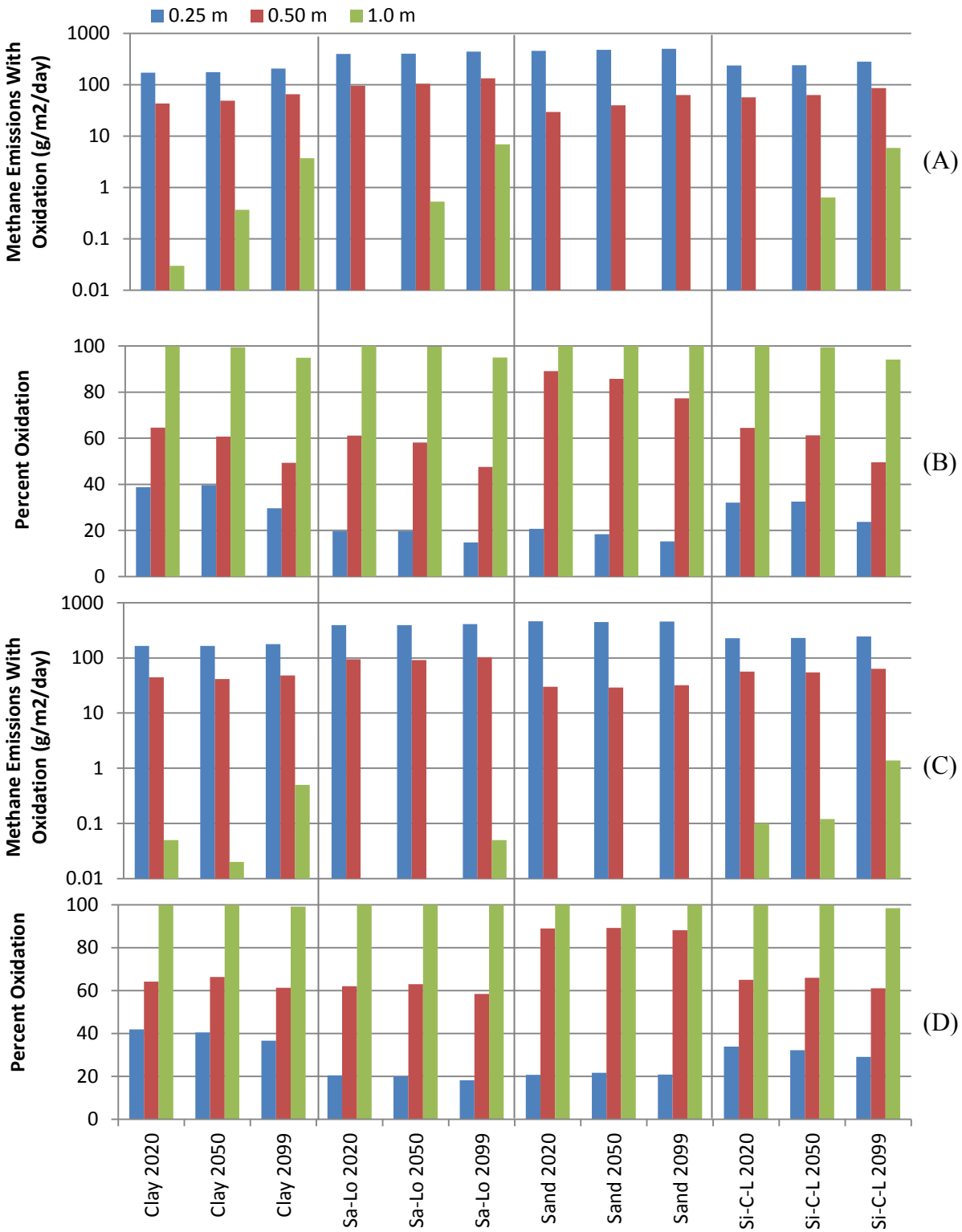


Figure 39.Macapa, Brazil. (A) Impact of climate change A2 scenario on landfill methane emissions with oxidation, (B) the corresponding percent CH_4 oxidation for the A2 scenario, (C) impact of scenario B1 on landfill emissions with oxidation and the (D) corresponding percent CH_4 oxidation.

Finally, Cape Town has a temperate coastal climate at the southern tip of Africa, all of the 0.25 m soil simulations in Figure 40 result in emissions inclusive of oxidation greater than 100 g CH_4 m^{-2} d^{-1}. For the 0.5 m soils, there is a wide range in emissions, depending on the soil type, with the sand soils generally <1 g CH_4 m^{-2} d^{-1} and the other soils generally >10 g CH_4 m^{-2} d^{-1}. The 1 m soils have low emissions at or below 0.1 g CH_4 m^{-2} d^{-1} for the A2 scenario but ranging up to 10 g CH_4 m^{-2} d^{-1} for the B1 scenario. For all of the 1 m soils, the % oxidation approaches or achieves 100%.

What are the lessons to be learned from these simulations? First, across the many soil types, contrasting climate regions, and scenarios, an intermediate long-term cover should be a minimum of 1 m thick to achieve moderate to low emissions at or <10 g CH_4 m^{-2} d^{-1}. For hot, dry climates such as Cairo, for most soil types, 1 m is not sufficiently thick to achieve these low emissions (Figure 37). The high % oxidation associated with the sand texture cover for all simulations can be explained by the typical shape of the sand soil moisture retention curve (Figure 41). At relatively low volumetric soil moisture contents (2 to 5% volumetric moisture; e.g., the Cairo simulations), there is still available moisture for the soil to be above the wilting point (or the point at which water is still available to plant roots and microbial cells) for a sandy texture (Fig. 41). This minute amount of water in a sandy soil is available to microbes. Compare this to a clay-rich soil, where in order to reach the wilting point a soil would need to be higher than 28% volumetric water (Fig. 41). This can be a very important consideration in arid climates with limited rainfall.

To conclude, the climate change simulations emphasize the importance of considering specific combinations of cover soils and thicknesses interacting with climate-driven variations in soil moisture and temperature. For a specific location, properly selecting the soil texture and thickness for a landfill cover soil can optimize CH_4 oxidation and reduce emissions or, conversely, reduce oxidation and increase emissions. In general, there is no single universal answer regarding how climate change will alter landfill CH_4 emissions for a particular global location as future emissions depend both on cover soil properties and the future climate. Soil oxidation may increase as the result of climate change, as for Lulea, Sweden, or decrease as for the fine-textured soils in Macapa, Brazil. Thus these simulations indicate that a cover soil needs to be tailored to the local climatic regime as well as to considerations of cover texture and thickness.

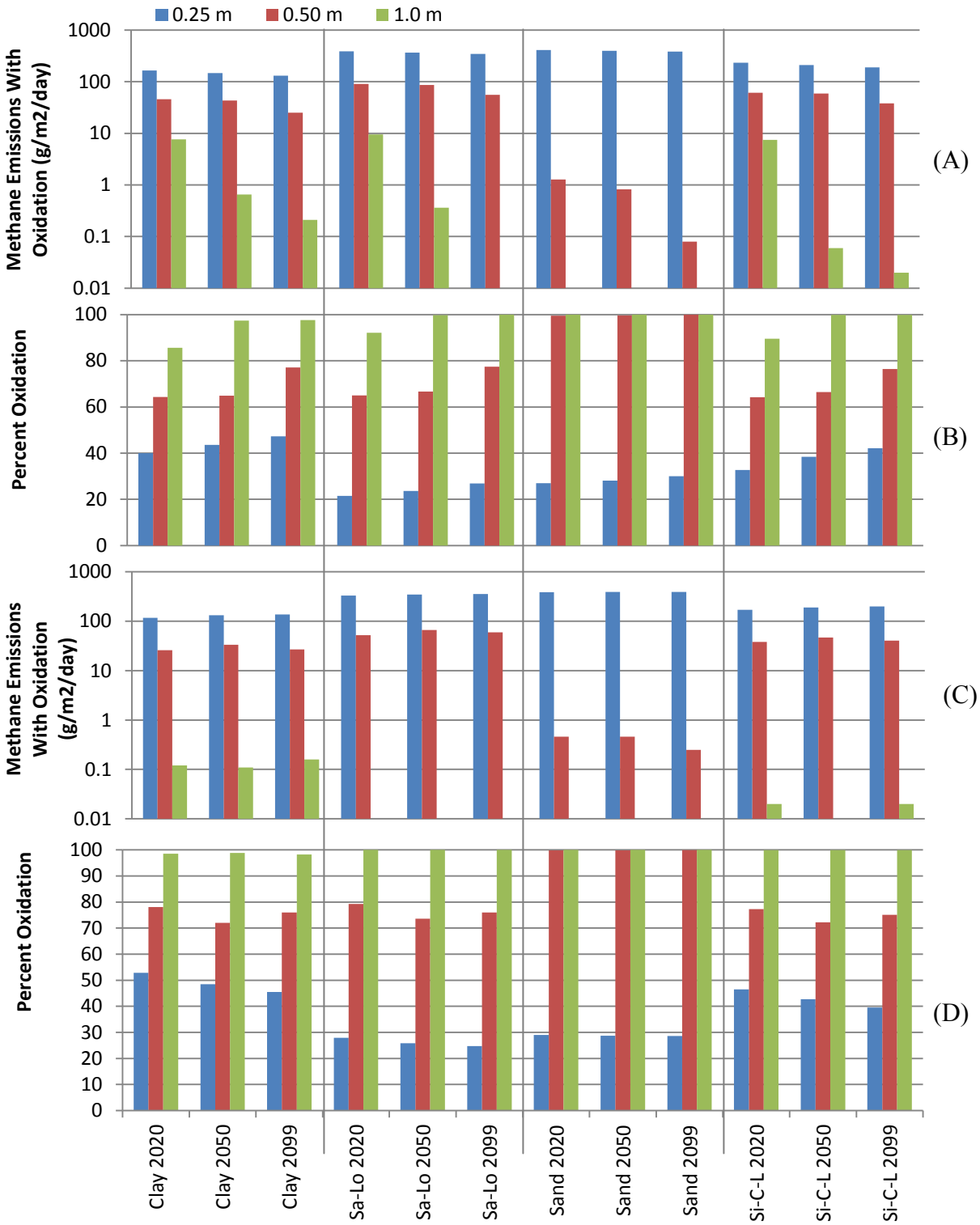


Figure 40.Cape Town, South Africa. (A) Impact of climate change A2 scenario on landfill methane emissions with oxidation, (B) the corresponding percent CH_4 oxidation for the A2 scenario, (C) impact of scenario B1 on landfill emissions with oxidation and the (D) corresponding percent CH_4 oxidation.

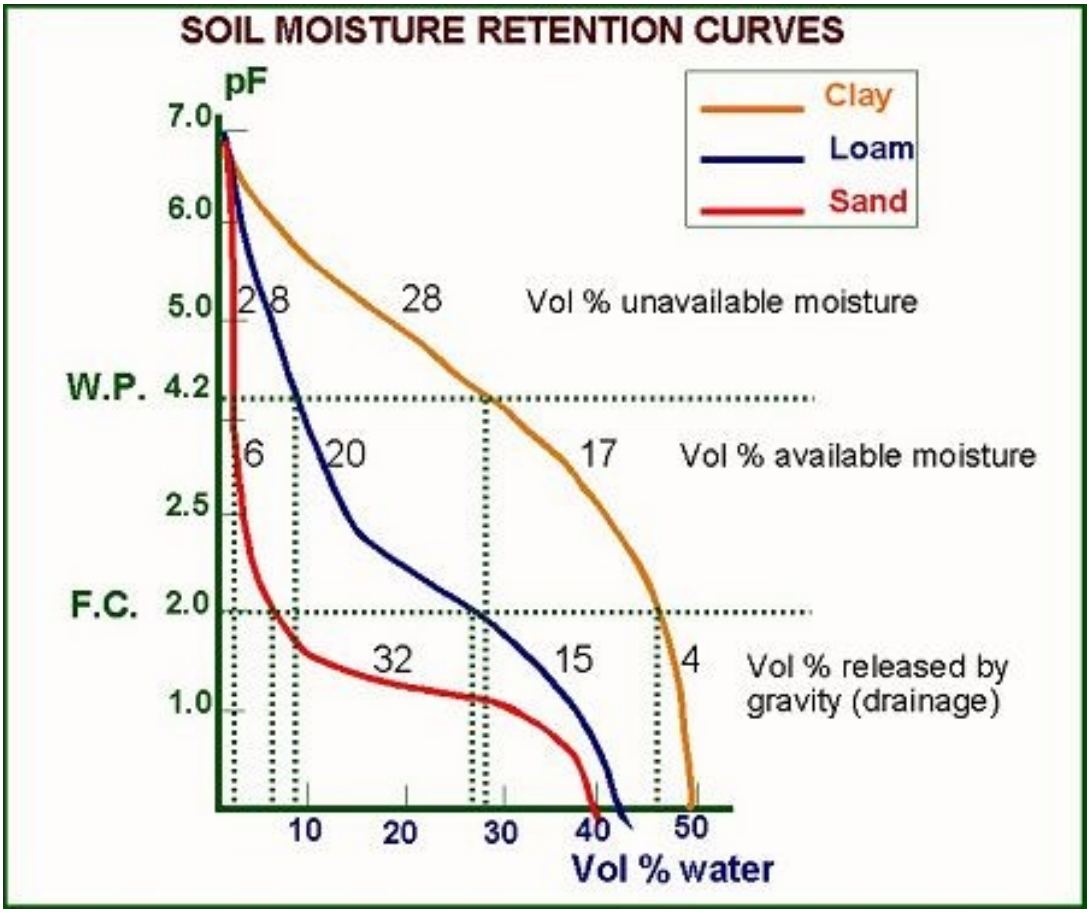


Figure 41. Figure of soil texture relationship to soil moisture potential [4]

[4] - Figure taken from www.aardappelpagina.nl/explorer/pagina/pictures/pfcurvey.jpg

4.5. FIELD PROJECT - INDIANA LANDFILL

4.5.1. May and August, 2012 field campaigns to quantify CH_4 and O_2 soil gas concentration gradients and variability for daily and intermediate cover soils

This section will summarize two field campaigns to develop recommendations for the minimum requirements for "custom" soil gas profiles to be used in CALMIM modeling. As discussed above under methods, we investigated soil gas profiles in parallel with static chamber fluxes at intermediate and "extended" daily cover materials at a central Indiana landfill site. Although this investigation was also part of a larger collaboration with Waste Management, Inc. and Purdue University to compare and contrast landfill CH_4 emissions using 4 techniques over a variety of spatial scales, this report will focus only on the UIC results. As of December, 2013, emissions data from the other investigators were still being finalized.

The major research question was: What are the magnitude and variability of soil gas CH_4 and O_2 concentrations at the base of the cover materials at this site? Although there is limited literature on soil gas CH_4 concentrations at the base of final cover materials and certain "biocovers", literature to date has not systematically addressed the variability of "base of cover" CH_4 under daily and intermediate cover materials in cells with and without gas recovery. Because CALMIM uses either a default or "custom" value for soil gas CH_4 at the base of the cover to establish a concentration profile driving gaseous flux, we were especially interested in quantifying the "base of cover" CH_4 over scales of tens of meters. Field data are required to begin to formulate recommendations for the site-specific determination of "custom" values for CALMIM input as the current CALMIM "default" values rely on conservative values (e.g., higher values) taken from previous literature (see further discussion in Spokas et al., 2011). At specific sites, it is also important to take into consideration whether there is a "proximal" (near gas recovery well) effect on observed emissions and soil gas concentration profiles.

Tasks for the UIC studies focused on field measurement of CH_4 emissions, soil gas concentrations at the base of the cover, soil gas profiles, and CH_4 oxidation rates. We focused on both the intermediate cover soil (May 2012) and an "extended" daily cover soil (August 2012). Direct field measurements included soil gas CH_4, CO_2, O_2, and N_2 concentrations at the base of the cover, soil gas concentration profiles, and determination of CH_4, N_2O, and CO_2 emissions to the atmosphere using a static closed chamber technique (previously described in Spokas et al., 2011; Bogner et al., 2011).

Figure 42 provides an overview of the field monitoring points for both campaigns. As discussed above, the purpose of the investigations described in this section was to determine a minimum field campaign for input of "custom" soil gas profiles into CALMIM. For the May 2012 field campaign on intermediate cover, we quantified "proximal" fluxes and soil gas soil profiles at constant 4 m distances from existing gas wells with "distal" fluxes and soil gas profiles at greater randomized distances from gas

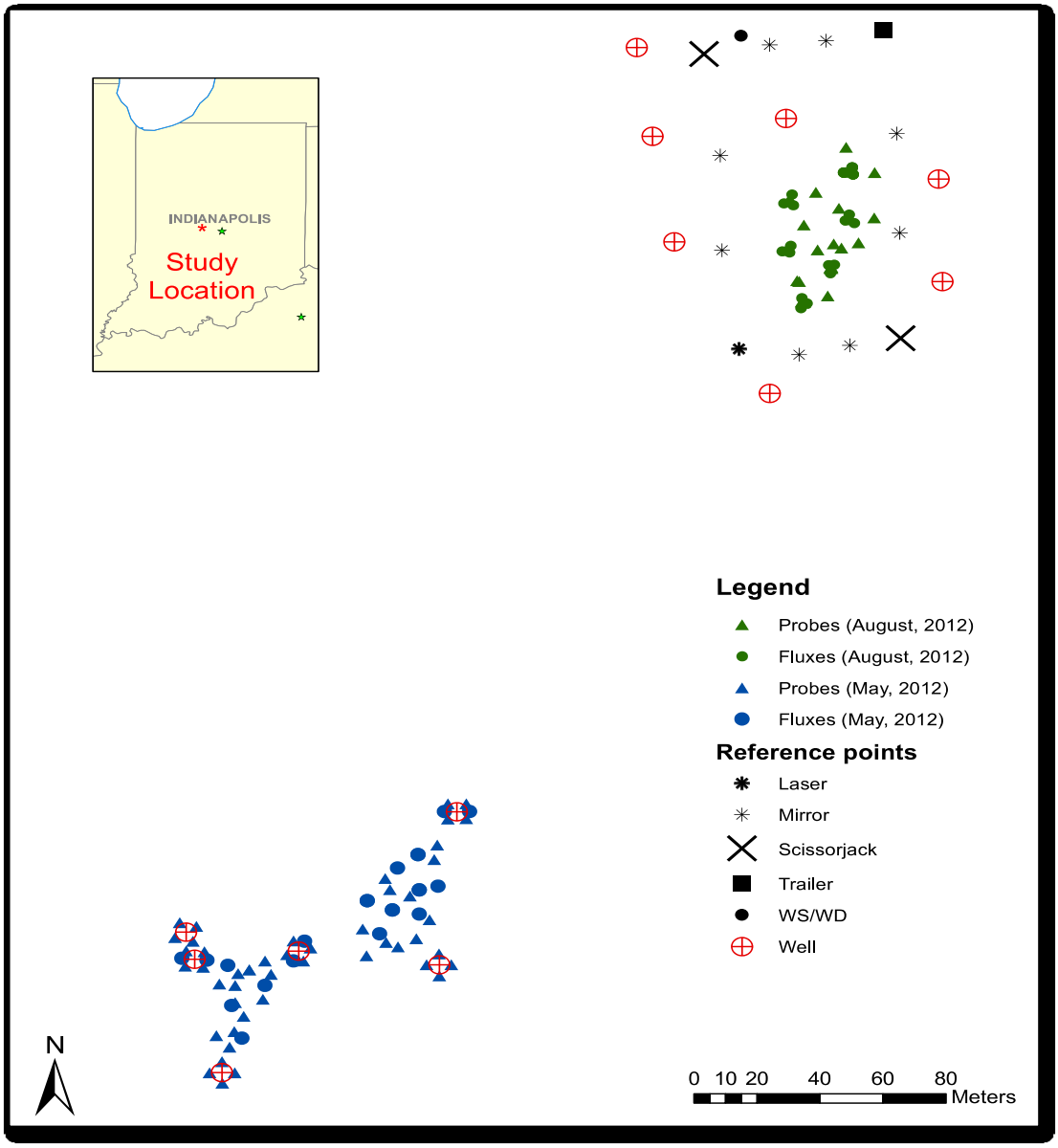


Figure 42.Overview of field monitoring locations at Indiana site IN-1, including locations for soil gas probes, static chamber fluxes, and associated gas recovery wells and other infrastructure in intermediate cover area (May 2012) and extended daily cover area (August 2012). [5]

[5] Map created by Meg Corcoran (2013)

wells. For the August 2012 field campaign on the "extended" daily cover area, each of 6 randomized soil gas profiles was paired with 3 static chamber fluxes. Additional randomized soil gas profiles to the base of the cover were also completed on this area, and three of the static chambers were replicated four times over an 18-hour period.

Table 6 summarizes the May, 2012 intermediate cover data for "base of cover" soil gas concentrations for major gases of interest in landfill cover soils: CH_4, CO_2, O_2, N_2, and N_2O. Although we located approximately half the locations for both probes and fluxes at a constant 4 m from the various gas recovery wells in the field area, there was no statistically significant difference between the proximal "near well" and distal randomized "between well" locations with respect to soil gas concentrations or fluxes. Therefore, the proximal and distal data were composited for this table. As shown in the table, average depth to the base of the cover was approximately 85 cm, much thicker than the permitted minimum of 30 cm. Also, due to aggressive gas recovery [high vacuums recorded at individual wellheads], average soil gas concentrations at the base of the cover indicated relatively low CH_4 (9.5% v/v) and high O_2 (15.5% v/v). The combination of highly compacted, thick silt loam cover soils and efficient gas recovery contributed to the low measured CH_4 emissions (see Table 7), averaging 0.03 g CH_4 m^{-2} d^{-1}. This table includes averaged replicates for fluxes which satisfied the criterion of r^2=0.9 or greater for the linear regression of CH_4 concentration vs. time. The relatively low total number of fluxes satisfying this criterion was due to the highly compacted cover soils (some difficulty with setting chamber bases), intermittent winds of variable wind speed and direction (site was located at the highest elevation on the site), and low fluxes which were near the minimum level of detection including approximately 1/3 negative CH_4 fluxes (uptake of atmospheric CH_4).

*Table 6.*Soil gas concentrations at base of intermediate cover. Note: Area has full gas recovery using vertical wells *[see Figure 42]*.

Unit	Depth (cm)	N_2O (ppb)	CH_4 (ppm)	CO_2 (ppm)	O_2 (%)	N_2 (%)
Average	**80.5**	**59.4**	**95685**	**69705**	**15.5**	**59.4**
Stand Dev	**14.7**	**19.5**	**1553027**	**104016**	**6.7**	**19.5**
GeoMean	**78.7**	**52.5**	**1752**	**7778**	**12.1**	**52.5**
Geo St Dev	**1.3**	**1.9**	**86.5**	**14.1**	**2.6**	**1.9**
Median	**85**	**68.6**	**6507**	**5524**	**19**	**68.6**
Min	**25**	**4.7**	**2.9**	**411**	**0.5**	**4.7**
Max	**100**	**75.7**	**515443**	**355199**	**21.4**	**75.7**
Count	**45**	**45**	**45**	**45**	**45**	**45**

*Table 7.*Summary of static chamber fluxes from intermediate cover area. Count includes averaged replicates and fluxes passing significance criterion of $r^2 = 0.9$ for linear regression of concentration vs. time.

	CH_4 Flux ($g\ CH_4\ m^{-2}\ d^{-1}$)	CO_2 Flux ($g\ CO_2\ m^{-2}\ d^{-1}$)	N_2O Flux ($g\ N_2O\ m^{-2}\ d^{-1}$)
Positive Flux (Emission to atmosphere)			
Average	0.027	6.62	0.0024
Standard Deviation	0.040	3.45	0.0013
Minimum	0.005	3.13	0.0009
Maximum	0.124	16.02	0.0059
Count	9	12	13
Negative Flux (Uptake from atmosphere)			
Average	-0.004		-0.0021
Standard Deviation	0.001		
Minimum	-0.006		
Maximum	-0.003		
Count	3	0	1

Table 8 summarizes the May, 2012 intermediate cover data for the first static chamber air sample, which we used as a surrogate for top of soil profile/atmospheric concentrations for "custom" CALMIM modeling. Note that atmospheric CH_4, on average, is slightly elevated above the worldwide average mixing ratio of <2 ppm v/v, averaging approximately 4 ppmv (v/v) and ranging from 2 to 12 ppmv (v/v). This is typical for landfill sites where the atmospheric CH_4 enrichment is a function of many spatial and temporal factors, including variability in cover soils, localized differences in soil moisture and temperature affecting oxidation rates, and, depending on the time of day, the variable height of the atmospheric boundary layer.

Examining contrasting data from late August, 2012, for the "extended daily cover" area, Table 9 indicates much higher average soil gas CH_4 concentrations of 46.6% v/v and much lower soil gas O_2 of 2.9% v/v at the base of the cover. Unlike the intermediate cover area discussed above, this area has no internal gas recovery wells; instead, wells were located only around the perimeter. Also, although this cover is similar in thickness to the intermediate cover, it has much lower compaction. Correspondingly, the CH_4 fluxes [Table 10], although still quite moderate, averaged almost 3 g CH_4 m^{-2} d^{-1}, or about 2 orders of magnitude higher than for the intermediate cover area discussed above. Basal soil gas O_2 concentrations were also correspondingly lower, averaging 2.9% v/v.

Table 8.First gas sample from May chamber measurements (time=0). Approximate air concentrations (v/v) near ground surface.

Unit	N_2O (ppb)	N_2O (ppm)	CH_4 (ppm)	CO_2 (ppm)	O_2 (%)	N_2 (%)
Average	**330**	**0.33**	**3.99**	**447**	**21.4**	**75.5**
Stand Dev	**18.8**	**0.02**	**2.20**	**30.6**	**0.36**	**1.30**
GeoMean	**330**	**0.33**	**3.61**	**446**	**21.4**	**75.5**
Geo St Dev	**1.1**	**1.1**	**1.5**	**1.1**	**1.0**	**1.0**
Median	**327**	**0.33**	**3.5**	**438**	**21.4**	**75.8**
Min	**302**	**0.3**	**2.0**	**417**	**20.4**	**71.9**
Max	**378**	**0.38**	**12.0**	**558**	**21.9**	**77.4**
Count	**22**	**22**	**22**	**22**	**22**	**22**

Table 9.Base of cover soil gas concentration data for "extended daily cover" area.

Unit	Depth (cm)	N_2O (ppb)	CH_4 (ppm)	CO_2 (ppm)	O_2 (%)	N_2 (%)
Average	**78**	**823**	**466230**	**296790**	**2.92**	**10.9**
Stand Dev	**13**	**1587**	**25379**	**64089**	**0.68**	**2.50**
Min	**60**	**61**	**427162**	**254327**	**2.07**	**7.68**
Max	**90**	**5928**	**504152**	**522117**	**4.89**	**17.8**
Count	**15**	**15**	**15**	**15**	**15**	**15**

Note: Includes 11 random probe locations and the deepest probe from soil gas profiles #3, #4, #5, and #6.

Table 10.Summary of static chamber fluxes from extended daily cover area. Count includes averaged replicates and fluxes with $r^2 > 0.9$ for the linear regression of concentration vs. time.

	CH_4 Flux ($g\ CH_4\ m^{-2}\ d^{-1}$)	**CO_2 Flux ($g\ CO_2\ m^{-2}\ d^{-1}$)**	**N_2O Flux ($mg\ N_2O\ m^{-2}\ d^{-1}$)**
Positive Flux (Emission to atmosphere)			
Average	2.2760	33.9482	1.0605
Standard Deviation	5.1810	34.1831	2.1134
Minimum	0.0024	4.23	0.00
Maximum	16.84	127.28	4.23
Count	10	15	4
Negative Flux (Uptake from atmosphere)			
Average			-0.0053
Standard Deviation			0.0030
Minimum			-0.01
Maximum			0.00
Count	0	0	5

4.5.2. Comparison of default and custom data entry for CALMIM modeling: How are CALMIM modeled CH_4 emissions with and without oxidation affected by the differing soil gas profiles?

To answer this question, we ran CALMIM simulations for both the intermediate cover and extended daily cover discussed above, including "default" simulations using default soil gas profiles and "custom" simulations using the measured soil gas CH_4 and O_2 profiles for both areas as discussed above. We also used 2012 custom weather data from a local airport source rather than CALMIM "default" weather, which relies on 30-year average data accurate to approximately ½ deg. latitude by ½ deg. longitude. Based on the field data, the custom boundary conditions for soil gas CH_4 and O_2 were as follows:

- May, 2012 intermediate cover

top	CH_4	4 ppmv (v/v)
	O_2	21.4% (v/v)
bottom	CH_4	9.5 % (v/v)
	O_2	15.5 % (v/v)

- August, 2012 extended daily cover

top	CH_4	53.5 ppmv (v/v)
	O_2	21.3% (v/v)
bottom	CH_4	46.6% (v/v)
	O_2	2.9% (v/v)

Table 11 compares the annual average CH_4 emissions from both custom and default soil gas profiles/weather to the CH_4 emissions measured during the field campaigns in May and August, 2012. Note the very high fractional oxidation (87-95%) for three of the four covers (low oxidation only for the daily cover default soil gas concentrations). Also note that measured CH_4 emissions for the extended daily cover compare favorably to the CALMIM modeled emissions. A major issue with the poorer match for the intermediate cover was that, at some chamber locations, cover thickness was greater than we were able to measure for the concurrent profiles (maximum depth of 1 m for soil gas probe); thus we attribute the lower field measurements compared to CALMIM modeling to inadequate deeper soil gas profile data. For determining custom profiles for other sites, a reasonable field investigation of this type, we recommend that soil gas sampling can attain depths of 2+ meters in order to provide reasonable concurrence with intermediate cover thicknesses. As previously discussed in this report, our experience has been that intermediate covers are typically thicker than typical regulatory minimum thicknesses of 12-18 inches (30-45 cm).

Table 11.Contrasting measured emissions to modeled emissions using CALMIM for default and custom soil gas profiles.

Location	Annual avg. CH_4 emissions with oxidation ($g\ CH_4\ m^{-2}\ d^{-1}$)	Annual avg. CH_4 emissions without oxidation ($g\ CH_4\ m^{-2}d^{-1}$)	Remaining oxidation capacity ($g\ CH_4\ m^{-2}\ d^{-1}$)	% oxidation	Actual avg. CH_4 emissions with oxidation: May, 2012 intermediate cover; August,2012 daily cover ($g\ CH_4\ m^{-2}\ d^{-1}$) [range]
Intermediate Cover-Custom	1.8	16.2	202.0	87.3	**0.03** [0.005-0.124]
Intermediate Cover-Default	3.5	50.9	147.9	91.2	
Extended Daily Cover-Custom	8.1	175.8	195.3	95.4	**2.3** [0.002 – 16.8]
Extended Daily Cover-Default	1.0	1.1	0.12	12.4	

Notes:

Custom weather data for custom soil gas profile; default weather data for default soil gas profile; intermediate cover 32 in silty clay loam; extended daily cover 31 in sandy loam; 100% gas recovery for intermediate cover and 0% for extended daily cover; no vegetation; intermediate soil organic matter.

We conclude that field investigations whose scope is similar to the Indiana project are suitable to spatially define "custom" soil gas profiles for CALMIM applications. However, site-to-site spatial and temporal variability should be expected as the soil gas CH_4 and O_2 concentrations at the base of cover, like the emissions, are dependent on soil properties, climate-related variables, and the gas extraction system. A PhD thesis currently in progress at Melbourne University (M. Asadi) is investigating the temporal and spatial variability of soil gas profiles at a single site for CALMIM applications.

4.6. New 2010 California GHG inventory using CALMIM and site-specific comparisons to California field measurements.

The realistic quantification of landfill CH_4 emissions from individual sites for improved local- and regional-scale GHG inventories requires an improved process-based field-validated methodology (see Section 3.6). In this section, we apply CALMIM5.4 to develop a new site-specific 2010 landfill CH_4 emissions inventory for California and compare the results to the current 2010 California inventory from the California Air Resources Board (ARB). As California is a large state with a variety of climatic regimes, we will discuss emissions over monthly, seasonal, and annual timescales for a range of spatial scales (site-specific to state). Through this modeling we demonstrate that landfill CH_4 emissions are highly dependent on the thickness and properties of cover soils as well as seasonal oxidation, neither of which are addressed by existing IPCC inventory methods.

4.6.1. 2010 CALMIM California GHG Inventory

Site-specific estimations of landfill CH_4 emissions compiled for the 2010 California GHG inventory were kindly supplied by the California ARB (L. Hunsaker, personal communication, 2012). These are based on the IPCC (2006) "mathematically exact" FOD methodology as discussed in detail in Crooks and Lang (2011). In general, regional California waste disposal data are used for the California inventory with differing gas generation potentials (k) and kinetic constants (L_o) for various waste fractions. The Walker (2012) database used for the comparative CALMIM modeling contains information for a total of 374 landfills as shown in Figure 43. As expected for the existing 2010 inventory estimates (see Figure 44), there is a very clear relationship with the total waste in place, since this is the fundamental property used to derive the estimated emissions using IPCC (2006). Total 2010 estimated California landfill CH_4 emissions from the ARB inventory were **301,748 Mg CH_4 yr^{-1}**.

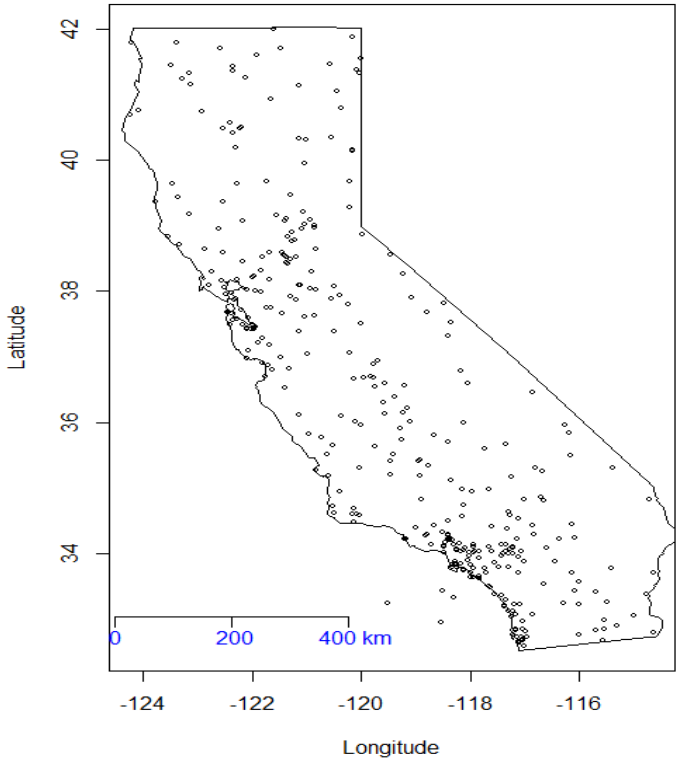


Figure 43. Geospatial location of all California landfills included in the database (Walker, 2012).

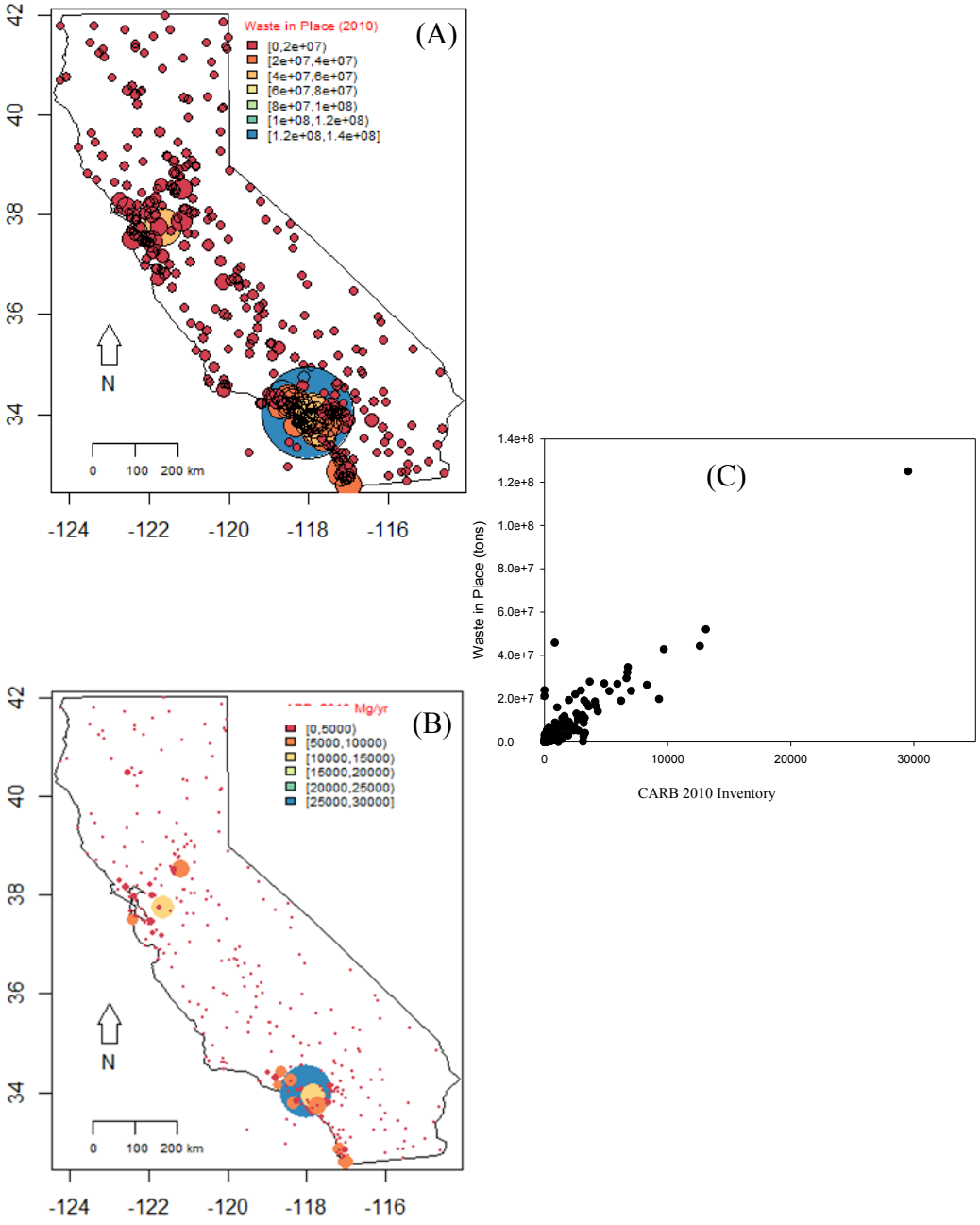


Figure 44.*Spatial distribution of the (A) California waste-in-place estimates from the Walker (2012) database and (B) the ARB 2010 landfill CH_4 emission estimates (Mg CH_4/yr). Notice the linear relationship between waste-in-place and the ARB inventory values, as clearly shown in (C).*

4.6.2. Spatial distribution of CALMIM predictions

The individual data for each landfill site in the Walker (2012) database and the corresponding CALMIM5.4 calculations are given in Appendix C. CALMIM predicts total 2010 California emissions of **337,430 Mg CH_4 yr^{-1}**.

Overall, the total 2010 emissions from CALMIM are similar to the 2010 CARB inventory value:

CARB 2010 Inventory	**301,748 Mg CH_4 yr^{-1}**
CALMIM Estimation	**337,430 Mg CH_4 yr^{-1}**

From CALMIM modeling, we can partition the CH_4 emissions by cover type. The emissions from daily cover (DC), intermediate cover (Int), and final cover (FC) are shown below:

DC	6" Composted Green Waste	10,576	Mg/yr
Int	36" sandy loam	325,343	Mg/yr
FC	CA CCR Title 27	1,505	Mg/yr

More than **96%** of the total estimated California landfill CH_4 emissions originate from intermediate cover areas. This represents a large source of emissions that will be mitigated in the future following final cover placement. As discussed below, these emissions can also be mitigated over shorter timeframes using thicker cover soils.

Moreover, if we reduce the intermediate cover to 30" thick, the statewide total increases significantly to:

DC	6" Composted Green Waste	10,576	Mg/yr
Int	30" sandy loam	444,593	Mg/yr
FC	CA CCR Title 27	1,505	Mg/yr

In this case, the intermediate cover is responsible for **97.4%** of the total estimated emissions.

Despite the similar total emissions derived from the two methods, there are more differences than similarities between the two inventory estimates. We note (Figure 45) that there is no correlation between the CALMIM and ARB site-specific emission estimates (r^2=0.08), nor is there a correlation between the CALMIM results and waste-in-place (r^2=0.09). Due to this lack of correlation, emission predictions using CALMIM possess a different spatial structure as compared to the 2010 ARB calculations (see Figure 46). This figure directly compares the location and magnitude of site-specific emissions from the two inventory calculations. As discussed in more detail below, it is important to note that CALMIM simulations for alternate cover thicknesses will replicate the same spatial distribution as shown in the figure, with differences only in the magnitude of emissions.

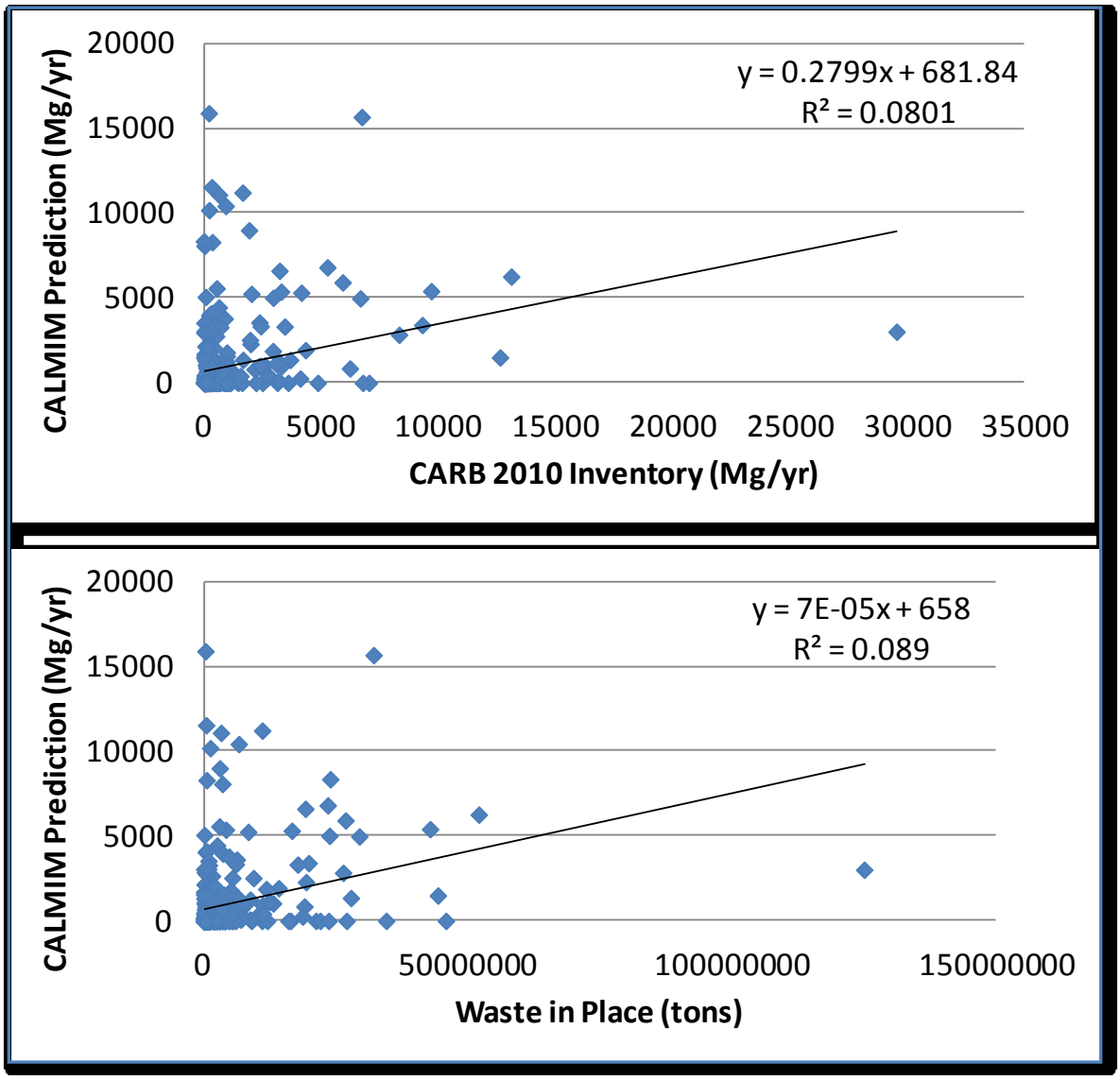


Figure 45.Comparison of estimated 2010 emissions using CALMIM (Mg $CH_4 y^{-1}$) to (A) ARB 2010 inventory estimates and (B) total waste in place (tons).

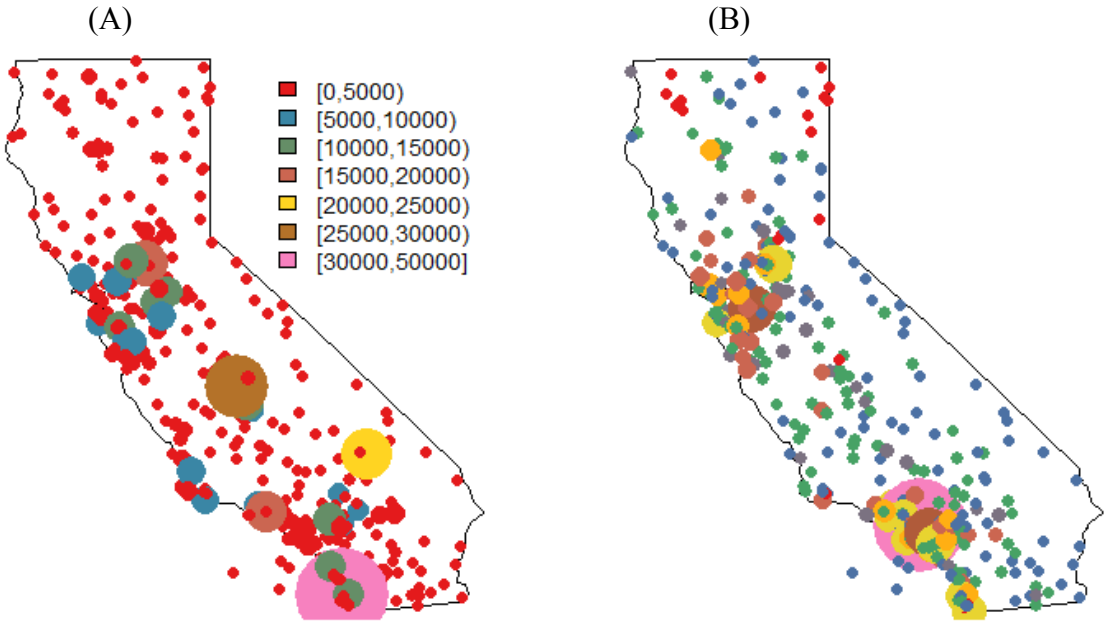


Figure 46.Comparison of the spatial distribution of the (A) CALMIM estimations and the (B) CARB 2010 inventory. Values are in Mg CH_4/yr for each site.

Figure 47 shows the position of the top 11 emitting landfills from 2010 CALMIM and CARB inventories.

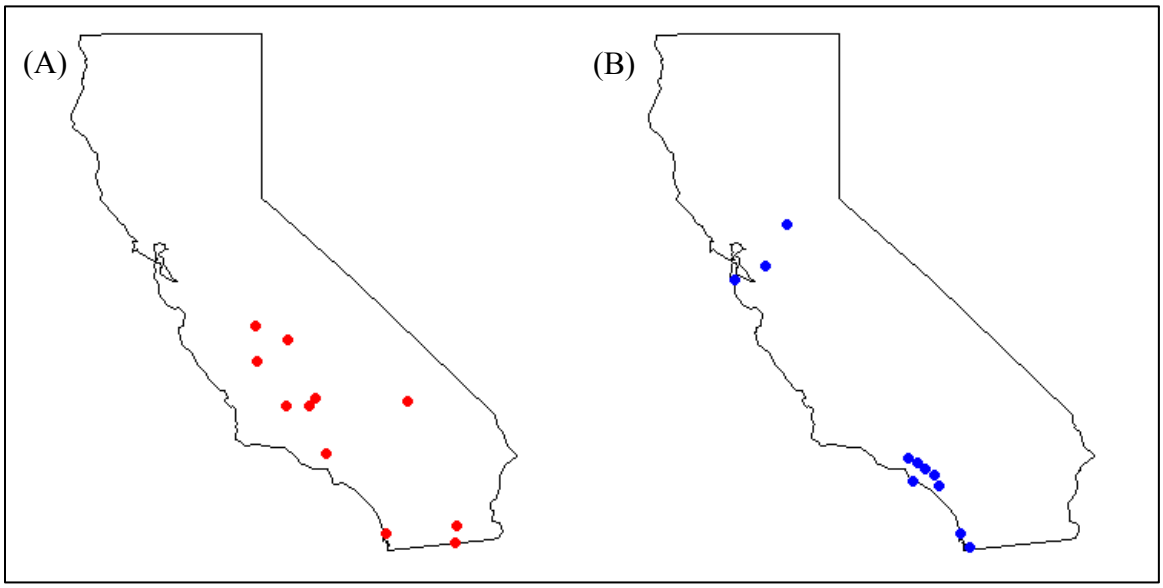


Figure 47.Comparing locations of the top eleven emitting sites with (A) CALMIM and (B)on the ARB 2010 inventory.

For the CALMIM methodology, the largest emitting landfill sites are characterized by the lack of a final cover, resulting in over 75% of the total waste footprint being covered with intermediate or daily cover materials. As mentioned earlier, the intermediate cover areas account for over 95% of the total state emissions by CALMIM calculations. Therefore, the statewide inventory could be drastically reduced solely by reducing the area of intermediate cover or, as already practiced by some sites in California, using thicker intermediate covers. For most California sites, if the intermediate cover conforms to the regulatory minimum thickness (typically 12 in.), the site-specific thickness is not currently tracked and recorded. The same is true in other U.S. states. Since thicker intermediate covers are a major mechanism to reduce emissions, tracking the intermediate cover thickness in connection with site-specific CALMIM simulations can give a more realistic estimation for site emissions.

As shown in Figure 44 for the ARB inventory, the largest landfills are the largest emitters based on the waste in place data (see Appendix D). A majority of these sites do have significant areas of final cover. Moreover, it is known from literature that final cover placement is known to greatly reduce surface emissions based on field data (Abichou et al., 2006a; Goldsmith Jr et al., 2012). However, since the FOD methodology does not consider the thickness and composition of cover materials, this results in a drastic difference between the FOD estimate and the more realistic CALMIM estimates for surface emissions (Amini et al., 2013). As the 2010 ARB inventory is based solely on the waste-in-place data, the net effect is to ignore the critical influence of climate and soil cover on reducing landfill CH_4 emissions. In summary, the fundamental differences in these two approaches are:

(1) The major driver for emissions in the existing ARB inventory is the mass of waste-in-place, while
(2) CALMIM utilizes climate and soil data as primary factors in determining site-specific emissions.

As shown in Figure 48, there is a seasonal trend in CALMIM emissions, with the peak of landfill emissions occurring in August – November. There have been limited studies examining the seasonal variation of CH_4 emissions. Yazdani and Imhoff (2010) measured lower CH_4 oxidation rates in November, with limited field samplings conducted in the fall (Nov) and spring (Feb, Mar, Apr). Park and Shin (2001) observed the lowest CH_4 surface flux when the surface soil temperature was at its minimum during a day. On the other hand, they observed maximum surface CH_4 fluxes when the soil temperature was at its peak. Overall, they concluded that the surface efflux changes with season. This has been postulated ever since the first modeling attempt of soil methane oxidation activity (Czepiel et al., 1996a). The entire 2010 California variability is predicted to be about 17x between the monthly minimum and maximum emission rates [5,183 (Apr) to 89,611 Mg/month (Oct) with soil oxidation]. As seen in the Figure 48, without soil oxidation, the total monthly difference is only two fold.

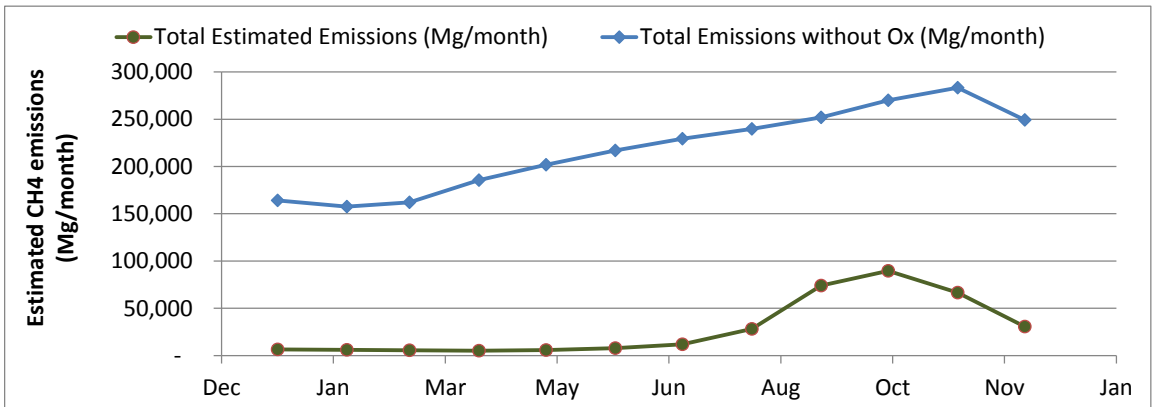


Figure 48.Predicted 2010 CALMIM California landfill CH_4 source strength by month.

Thus, there is a strong seasonal imprint on CH_4 emissions from landfills in California, which agrees with field assessments of the seasonality of landfill emissions. This difference can be directly attributed to differences in predicted CH_4 oxidation in the cover soils. As seen in Figure 49, for the entire state, the calculated total mass of methane that is oxidized monthly in landfill cover soils ranges from 151,000 to 218,000 Mg. Translated to an area basis, this amounts to a statewide average landfill CH_4 oxidation flux density of **62 g CH_4/m^2/day.** The seasonal (monthly) variability in the spatial distribution of California landfill emissions is shown in Figure 50, with the numbers given in Table 12.

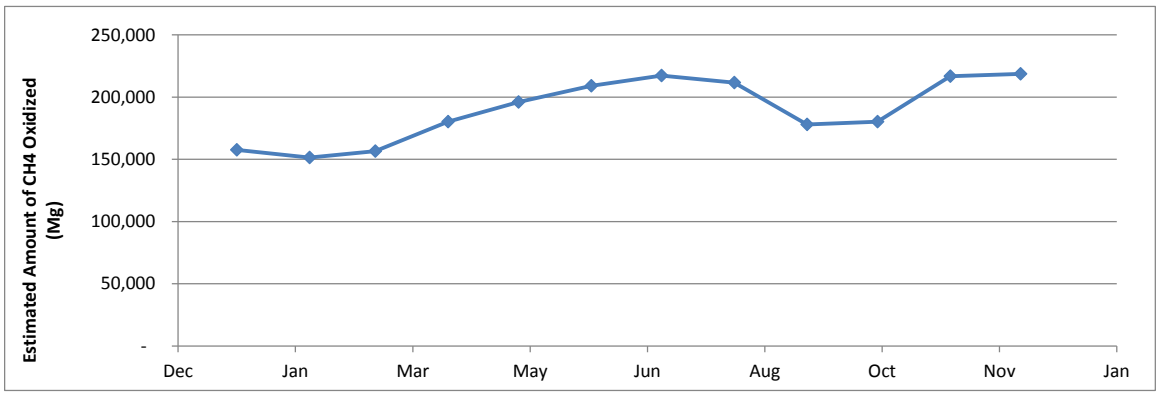


Figure 49.Predicted 2010 CALMIM total monthly landfill CH_4 oxidization in landfill cover soils.

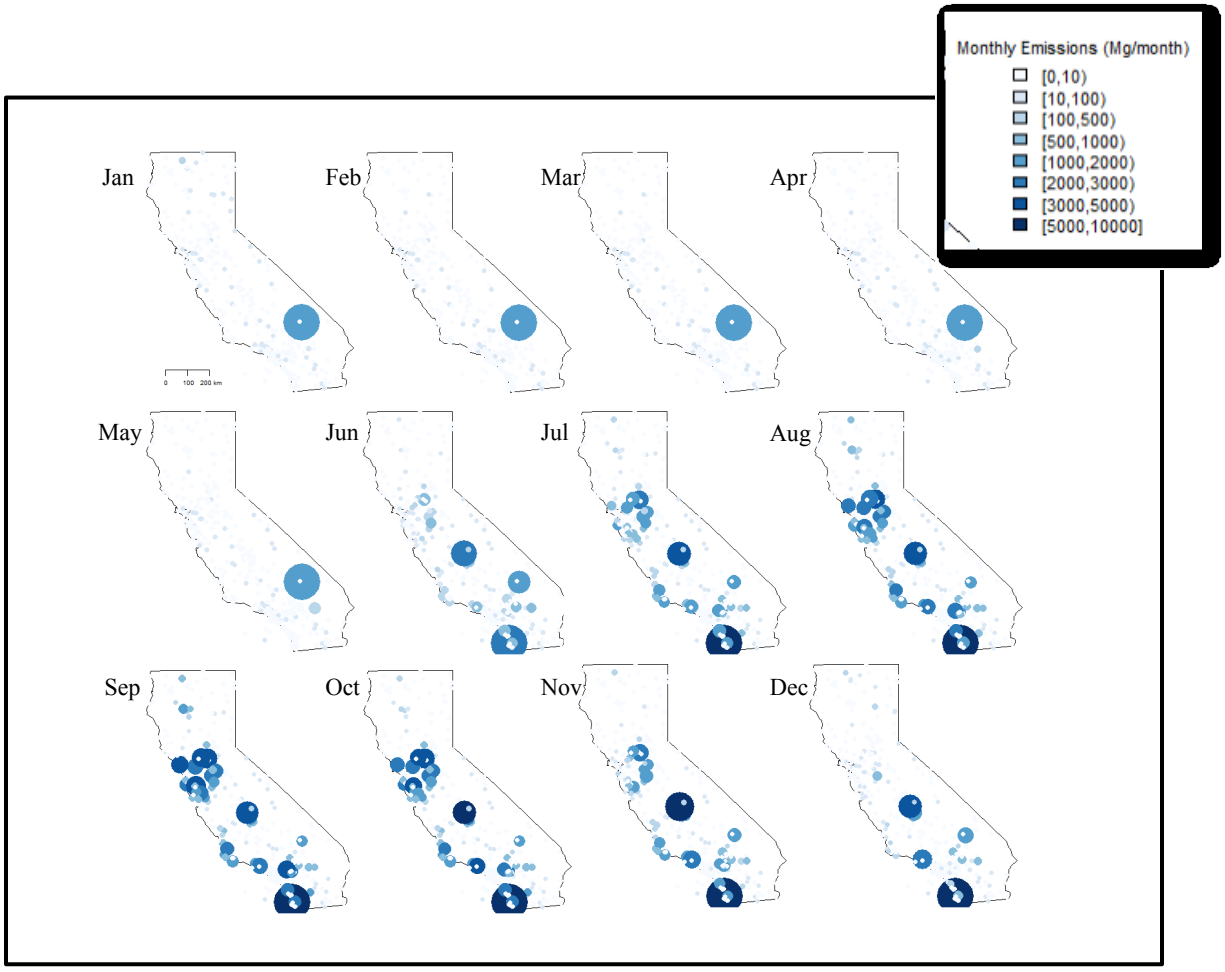


Figure 50.Spatial and temporal variable in CALMIM 2010 landfill emissions (monthly seasonality).

*Table 12.*Monthly totals (Mg CH_4/month) for the California statewide inventory summarizing the amount of methane oxidized, percent oxidation, and the estimated surface emissions with and without soil oxidation.

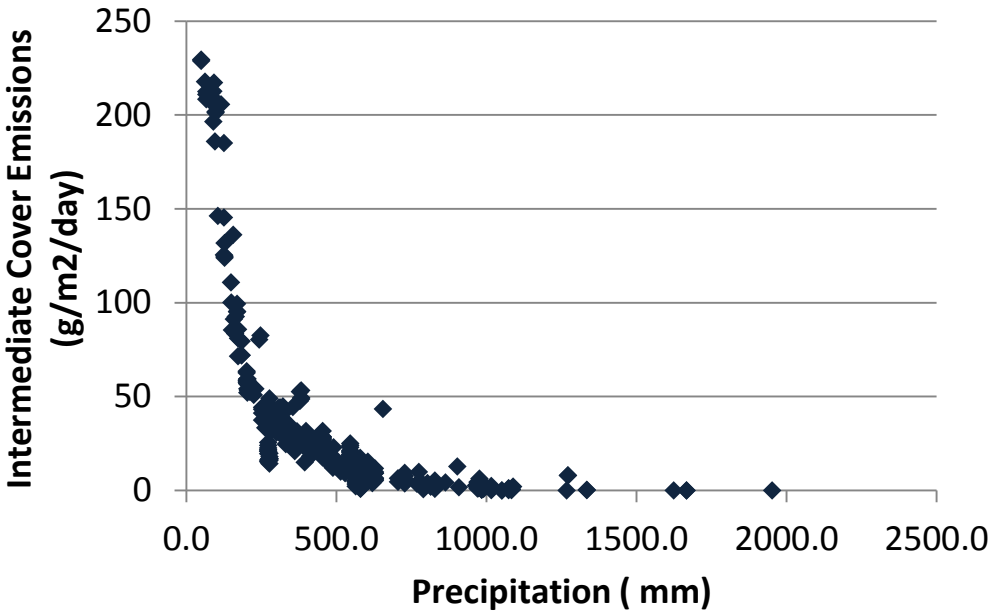
	CH_4 Oxidized (Mg/month)	Total Estimated Emissions (Mg/month)	Total Emissions without oxidation (Mg/month)	% Oxidation Prediction
Jan	**157,641**	**6,403**	164,045	96
Feb	151,489	5,972	157,461	96
Mar	156,589	5,500	162,088	97
Apr	180,267	5,183	185,449	97
May	195,962	5,849	201,810	97
Jun	209,011	7,874	216,885	96
Jul	217,271	12,005	229,276	95
Aug	211,672	28,114	239,786	88
Sep	178,022	73,885	251,906	71
Oct	180,303	89,611	269,914	67
Nov	216,782	66,465	283,247	77
Dec	218,749	30,569	249,318	88
Annual Totals (Mg/yr)	**2,273,758**	**337,430**	**2,611,187**	**87 %**

4.6.3. Factors influencing CALMIM predictions

Figure 51 indicates relationships between major climatic factors (air temperature and annual precipitation) and predicted emissions for intermediate cover areas at all California landfill sites (n=371). As seen in the figure, there is a very strong relationship with precipitation, with the predicted emissions of <15 g CH_4 m^{-2} day^{-1} for sites receiving at least 500 mm annually. At sites that receive less than 500 mm of precipitation, there is an exponential increase in the emission rate with decreasing precipitation. With respect to annual air temperature, the relationship is not as strong (Figure 51B). This could be due to the scatter imposed with respect to sites having the same annual air temperature with variable annual precipitation. However, this figure also suggests that, for this dataset, an optimum average air temperature of 11 ^{o}C is associated with the highest soil oxidation (lowest surface emissions). Because the precipitation relationship is more robust, however, this suggests that precipitation is the major limitation for soil oxidation activity in California landfill cover soils.

Moreover, CALMIM predicts a distribution of landfill emissions which follow climatic patterns across the state for a common cover material (intermediate cover) (see Figure 52). The location of the highest predicted emissions for the intermediate cover is the southeast corner of the state. This is the region with the highest annual temperature and lowest annual precipitation (see Figure 53). Therefore, we conclude that local climate can drastically impact the resulting emissions with hot and dry desert areas predicted to have the highest emissions due to drastically reduced soil methanotrophic activity.

(A)



(B)

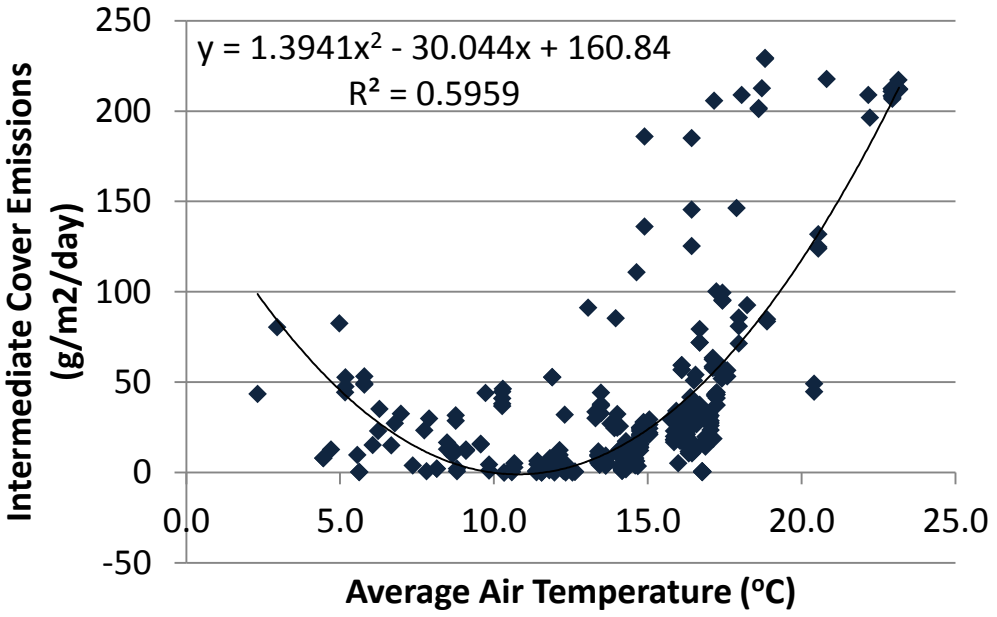


Figure 51.Relationship between predicted intermediate cover emission rate (g/m^2/day) and the site-specific (A) average annual precipitation and (B) the average air temperature.

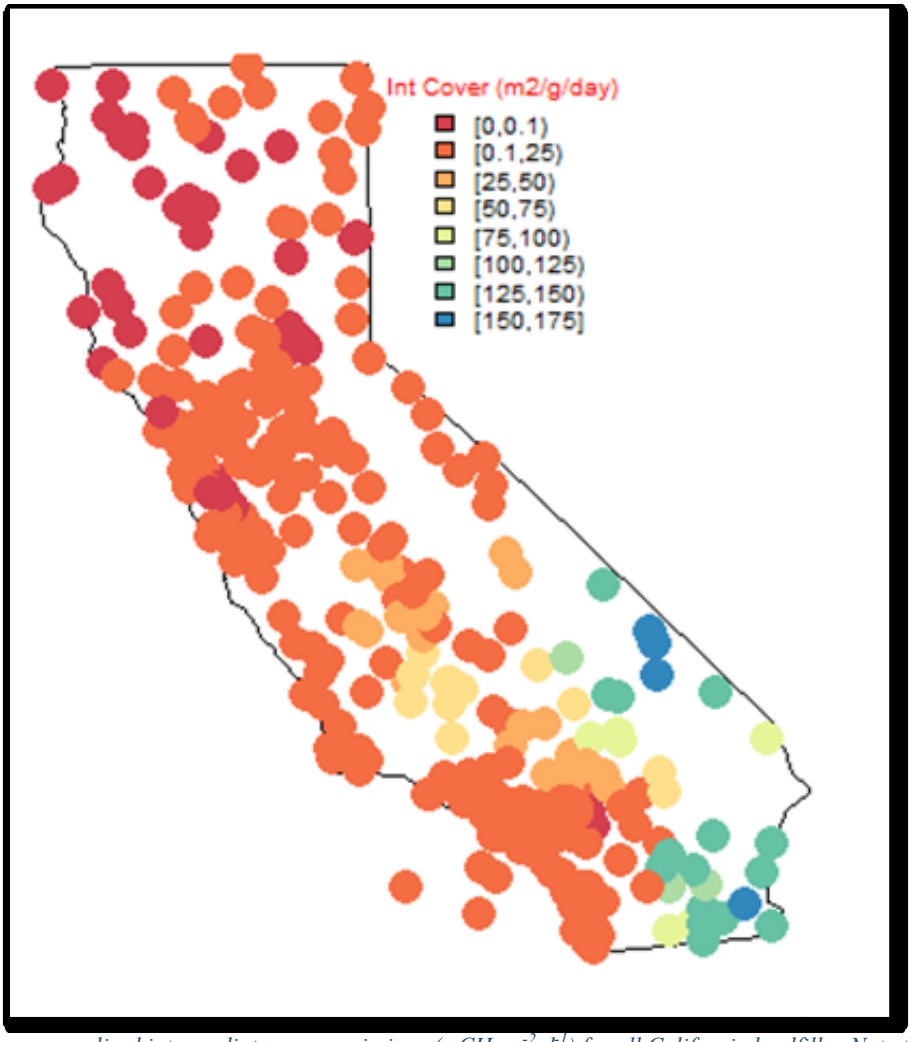
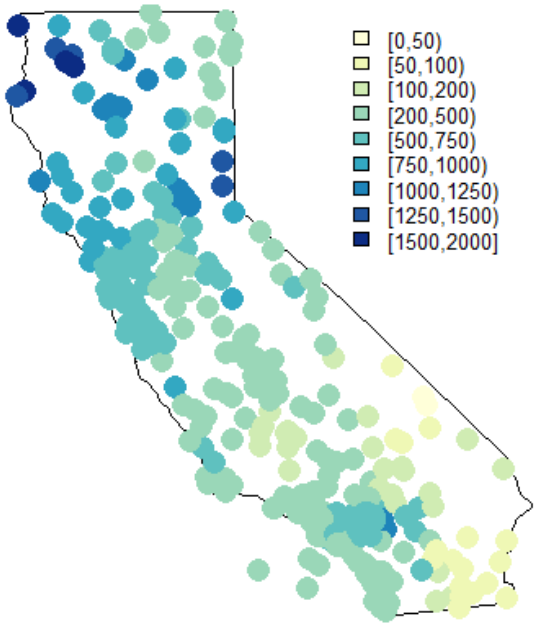


Figure 52.Area normalized intermediate cover emissions (g CH_4 m^{-2} d^{-1}) for all California landfills. Note the clustering of similar emission values.

(A)



(B)

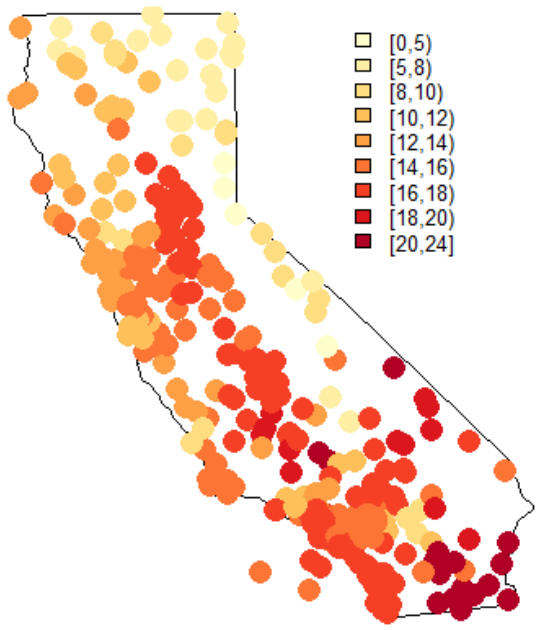
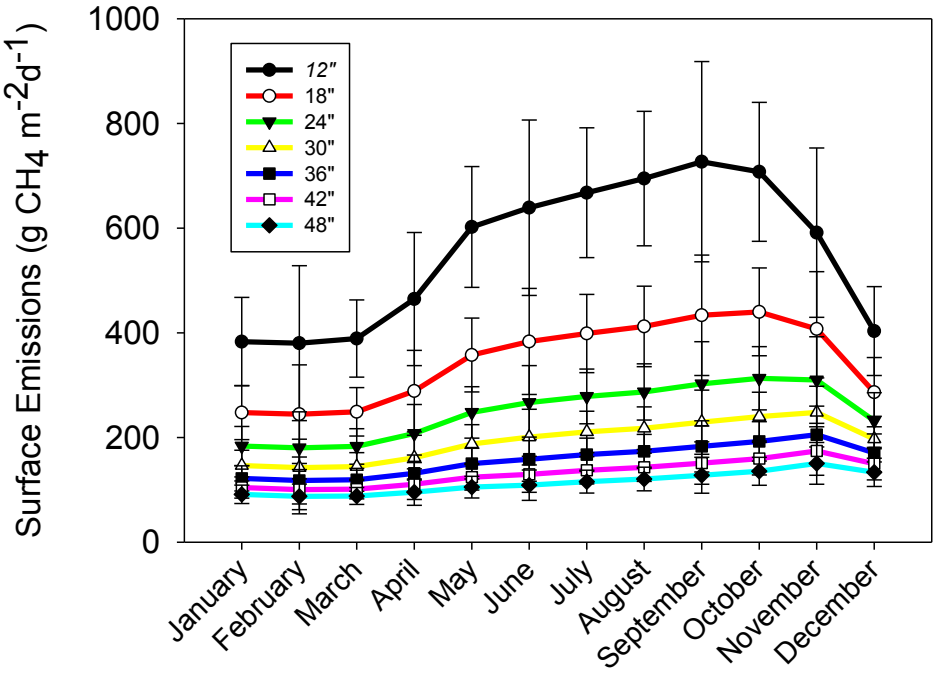


Figure 53.Geospatial distribution of annual mean (A) precipitation (mm of water) and (B) air temperature (^{o}C) for California landfill sites.

Landfill gas recovery and cover thickness are the two control measures which have the largest mitigating effect on surface emissions. Figure 54 illustrates the impact on total monthly emissions of increasing the intermediate cover thickness from 12 to 48" at a simulated California landfill site (36.9 ^{o}N; 121.8 ^{o}W). As seen in the figure, there is the direct attenuating impact of a thicker cover on reducing the surface emissions. In addition, Figure 56 shows the concurrent effect on oxidation. However, as shown in Figure 57, the overall capacity of methane oxidation is not drastically increased after the thickness of cover increases beyond 24". This is hypothesized to be due to the oxygen diffusion limitation. Since the maximum rate of oxidation for "infinite" methane sources would be the diffusive rate of the oxygen and be independent of the CH_4 source, as long as there is enough methane present. The amount of methane oxidation is maximized at approximately 30-36" (Figure 55). Thus, even though the amount of oxidation does increase with cover thickness, the overall emission rate of CH_4 is certainly drastically reduced as a function of thickness alone (Figure 56). The impact of CH_4 oxidation becomes more critical as the supply of methane is reduced by the thicker covers (Figure 56). In addition, with thicker covers, there is reduced seasonal variability in oxidation.

(A)



(B)

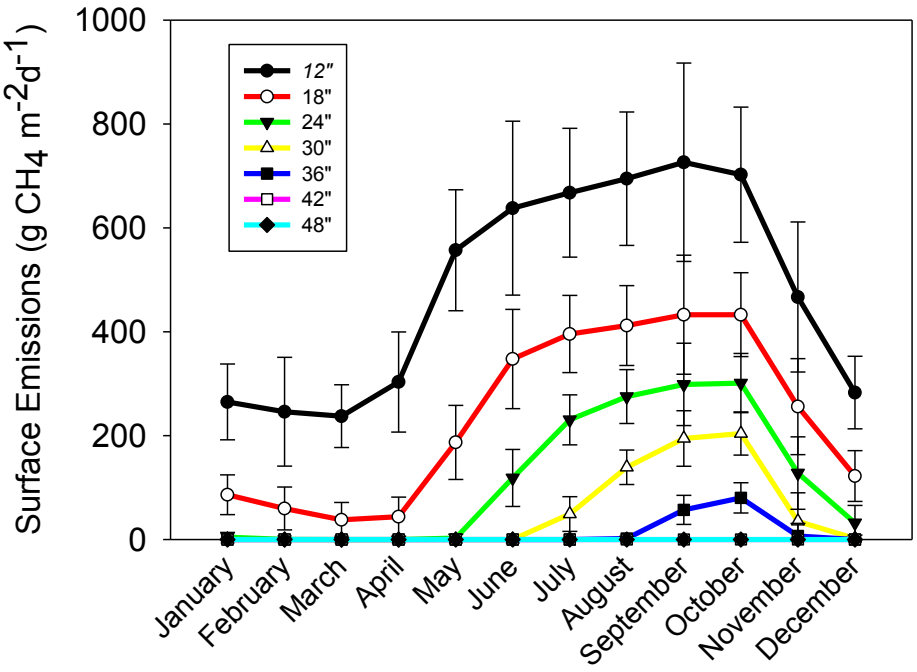
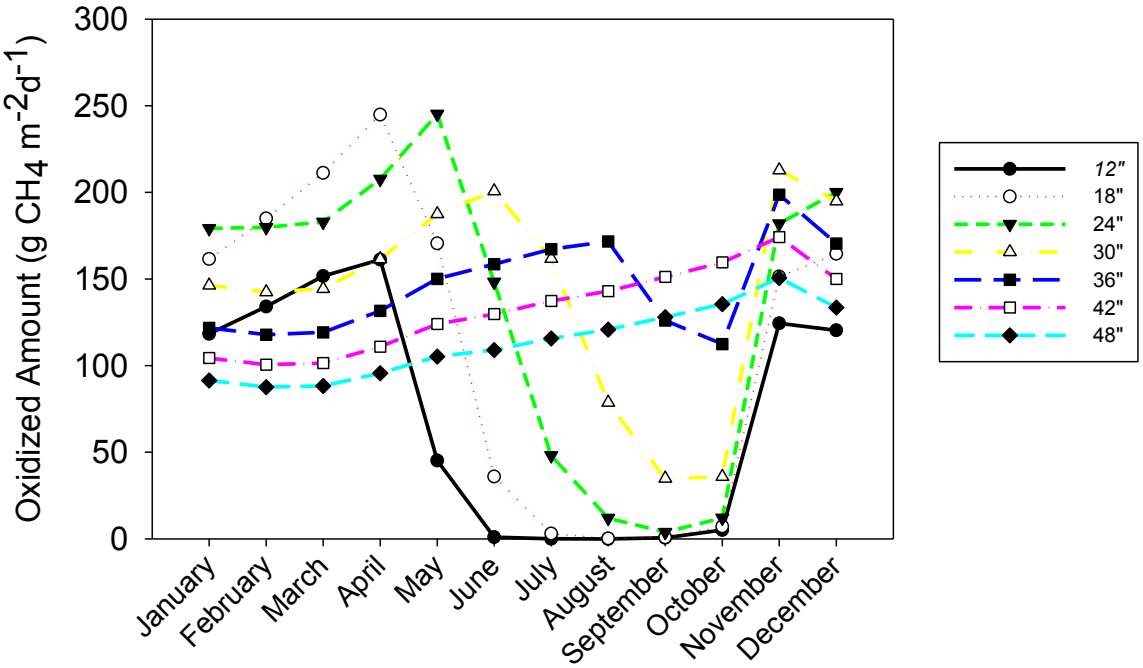


Figure 54.Predicted seasonal (monthly) emissions from a loamy sand intermediate cover with thickness varying from 12" to 48" for (A) emissions without soil oxidation and (B) emissions with soil CH_4 oxidation. Typical annual cycle for simulated California landfill (36.9 °N; 121.8 °W). The error bars are the standard deviations for the monthly means.

(A)



(B)

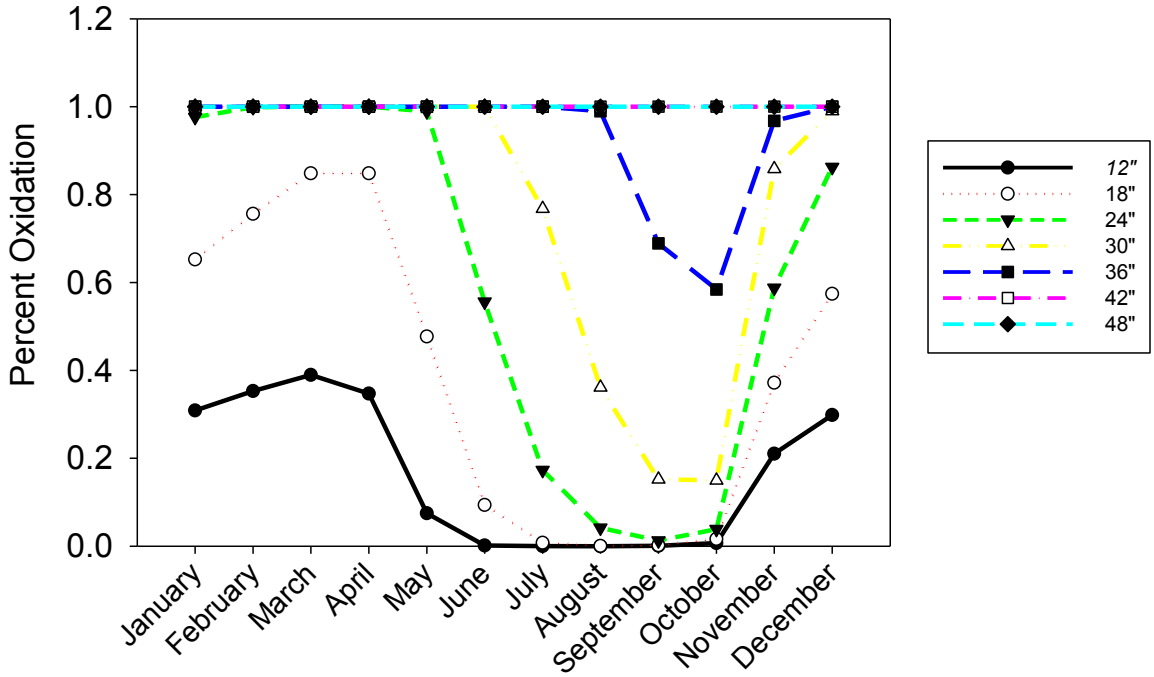
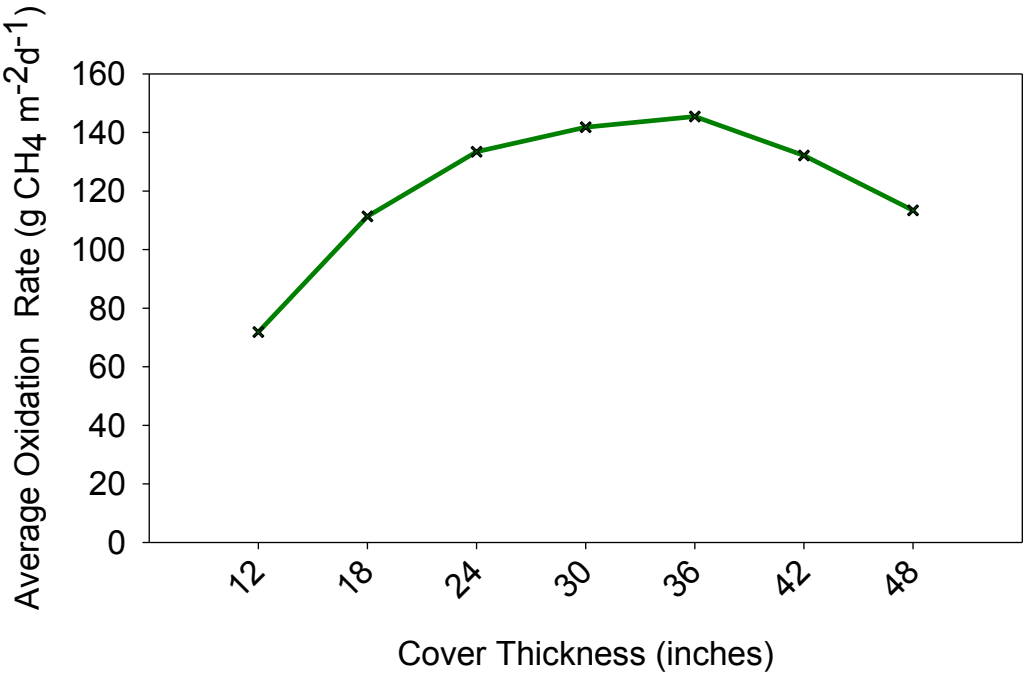


Figure 55.Predicted CH_4 oxidation from the same intermediate cover [Fig. 4-44] with variable thickness in (A) areal normalized rates and (B) % oxidation for simulated California landfill (36.9 °N; 121.8 °W).

(A)



(B)

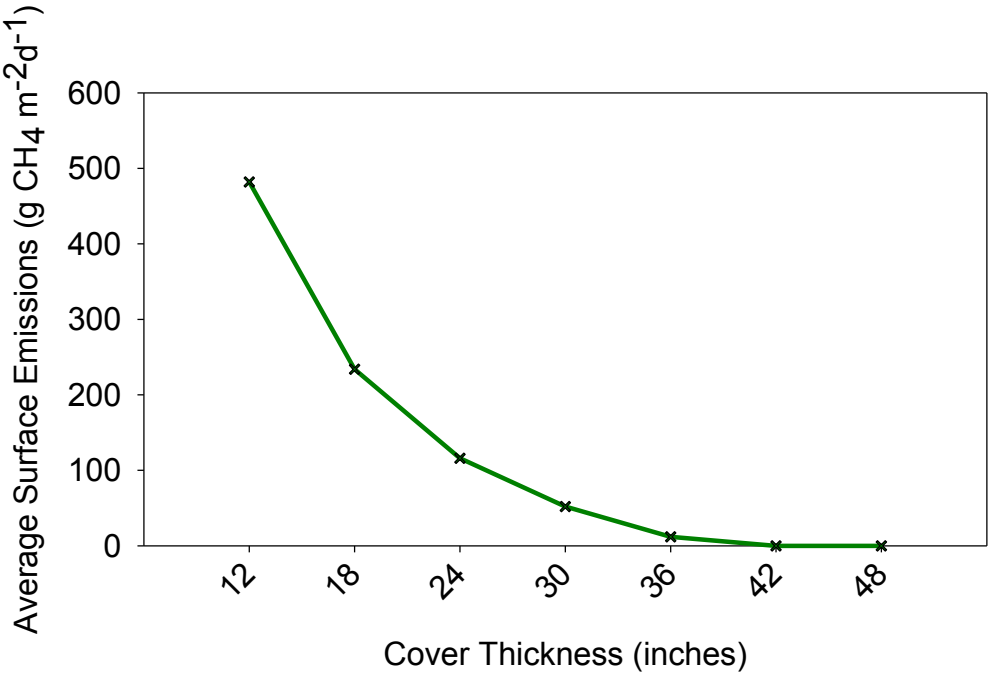


Figure 56.(A) Average net soil oxidation rate and (B) surface emission rates as a function of soil thickness for the same intermediate cover [Fig. 4-44] at a simulated California landfill (36.9 °N; 121.8 °W).

4.6.4 Site-specific comparisons for California sites

Figure 19 [shown previously] was a simple scatter plot comparing the site-specific 2010 CALMIM inventory results to the 2010 ARB inventory calculations—the same data are shown on a log-log plot in Figure 57. The CALMIM results include all cover types (daily, intermediate, final) as discussed previously, and both sets of data are based on 2010 waste footprints and cover areas from the Walker (2012) database. Because of the very different drivers for the two sets of inventory calculations, no relationship exists (r^2=0.08). However, note that due to the inclusion of site-specific soils and CH_4 oxidation in the CALMIM inventory, emissions at a large number of sites are orders of magnitude lower than emissions from the ARB inventory. Figure 58 is a subset of the previous plot which is limited to the 10 sites with field measurements of emissions using a variety of techniques (chambers, VRPM, tracer methods, micrometeorological methods, and aircraft-based mass balance methods). Coincidentally, we note that a limited number of these sites have similar annual CH_4 emissions resulting from the two methodologies (Figure 59). However, due to the very different drivers for the two methodologies, we would caution against using a very limited number of sites to "validate" comparisons between the methodologies, as comparable results may occur by chance.

Figure 59 compares site-specific 2010 CALMIM inventory estimates for the 10 sites to field measurements using multiple methods taken at various times and various dates during 2005-2012. All of the total site emissions, where available, were normalized on an area basis (g CH_4 m^{-2} d^{-1}) for this comparison using the Walker (2012) database for 2010 footprint areas. For five of these sites (CA-1 through CA-5), the field measurements only included intermediate covers, so the comparison was made only for 2010 intermediate cover areas. As shown in the figure, for all of the sites, the field measurements and CALMIM inventory estimates are within the same order of magnitude consistent with previous site-specific comparisons and discussions in this report (Section 4-2). Moreover, for 8 of the 10 sites, the CALMIM estimates are higher than the available field measurements, also consistent with previous discussions on the conservative defaults in CALMIM for GHG inventory purposes. One must also keep in mind that a field measurement campaign only represents a "snapshot" in time without any information regarding the temporal variability in emissions or oxidation over an annual cycle. To a large extent, this figure also illustrates the difficulty of site-specific emissions comparisons to CALMIM modeling in the absence of site-specific data for the major drivers for oxidation and emissions (soil moisture, soil temperature), as was also The site-specific differences between measured and modeled values can largely be attributed to variability in the physical characteristics of site-specific cover soils (texture, thickness) and annual soil microclimate (soil moisture, temperature).

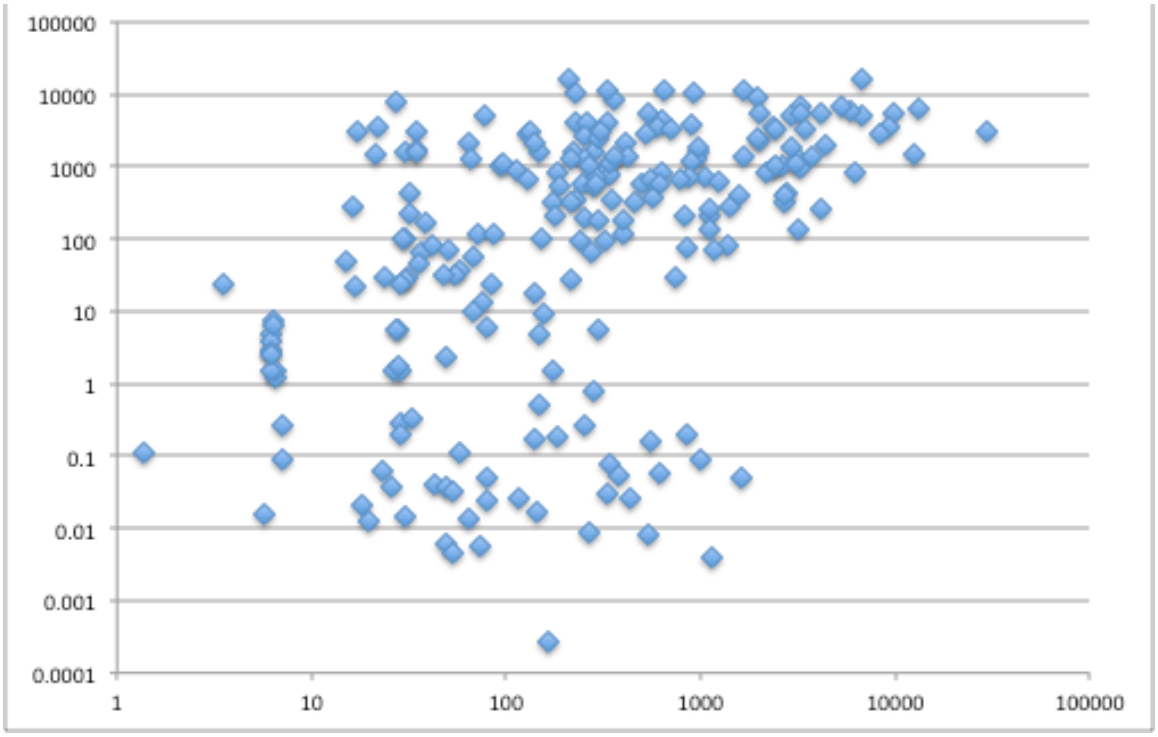


Figure 57.Scatter plot comparing site-specific 2010 CALMIM landfill CH_4 emissions to 2010 ARB landfill CH_4 emissions for all California sites. Note log-log scale.

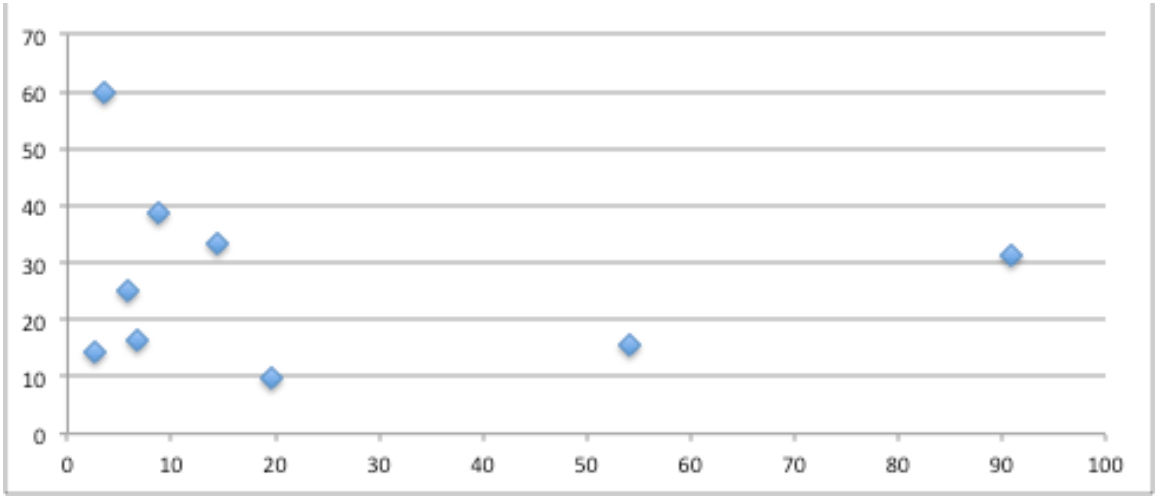
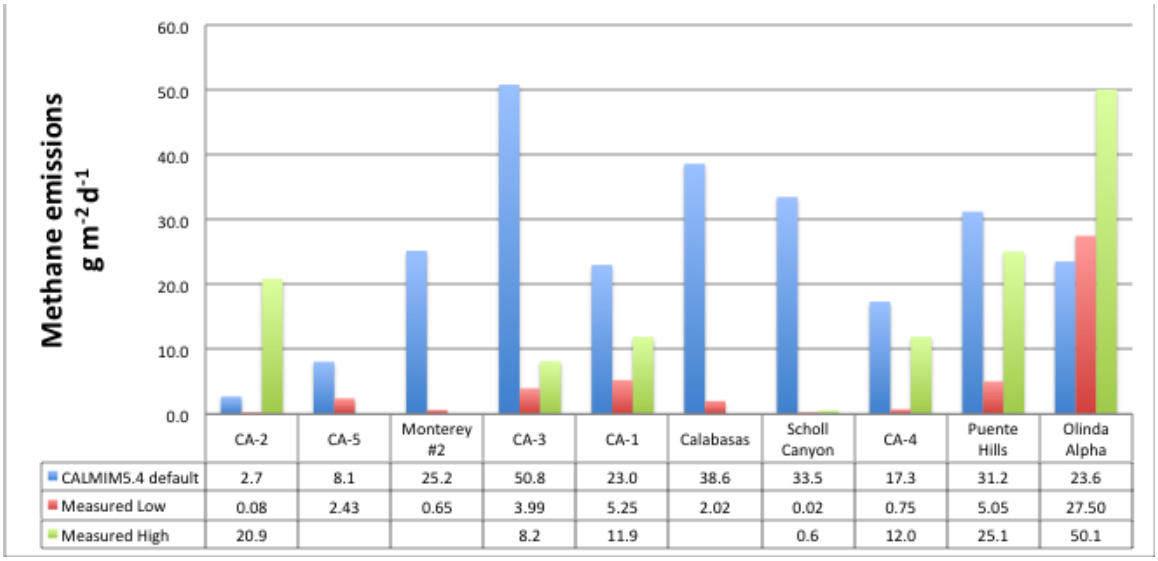


Figure 58.Scatter plot comparing site-specific 2010 CALMIM landfill CH_4 emissions to 2010 ARB landfill CH_4 emissions for 10 selected California sites with field emissions data.



	CA-2	CA-5	Monterey #2	CA-3	CA-1	Calabasas	Scholl Canyon	CA-4	Puente Hills	Olinda Alpha
CALMIM5.4 default	2.7	8.1	25.2	50.8	23.0	38.6	33.5	17.3	31.2	23.6
Measured Low	0.08	2.43	0.65	3.99	5.25	2.02	0.02	0.75	5.05	27.50
Measured High	20.9			8.2	11.9		0.6	12.0	25.1	50.1

Figure 59.Comparison of modeled to measured CH_4 emissions (various dates 2006-2012; methods include static chambers, VRPM, tracer methods, micrometeorological methods, and aircraft-based mass balance methods). See Appendix B for detailed site information. High results for Olinda-Alpha and Puente Hills are both from Peischl et al., 2013.

5. Conclusions and Recommendations

5.1. GENERAL TECHNICAL CONCLUSIONS AND RECOMMENDATIONS FOR USING CALMIM.

Our current understanding of landfill CH_4 emissions relies on over two decades of published literature consisting of field measurements, supporting laboratory studies, and the development and application of process-based models. We know that measured CH_4 emission rates are characterized by high spatial and temporal variability, ranging from the highest unit rates (g CH_4 m^{-2} d^{-1}) reported in the literature from soil systems down to negative values representing uptake of atmospheric CH_4 by cover soils with high methanotrophic oxidation capacities.

We also know that the major drivers for emissions are the thickness and physical characteristics of individual cover soils (daily, intermediate, final), seasonal CH_4 oxidation in cover soils as related to dynamic soil moisture and temperature changes, and the physical effect of engineered gas recovery systems. The relationships between these drivers and the resulting emissions are complex, non-linear, and intimately related to site-specific climate and soil microclimate variability during an annual cycle. Importantly, more than for any other managed soil system, site-specific engineering design and operational factors are major determinants of net CH_4 emissions to the atmosphere. However, all of the existing landfill GHG inventory methods (FOD models) are based on waste-in-place data. As detailed in this report, CALMIM takes a first-step towards utilizing the climate, soil type, and soil gas concentration gradients as primary factors in determining the overall site emission.

As discussed in this report, the majority of field measurements to date are "snapshots" of emission rates at a specific site at a specific time whose broader relationship to the major drivers for emissions has not been successfully modeled to date. Thus field measurements quantify emissions at a specific time and place but do not give any information on the expected variability over an annual cycle under longer-term climate conditions as opposed to annual meteorological variability. A major conclusion from the bulk of existing literature is that simple linear relationships to single variables or relationships fitted only to site-specific field or laboratory data are insufficiently complex to provide a systematic and robust framework for modeling landfill CH_4 emissions.

To date, available U.S. and international GHG inventory models for estimating landfill CH_4 emissions (e.g., IPCC, 2006) have not advanced beyond reliance on a 1^{st} order kinetic equation for CH_4 generation where the resulting CH_4 is partitioned into the CH_4 recovered, oxidized (maximum 10%), and emitted. Conceived more than three decades ago, before there was a critical mass of field and laboratory data on the rates and drivers for emissions, we now know that there are two major flaws to this approach: (1) exclusion of dynamic site-specific oxidation rates related to local climate and soil microclimate; and (2) as shown by field data, lack of correlation between the presumed major driver for CH_4 generation (mass of waste-in-place) and emissions. Also, as

discussed in this report, with respect to (2), a recently-available 2010 dataset for well-managed California landfills (Walker, 2012) refutes the historical dependence of LFG generation & recovery on a 1st order model. As shown in plots previously discussed in this report (Fig. 2-1 and Fig. 2-2), an extremely robust linear correlation exists between the mass of "welled" waste in place and average annual LFG or CH_4 recovery rates—providing strong empirical evidence for a more steady-state rate of gas recovery from a given mass of waste in place.

Developing a more realistic model for estimating site-specific landfill CH_4 emissions for GHG inventory reporting was a significant challenge. On one hand, the model needs to adequately represent site-specific conditions with respect to the major drivers for emissions and, on the other hand, the model needs to include local climate at a level of detail appropriate for inventory reporting. Our original concept was to maintain the 1st order kinetic model basis and focus on improving the CH_4 oxidation calculation for individual sites. However, as discussed above, the overall dependency of emissions on generation was not substantiated by existing field measurements. Moreover, as shown by recent empirical data (Fig. 2-1) demonstrating that even the dependence of generation & recovery on the mass of waste was doubtful, we developed a completely new model, focusing solely on emissions.

As now developed and internationally field-validated through two related research projects, CALMIM5.4 models the interaction of site-specific cover soils and management practices with climate and soil microclimate via embedded, globally-validated 0.5 deg. X 0.5 deg. climate and soil microclimate models (Global TEMPSIM, GlobalRAINSIM, SOLARCALC, STM^2). In general, this means that longer-term climate drivers (typically 30-year average data) are used to develop a "typical" annual cycle for site-specific and cover-specific "CH_4 emissions with oxidation" and "CH_4 emissions without oxidation." For mathematical simplicity, previous work (Spokas and Bogner, 2011) elucidating the moisture and temperature dependencies of oxidation for various cover soils was used to scale rates to an optimum oxidation capacity. The default parameters and boundary conditions were chosen from literature to be conservative for emission inventory purposes. A freely-available model (www.ars.usda.gov) which includes default parameters and boundary conditions appropriate for GHG inventory reporting, CALMIM also requires a limited number of site-specific inputs. For ease of use, these inputs for each cover soil (area, physical characteristics) and site management practices (existence of gas recovery, vegetation during growing season) are entered into drop boxes while the model is running. CALMIM also provides detailed EXCEL-compatible output files so that, if desired, users can examine the relationships between emissions and site-specific factors (soils, management factors, soil microclimate, and climate) for 10-min time steps and 2.5 cm-depth increments for the 365-d year. As discussed in this report and expanded through a new statewide GHG inventory calculation for the state of California, CALMIM can be readily applied to regional inventory calculations to predict field values that are representative of longer-term climate and soil microclimate variability. Positive feedback from users to date has indicated that, even though the model contains more mathematical complexity than previous models for landfill CH_4 emissions, CALMIM can be readily accessed and implemented, even by previously inexperienced users. As

discussed in the next section, in addition to standard defaults for GHG inventory reporting, CALMIM can also facilitate the analysis of site-specific research data, optimize scheduling of field campaign sampling time periods to include annual climate variability, and provide guidance for management decisions through the use of site-specific annual weather data and soil gas profiles.

The ability to simultaneously examine combinations of variables for a given site has suggested that, for a given global location, there is an "optimum" thickness as well as soil texture for maximizing oxidation and minimizing residual surface emissions over a yearly cycle. Thin soil covers (<12") have lower oxidation and higher emissions whereas thicker covers are characterized by O_2 diffusion limitations for methane oxidation activity. This idea of a "sweet spot" for cover thickness can be demonstrated by CALMIM modeling, but has yet to be systematically examined in field settings with soils of variable texture in a given climatic setting.

In addition, to date, there has been negligible study of daytime emissions from the working face which, when previous intermediate cover has been stripped from fully methanogenic waste in older underlying refuse cells, may have substantial emissions. These emissions would, of course, be reduced by daily cover during non-working hours. Even though working face emissions represent a small area, CALMIM simulations indicate that these emissions may contribute to some existing observed discrepancies between measured and modeled emissions.

Another major finding of this project was the fact that the intermediate cover areas account for most of the statewide emissions for California, representing over 95% of the total CH_4 emission [CALMIM modeling]. Therefore, the statewide emissions could be reduced solely by reducing intermediate cover area or using thicker intermediate covers.

In general, this project confirms that CALMIM does provide a conservative order-of-magnitude estimate for "typical annual emissions" from site-specific landfill cover materials. This was demonstrated successfully through the international and US comparisons. With a few exceptions, CALMIM adequately bracketed the field measurements between the oxidized and non-oxidized methane flux predictions. These comparisons could be improved using site-specific "custom" data for soil gas profiles and annual weather, where those data exist. Importantly, based on 30-year average climate data, CALMIM replicates the typical annual variability of emissions with respect to gaseous transport in site-specific soils and temperature/moisture-dependent CH_4 oxidation rates. Thus CALMIM can provide an improved estimate of annual emissions based on the major processes which directly control CH_4 emission rates—namely, the thickness and physical properties of various cover materials, their surface areas, the presence of engineered gas extraction, and seasonally-variable CH_4 oxidation rates in each cover.

5.2. HOW TO USE CALMIM

CALMIM can be used for a variety of applications, including "what if?" operational and engineering decisions, guidance for scheduling field campaigns to quantify seasonal variability in emissions, and addressing site-specific research questions related to climate change & improved mitigation of GHG emissions. For selected sites and for hypothetical sites over broad latitudinal gradients, CALMIM can also be used to answer certain critical science questions regarding landfill CH_4 emissions relative to various design, operational, and climatic considerations (including future climate change). Those questions include:

- What is the relative impact of gas recovery vs. methanotrophic CH_4 oxidation with respect to reducing net CH_4 emissions to the atmosphere?

- What design and operational strategies could be employed at specific sites to reduce emissions to negligible values (cover thickness, texture, water management)?

- How can scheduling of field measurement campaigns in order to quantify seasonal variability in emissions and oxidation? To date, the literature clearly indicates a bias with respect to a paucity of winter field campaigns in colder climatic regions.

- What are expected landfill CH_4 emissions under future climate change scenarios?

5.3 SUGGESTIONS FOR FUTURE WORK

The ability to directly compare field data with a more robust modular process-based model such as CALMIM leads to a number of suggestions for future work which were beyond the scope of the current project. These include:

- More extensive comparison of modeled landfill CH_4 emissions to measured emissions using multiple techniques. As each field measurement technique has its limitations and inherent error bars, we need better understanding of both the technique and the field-derived uncertainties associated with a specific technique deployed at a specific landfill site.

- More extensive monitoring and modeling of seasonal landfill CH_4 emissions. There are very few sites in the current landfill literature which monitored emissions over a full annual cycle and, critically for seasonal temperate climates, during the colder parts of the year. Thus the existing database for "seasonal" emissions is very limited and incomplete.

- More extensive monitoring of soil gas profiles. Soil gas profiles, as a major driver of diffusive landfill CH_4 and other gaseous emissions, are infrequently monitored in landfill field settings. However, even though such measurements are time-consuming and difficult in highly-compacted landfill soils, a more comprehensive understanding of the spatial and temporal variability of soil gas profiles in field settings is required. Laboratory column studies cannot adequately replicate the variability of field conditions.

- Fundamental modeling advances [validated with laboratory column studies and field measurements] addressing gaseous transport in landfill cover soils could lead to CALMIM improvements or extensions, including:

    - Inclusion of other gaseous transport mechanisms (convection; plant-mediated transport).

    - Inclusion of other gases (i.e., selected non-methane hydrocarbons).

    .

    - Inclusion of isotopic fractionation and better definition of transport and oxidation coefficients for ^{13}C and ^{2}D for CH_4 transport and oxidation in landfill cover soils.

    - Development of a CALMIM-compatible soils database specifically for compacted landfill cover soils and ADC materials [currently CALMIM is based on agricultural soils with lower compaction].

6. Acknowledgements

The project team gratefully acknowledges the financial support and encouragement of the Environmental Research & Education Foundation (Dr. Bryan Staley, President) during 2011-2013 under UIC grant #G5534-555200 and UIC subcontract agreement #2010-03400-01-00 with U.S. Dept. of Agriculture, Agricultural Research Service.

We also wish to recognize and acknowledge informal collaborations with many organizations and individuals since the beginning of the CALMIM project (2007) who generously shared their time, resources, and data:

- California Dept. of Resources Recovery & Recycling (CALRECYCLE), especially S. Walker.
- California Air Resources Board (ARB), especially L. Hunsaker.
- Los Angeles County Sanitation Districts, especially F. Capone and D. Kong.
- Monterey Bay Regional Waste Management Authority, especially W. Merry.
- USDA field and laboratory personnel, including C. Rollofson, M. duSaire, D. Peterson.
- UIC students, including M. Corcoran, P. Pilosi, P. Roots, and T. Badger.
- Cooperation and discussions with:
    - Florida State University, Tallahassee, Florida, especially J. Chanton.
    - Waste Management, Inc., especially R. Green and G. Hater.
    - Veolia Environmental Services Solid Waste, Inc. (US), now Advanced Disposal, Inc. (after November, 2012).
    - Veolia Environment (FR)
    - University of Agricultural Sciences/Vienna, especially M. Huber-Humer.
    - University of Hamburg (DE)
    - University of the Witwatersrand (SA)
    - Danish Technical University
    - Melbourne University, especially S. Yuen, D. Chen, J. Sun, and M. Asadi.
    - Purdue University, especially M. Cambaliza, P. Shepson.

- Initial support for the CALMIM project was provided by the California Energy Commission PIER (Public Interest Energy Research) Program during 2007-2010 (G. Franco).

7. References

Abichou, T., Chanton, J., Powelson, D., Fleiger, J., Escoriaza, S., Lei, Y., Stern, J., 2006a. Methane flux and oxidation at two types of intermediate landfill covers. Waste Management 26, 1305-1312.

Abichou, T., Mahieu, K., Chanton, J., Romdhane, M., Mansouri, I., 2011. Scaling methane oxidation: From laboratory incubation experiments to landfill cover field conditions. Waste Management 31, 978-986.

Abichou, T., Powelson, D., Chanton, J., Escoriaza, S., Stern, J., 2006b. Characterization of methane flux and oxidation at a solid waste landfill. Journal of Environmental Engineering 132, 220-228.

Abushammala, M.F.M., Basri, N.E.A., Elfithri, R., Younes, M.K., Irwan, D., 2013a. Modeling of CH_4 oxidation in landfill cover soil using an artificial neural network. Journal of the Air & Waste Management Association, null-null.

Abushammala, M.M., Basri, N., Basri, H., Kadhum, A., El-Shafie, A., 2013b. Empirical gas emission and oxidation measurement at cover soil of dumping site: example from Malaysia. Environmental Monitoring and Assessment 185, 4919-4932.

Albanna, M., Fernandes, L., Warith, M., 2007. Methane oxidation in landfill cover soil; the combined effects of moisture content, nutrient addition, and cover thickness. J. Environ. Eng. Sci. 6, 191-200.

Amini, H.R., Reinhart, D.R., Mackie, K.R., 2012. Determination of first-order landfill gas modeling parameters and uncertainties. Waste management 32, 305-316.

Amini, H.R., Reinhart, D.R., Niskanen, A., 2013. Comparison of first-order-decay modeled and actual field measured municipal solid waste landfill methane data. Waste Management 33, 2720-2728.

Ascher, U.M., Petzold, L.R., 1998. Computer Methods for Ordinary Differential and Differential-Algebraic Equations Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA.

Aubinet, M., Vesala, T., Papale, D., 2012. Eddy covariance: a practical guide to measurement and data analysis. Springer.

Australia, C.o., 2012a. Carbon Farming Initiative Handbook. Department of Climate Change and Energy Efficiency, Commonwealth of Australia.

Australia, C.o., 2012b. Explanantory Statement: Carbon Credits (Carbon Farming Initiative) Act 2011. in: Efficiency, A.o.t.P.S.f.C.C.a.E. (Ed.), Australia, p. 15.

Babilotte, A., Lagier, T., Fiani, E., Taramini, V., 2010. Fugitive methane emissions from landfills: Field comparison of five methods on a French landfill. Journal of Environmental Engineering 136, 777-784.

Banuri, T., Weyant, J., Akumu, G., Najam, A., Rosa, L.P., Rayner, S., Sachs, W., Sharma, R., Yohe, G., 2001. Setting the stage: climate change and sustainable development. Cambridge University Press, Cambridge, UK.

Barlaz, M.A., Milke, M., Ham, R., 1987. Gas production parameters in sanitary landfill simulators. Waste Management & Research 5, 27-39.

Bellucci, F., Bogner, J.E., Sturchio, N.C., 2012. Greenhouse gas emissions at the urban scale. Elements 8, 445-449.

Black, C.M., 2012. Linking land sector activities to emissions trading: Australia's carbon farming initiative. Carbon Pricing, Growth and the Environment 11, 184.

Boeckx, P., Cleemput, O.v., Villaralvo, I., 1996. Methane emission from a landfill and the methane oxidising capacity of its covering soil. Soil Biology and Biochemistry 28, 1397-1405.

Bogner, J., Ahmed, M.A., Diaz, C., Gao, Q., Faaij, A., Hashimoto, S., Mareckova, K., Pipatti, R., Zhang, T., 2007. Waste Management. in: B. Metz, O.R.D., P.R. Bosch, R. Dave, L.A. Meyer (Ed.). Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, NY, USA.

Bogner, J., Meadows, M., Czepiel, P., 1997a. Fluxes of methane between landfills and the atmosphere: natural and engineered controls. Soil Use and Management 13, 268-277.

Bogner, J., Spokas, K., Burton, E., 1999. Temporal variations in greenhouse gas emissions at a midlatitude landfill. Journal of Environmental Quality 28, 278-288.

Bogner, J.E., Sass, R.L., Walter, B.P., 2000. Model comparisons of methane oxidation across a management gradient: Wetlands, rice production systems, and landfill. Global biogeochemical cycles 14, 1021-1033.

Bogner, J.E., Spokas, K., Burton, E.A., 1997b. Kinetics of Methane Oxidation in a Landfill Cover Soil: Temporal Variations, a Whole-Landfill Oxidation Experiment, and Modeling of Net CH_4 Emissions. Environmental Science and Technology 31, 2504-2514.

Bogner, J.E., Spokas, K.A., Burton, E.A., 1997c. Kinetics of methane oxidation in a landfill cover soil: temporal variations, a whole-landfill oxidation experiment, and modeling of net CH4 emissions. Environmental science & technology 31, 2504-2514.

Bogner, J.E., Spokas, K.A., Chanton, J.P., 2011. Seasonal greenhouse gas emissions (methane, carbon dioxide, nitrous oxide) from engineered landfills: Daily, intermediate, and final California cover soils. Journal of Environmental Quality 40, 1010-1020.

Börjesson, G., Svensson, B.H., 1997. Seasonal and Diurnal Methane Emissions From a Landfill and Their Regulation By Methane Oxidation. Waste Management & Research 15, 33-54.

Bousquet, P., Ciais, P., Miller, J., Dlugokencky, E., Hauglustaine, D., Prigent, C., Van der Werf, G., Peylin, P., Brunke, E.-G., Carouge, C., 2006. Contribution of anthropogenic and natural sources to atmospheric methane variability. Nature 443, 439-443.

Bridgham, S.D., Cadillo-Quiroz, H., Keller, J.K., Zhuang, Q., 2013. Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. Global Change Biology 19, 1325-1346.

Cao, M., Dent, J.B., Heal, O.W., 1995. Modeling methane emissions from rice paddies. Global Biogeochemical Cycles 9, 183-195.

Carraro, C., Barbante, C., Ruti, P., Navarra, A., 2014. Climate change: Everything you need to know about the IPCC 5th Assessment Report. Review of Environment, Energy and Economics, In Press.

Chanton, J., Liptay, K., 2000. Seasonal variation in methane oxidation in a landfill cover soil as determined by an in situ stable isotope technique. Global Biogeochemical Cycles 14, 51-60.

Chanton, J., Rutkowski, C., Mosher, B., 1999. Quantifying methane oxidation from landfills using stable isotope analysis of downwind plumes. Environmental science & technology 33, 3755-3760.

Chanton, J.P., Powelson, D.K., Green, R.B., 2009. Methane oxidation in landfill cover soils, is a 10% default value reasonable? J. Environ. Qual. 38, 654-663.

Chiemchaisri, C., Chiemchaisri, W., Kumar, S., Wicramarachchi, P.N., 2011. Reduction of Methane Emission From Landfill Through Microbial Activities in Cover Soil: A Brief Review. Critical Reviews in Environmental Science and Technology 42, 412-434.

Czepiel, P., Mosher, B., Crill, P., Harriss, R., 1996a. Quantifying the effect of oxidation on landfill methane emissions. Journal of Geophysical Research: Atmospheres (1984–2012) 101, 16721-16729.

Czepiel, P., Mosher, B., Harriss, R., Shorter, J., McManus, J., Kolb, C., Allwine, E., Lamb, B., 1996b. Landfill methane emissions measured by enclosure and atmospheric tracer methods. Journal of Geophysical Research: Atmospheres (1984–2012) 101, 16711-16719.

Davi, H., Bouriaud, O., Dufrêne, E., Soudani, K., Pontailler, J., Le Maire, G., Francois, C., Bréda, N., Granier, A., Le Dantec, V., 2006. Effect of aggregating spatial parameters on modelling forest carbon and water fluxes. Agricultural and Forest Meteorology 139, 269-287.

De Visscher, A., Van Cleemput, O., 2003. Simulation model for gas diffusion and methane oxidation in landfill cover soils. Waste Management 23, 581-591.

Di Trapani, D., Di Bella, G., Viviani, G., 2013. Uncontrolled methane emissions from a MSW landfill surface: Influence of landfill features and side slopes. Waste Management 33, 2108-2115.

Diot, M., Golvan, Y.M.L., Hebe, I., Bogner, J.E., Chanton, J., Spokas, K., Tregoures, A., Guerbois, M., 2001. LFG Mass Balance: A Key to Optimize LFG Recovery. in: Stegmann, R., Christensen, T.H., Cossu, R. (Eds.). SARDINIA 2001 – Eighth International Waste Management and Landfill Symposium. Environmental Sanitary Engineering Centre (CISA), Cagliari, Italy.

Dreyfus, M., 2012. Carbon Credits (Carbon Farming Initiative) (Capture and Combustion of Methane in Landfill Gas from Legacy Waste: Upgrade projects) Methodology Determination 2012. in: Efficiency, P.S.f.C.C.a.E. (Ed.), Australia.

El-Fadel, M., Findikakis, A., Leckie, J., 1996. Numerical modelling of generation and transport of gas and heat in sanitary landfills II. Model application. Waste management & research 14, 537-551.

El-Fadel, M., Findikakis, A.N., Leckie, J.O., 1997. Gas simulation models for solid waste landfills. Crit. Rev. Environ. Sci. Technol. 27, 237-283.

Emcon, 1980. Methane Generation and Recovery from Landfills. Ann Arbor Science, Ann Arbor, MI, USA.

Findikakis, A.N., Leckie, J.O., 1979. Numerical simulation of gas flow in sanitary landfills. Journal of the Environmental Engineering Division 105, 927-945.

Foken, T., Leuning, R., Oncley, S.R., Mauder, M., Aubinet, M., 2012. Corrections and data quality control. Eddy Covariance. Springer, pp. 85-131.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., 2007. Changes in atmospheric constituents and in radiative forcing. Climate change 20.

Fredenslund, A.M., Scheutz, C., Kjeldsen, P., 2010. Tracer method to measure landfill gas emissions from leachate collection systems. Waste management 30, 2146-2152.

Gardner, N., Probert, S., 1993. Forecasting landfill-gas yields. Applied Energy 44, 131-163.

Garman, K., Hill, K., Wyss, P., Carlsen, M., Zimmerman, J., Stirm, B., Carney, T., Santini, R., Shepson, P., 2006. An Airborne and Wind Tunnel Evaluation of a Wind Turbulence Measurement System for Aircraft-Based Flux Measurements*. Journal of Atmospheric and Oceanic Technology 23, 1696-1708.

Gebert, J., Groengroeft, A., Pfeiffer, E.-M., 2011. Relevance of soil physical properties for the microbial oxidation of methane in landfill covers. Soil Biology and Biochemistry 43, 1759-1767.

Goldsmith Jr, C.D., Chanton, J., Abichou, T., Swan, N., Green, R., Hater, G., 2012. Methane emissions from 20 landfills across the United States using vertical radial plume mapping. Journal of the Air & Waste Management Association 62, 183-197.

Gregory, R.G., Rosevear, A., 2005. GasSim 2: Landfill gas management quantified. Tenth International Waste Management and Landfill Symposium. IWWG, Santa Margherita di Pula, Cagliari, Sardinia.

Harborth, P., Fuß, R., Münnich, K., Flessa, H., Fricke, K., 2013. Spatial variability of nitrous oxide and methane emissions from an MBT landfill in operation: Strong N_2O hotspots at the working face. Waste Management.

Hauser, V.L., Weand, B.L., Gill, M.D., 2001. Natural covers for landfills and buried waste. Journal of Environmental Engineering 127, 768-775.

Hegde, U., Chang, T.-C., Yang, S.-S., 2003. Methane and carbon dioxide emissions from Shan-Chu-Ku landfill site in northern Taiwan. Chemosphere 52, 1275-1285.

Hensen, A., Scharff, H., 2001. Methane emission estimates from landfills obtained with dynamic plume measurements. Water, Air and Soil Pollution: Focus 1, 455-464.

Holmes, C.D., Prather, M.J., Søvde, O., Myhre, G., 2013. Future methane, hydroxyl, and their uncertainties: key climate and emission parameters for future predictions. Atmospheric Chemistry and Physics 13, 285-302.

IPCC, 1996. (Intergovernmental Panel on Climate Change) Climate Change 1995—The Science Of Climate Change. in: Houghton, J.T., Filho, L.G.M., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.). The second assessment report of the IPCC: contribution of Working Group I. Cambridge University Press, Cambridge, UK.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan.

IPCC, 2013. Summary For Policymakers of the Working Group I Contribution to the IPCC Fifth Assessment Report (WGI AR5). www.climatechange2013.
org/images/uploads/WGIAR5-SPM_Approved-
27Sep2013.pdf; IPCC Press Release: Human influence on climate
clear, IPCC report says: .

Jones, H.A., Nedwell, D.B., 1990. Soil atmosphere concentration profiles and methane emission rates in the restoration covers above landfill sites: Equipment and preliminary results. Waste Management & Research 8, 21-31.

Karanjekar, R.V., 2012. An Improved Model For Predicting Methane Emissions From Landfills Based On Rainfall, Ambient Temperature And Waste Composition. University of Texas at Arlington, p. 293.

Kightley, D., Nedwell, D.B., Cooper, M., 1995. Capacity for methane oxidation in landfill cover soils measured in laboratory-scale soil microcosms. Appl. Environ. Microbiol. 61, 592-601.

Kindlein, J., Dinkler, D., Ahrens, H., 2006. Numerical modelling of multiphase flow and transport processes in landfills. Waste management & research 24, 376-387.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., 2013. Three decades of global methane sources and sinks. Nat. Geosci. 6, 813-823.

Kossoy, A., Guigon, P., 2012. State and trends of the carbon market 2012.

Kumar, S., Gaikwad, S.A., Shekdar, A.V., Kshirsagar, P.S., Singh, R.N., 2004. Estimation method for national methane emission from solid waste landfills. Atmospheric Environment 38, 3481-3487.

Lee, S.-W., Im, J., DiSpirito, A., Bodrossy, L., Barcelona, M., Semrau, J., 2009. Effect of nutrient and selective inhibitor amendments on methane oxidation, nitrous oxide production, and key gene presence and expression in landfill cover soils: characterization of the role of methanotrophs, nitrifiers, and denitrifiers. Applied Microbiology and Biotechnology 85, 389-403.

Legates, D.R., Willmott, C.J., 1990. Mean seasonal and spatial variability in gauge-corrected, global precipitation. International Journal of Climatology 10, 111-127.

Maurice, C., Lagerkvist, A., 2003. LFG emission measurements in cold climatic conditions: seasonal variations and methane emissions mitigation. Cold Regions Science and Technology 36, 37-46.

Mays, K.L., Shepson, P.B., Stirm, B.H., Karion, A., Sweeney, C., Gurney, K.R., 2009. Aircraft-based measurements of the carbon footprint of Indianapolis. Environmental science & technology 43, 7816-7823.

McBean, E.A., 2011. In-situ estimation of the methane generation rate for a wet and highly organic solid waste landfill. International Journal of Environment and Waste Management 8, 123-132.

Miller, S.M., Wofsy, S.C., Michalak, A.M., Kort, E.A., Andrews, A.E., Biraud, S.C., Dlugokencky, E.J., Eluszkiewicz, J., Fischer, M.L., Janssens-Maenhout, G., Miller, B.R., Miller, J.B., Montzka, S.A., Nehrkorn, T., Sweeney, C., 2013. Anthropogenic emissions of methane in the United States. Proceedings of the National Academy of Sciences.

Molins, S., Mayer, K., Scheutz, C., Kjeldsen, P., 2008. Transport and reaction processes affecting the attenuation of landfill gas in cover soils. Journal of environmental quality 37, 459-468.

Möllersten, K., Grönkvist, S., 2007. All CO_2 is equal in the atmosphere—A comment on CDM GHG accounting standards for methane recovery and oxidation projects. Energy Policy 35, 3675-3680.

Moore, T.R., Roulet, N.T., Waddington, J.M., 1998. Uncertainty in Predicting the Effect of Climatic Change on the Carbon Cycling of Canadian Peatlands. Climatic Change 40, 229-245.

Mosher, B.W., Czepiel, P.M., Harriss, R.C., Shorter, J.H., Kolb, C.E., McManus, J.B., Allwine, E., Lamb, B.K., 1999. Methane Emissions at Nine Landfill Sites in the Northeastern United States. Environmental Science & Technology 33, 2088-2094.

Müller, C., Bondeau, A., Lotze-Campen, H., Cramer, W., Lucht, W., 2006. Comparative impact of climatic and nonclimatic factors on global terrestrial carbon and water cycles. Global biogeochemical cycles 20.

Nakicenovic, N., Swart, R., 2000. IPCC special report on emissions scenarios (SRES). Intergovernmental Panel on Climate Change, Geneva, Geneva, Switzerland, p. 570.

NCAR, 2012a. (NCAR GIS Program) Climate Change Scenarios, version 2.0. Community Climate System Model, June 2004 Version 3.0 (http://www.cesm.ucar.edu/models/ccsm3.0/ was used to derive data products). Downscaling procedure in: T. Hoar and D. Nychka, 2008, Statistical Downscaling of the Community Climate System Model (CCSM) monthly temperature and precipitation projections (URL: http://www.gisclimatechange.org). Date accessed: Oct. 15, 2013.

NCAR, 2012b. (NCAR GIS Program) Climate Change Scenarios, Version 2.0. Community Climate System Model, June 2004 version 3.0. NCAR/UCAR. .

NCRR, 1974. Sanitary landfill: a state-of-the-art study. Lexington Books.

Newell, R.G., Pizer, W.A., Raimi, D., 2013. Carbon Markets 15 Years after Kyoto: Lessons Learned, New Challenges. The Journal of Economic Perspectives 27, 123-146.

Oonk, H., 2010. Literature review: methane from landfills, methods to quantify generation, oxidation and emission. Innovations in Environmental Technology.

Oonk, H., 2012. Efficiency of landfill gas collection for methane emission reduction. Greenhouse Gas Measurement and Management 2, 129-145.

Oonk, H., Boom, T., 1995. Validation of landfill gas formation models. Studies in Environmental Science 65, 597-602.

Owens, J., Chynoweth, D., 1993. Biochemical methane potential of municipal solid waste (MSW) components. Water Science & Technology 27, 1-14.

Park, J.-W., Shin, H.-C., 2001. Surface emission of landfill gas from solid waste landfill. Atmospheric Environment 35, 3445-3451.

Parton, W., 1996. The CENTURY model. Evaluation of soil organic matter models. Springer, pp. 283-291.

Pawłowska, M., Stępniewski, W., Czerwiński, J., 2003. The effect of texture on methane oxidation capacity in a sand layer — a model laboratory study. in: Pawłowski, L., Dudzińska, M., Pawłowski, A. (Eds.). Environmental Engineering Studies. Springer US, pp. 339-354.

Peer, R.L., Thorneloe, S., Epperson, D., 1993. A comparison of methods for estimating global methane emissions from landfills. Chemosphere 26, 387-400.

Peischl, J., Ryerson, T., Brioude, J., Aikin, K., Andrews, A., Atlas, E., Blake, D., Daube, B., Gouw, J., Dlugokencky, E., 2013. Quantifying sources of methane using light alkanes in the Los Angeles basin, California. Journal of Geophysical Research: Atmospheres.

Peyton, R., Schroeder, P., 1988. Field Verification of HELP Model for Landfills. Journal of Environmental Engineering 114, 247-269.

Pratt, C., Walcroft, A.S., Deslippe, J., Tate, K.R., 2013. CH_4/CO_2 ratios indicate highly efficient methane oxidation by a pumice landfill cover-soil. Waste Management 33, 412-419.

Rachor, I., Gebert, J., Gröngröft, A., Pfeiffer, E.M., 2013. Variability of methane emissions from an old landfill over different time-scales. Eur. J. Soil Sci. 64, 16-26.

Rannik, Ü., Sogachev, A., Foken, T., Göckede, M., Kljun, N., Leclerc, M.Y., Vesala, T., 2012. Footprint analysis. Eddy Covariance. Springer, pp. 211-261.

Rogner, H.-H., Zhou, D., Bradley, R., Crabbé, P., Edenhofer, O., Hare, B., Kuijpers, L., Yamaguchi, M., 2007. Introduction. in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY USA.

Scharff, H., Jacobs, J., 2006. Applying guidance for methane emission estimation for landfills. Waste Management 26, 417-429.

Scheutz, C., Kjeldsen, P., Bogner, J.E., De Visscher, A., Gebert, J., Hilger, H.A., Huber-Humer, M., Spokas, K., 2009. Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions. Waste Manage. Res. 27, 409-455.

Schuetz, C., Bogner, J., Chanton, J., Blake, D., Morcet, M., Kjeldsen, P., 2003. Comparative oxidation and net emissions of methane and selected non-methane organic compounds in landfill cover soils. Environmental science & technology 37, 5150-5158.

Shindell, D.T., Walter, B.P., Faluvegi, G., 2004. Impacts of climate change on methane emissions from wetlands. Geophysical Research Letters 31.

Siebel, M.A., Rotter, V.S., Nabende, A., Gupta, J., 2013. Clean development mechanism: a way to sustainable waste management in developing countries? Österreichische Wasser-und Abfallwirtschaft, 1-5.

Sormunen, K., Laurila, T., Rintala, J., 2013. Determination of waste decay rate for a large Finnish landfill by calibrating methane generation models on the basis of methane recovery and emissions. Waste Management & Research 31, 979-985.

Spokas, K., Bogner, J., Chanton, J., 2011. A process-based inventory model for landfill CH4 emissions inclusive of seasonal soil microclimate and CH4 oxidation. Journal of Geophysical Research: Biogeosciences (2005–2012) 116.

Spokas, K., Forcella, F., 2006. Estimating hourly incoming solar radiation from limited meteorological data. Weed science 54, 182-189.

Spokas, K., Forcella, F., 2009. Software tools for weed seed germination modeling. Weed science 57, 216-227.

Spokas, K.A., Bogner, J.E., 2011. Limits and dynamics of methane oxidation in landfill cover soils. Waste management 31, 823-832.

Sutter, C., Parreño, J.C., 2007. Does the current Clean Development Mechanism (CDM) deliver its sustainable development claim? An analysis of officially registered CDM projects. Climatic Change 84, 75-90.

Tregoures, A., Beneito, A., Berne, P., Gonze, M.A., Sabroux, J.C., Savanne, D., Pokryszka, Z., Tauziede, C., Cellier, P., Laville, P., Milward, R., Arnaud, A., Levy, F., Burkhalter, R., 1999. Comparison of seven methods for measuring methane flux at a municipal solid waste landfill site. Waste Management & Research 17, 453-458.

Tummescheit, H., Eborn, J., 2002. Chemical reaction modeling with ThermoFluid/MF and MultiFlash. Proceedings of 2nd International Modelica Conference, pp. 31-39.

USEPA, 2013. Inventory of US Grennhouse Gas Emissions and Sinks: 1990-2011. USEPA, Washington, DC.

Van Zanten, B., Scheepers, M.J.J., 1995. Modeling of landfill gas potentials. Proceedings of SWANA 18th Annual Landfill Gas Symposium, New Orleans, LA.

Walker, S., 2012. Landfill Data Compilation. with the assistance of W. Gin (Senior Eng.; deceased), M. Holmes, and H. Hansra. in: CALRecycle (Ed.). CalRecycle Engineering Support Branch.

Wang, H., Su, W., 2013. Evaluating and understanding top of the atmosphere cloud radiative effects in Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Coupled Model Intercomparison Project Phase 5 (CMIP5) models using satellite observations. Journal of Geophysical Research: Atmospheres.

Wang, J., Xia, F.-F., Bai, Y., Fang, C.-R., Shen, D.-S., He, R., 2011. Methane oxidation in landfill waste biocover soil: Kinetics and sensitivity to ambient conditions. Waste Management 31, 864-870.

Wang, X., Nagpure, A.S., DeCarolis, J.F., Barlaz, M.A., 2013. Using observed data to improve estimated methane collection from select US landfills. Environmental Science & Technology 47, 3251-3257.

Wennberg, P.O., Mui, W., Wunch, D., Kort, E.A., Blake, D.R., Atlas, E.L., Santoni, G.W., Wofsy, S.C., Diskin, G.S., Jeong, S., 2012. On the sources of methane to the Los Angeles atmosphere. Environmental science & technology 46, 9282-9289.

Whalen, S.C., Reeburgh, W.S., Sandbeck, K.A., 1990. Rapid Methane Oxidation in a Landfill Cover Soil. Appl. Environ. Microbiol. 56, 3405-3411.

Wickramarachchi, P., Kawamoto, K., Hamamoto, S., Nagamori, M., Moldrup, P., Komatsu, T., 2011. Effects of dry bulk density and particle size fraction on gas transport parameters in variably saturated landfill cover soil. Waste management (New York, N.Y.) 31, 2464-2472.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D., Pfeiffer, E.-M., 2008. Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling. Global Change Biology 14, 1395-1408.

Willmott, C.J., 1981. On the validation of models. Physical geography 2, 184-194.

Willumsen, H., Terraza, H., 2007. CDM landfill gas projects. World Bank Report. World Bank Workshop, Washington, DC.

Yazdani, R., Imhoff, P., 2010. Biocovers at landfills for methane emissions reduction demonstration. California Department of Resources Recycling and Recovery Sacramento, CA, p. 77.

Young, A., 1989. Mathematical modeling of landfill gas extraction. Journal of Environmental Engineering 115, 1073-1087.

Young, I., Crawford, J., Rappoldt, C., 2001. New methods and models for characterising structural heterogeneity of soil. Soil and Tillage Research 61, 33-45.

Zhang, H., He, P., Shao, L., 2008. Methane emissions from MSW landfill with sandy soil covers under leachate recirculation and subsurface irrigation. Atmospheric Environment 42, 5579-5588.

Zhang, N., Zhou, X., Shepson, P.B., Gao, H., Alaghmand, M., Stirm, B., 2009. Aircraft measurement of HONO vertical profiles over a forested region. Geophysical Research Letters 36, L15820.

Zhuang, Q., Chen, M., Xu, K., Tang, J., Saikawa, E., Lu, Y., Melillo, J.M., Prinn, R.G., McGuire, A.D., 2013. Response of global soil consumption of atmospheric methane to changes in atmospheric climate and nitrogen deposition. Global Biogeochemical Cycles.

Zitouna-Chebbi, R., Prévot, L., Jacob, F., Mougou, R., Voltz, M., 2012. Assessing the consistency of eddy covariance measurements under conditions of sloping topography within a hilly agricultural catchment. Agricultural and Forest Meteorology 164, 123-135.

Zornberg, J., LaFountain, L., Caldwell, J., 2003. Analysis and design of evapotranspirative cover for hazardous waste landfill. Journal of Geotechnical and Geoenvironmental Engineering 129, 427-438.

VIII. Appendices

Appendix A. User Manual for CALMIM Model

User Manual

Version 5.4

June 2014

Contents

1.0 INTRODUCTION....144

2.0 INSTALLATION GUIDE....147

2.1.1 INSTALLATION TYPE.... 148
2.1.2 PROGRAM FILE LOCATION.... 149
2.1.3 FILE EXTENSION ASSOCIATION 150
2.1.4 INSTALLATION PROGRESS WINDOW 151
2.1.5 INSTALLATION COMPLETED 152

2.2 INSTALLATION ON A MACINTOSH (MAC OSX) COMPUTER 153

2.3 LINUX....155

3.0 MAIN SCREEN....157

3.1 UPDATE AVAILABILITY 160

4.0 SITE LOCATION/MAPS & TOTAL AREA SCREENS 161

4.1 STRUCTURAL OVERVIEW OF MAIN MODEL WINDOW.... 161
4.1.1 Menu:.... 162
4.1.2. Menu Options:.... 162
5.0 SITE PROPERTIES PANEL 164

6.0 COVER EDITOR PANEL....171

7.0 WEATHER SIMULATION SCREEN 186

8.0 FINAL RESULTS SCREEN....189

1.0 Introduction

CALMIM (**CA**lifornia **L**andfill **M**ethane **I**nventory **M**odel) is a field-validated, 1-dimensional transport and oxidation model that calculates annual methane emissions for a landfill site based on the major processes that control emissions, including the:

- Physical properties and surface area of each daily, intermediate, and final cover material,
- Presence of engineered gas recovery, simply expressed as the % surface area of each cover overlying waste where vertical wells or horizontal collectors have been installed.
- Seasonal methane oxidation in each cover type as controlled by climate and soil microclimate.

The driving force for emissions is the methane concentration gradient through each cover type coupled with dynamic soil moisture and temperature profiles which control methane transport and microbial methane oxidation rates over a typical annual cycle. As a field-validated, higher quality model, CALMIM is compliant with the IPCC (Intergovernmental Panel on Climate Change) Tier III methodology for methane emissions from solid waste disposal sites (IPCC, 2006). CALMIM was originally developed and field-validated for California during 2007-2010 (Spokas et al., 2011, Bogner et al., 2011, Spokas and Bogner, 2011) and internationally field-validated during 2011-2013.

Based on 2.5-cm (1 inch) depth increments and 10 minute time steps, CALMIM calculates daily methane (CH_4) emissions on an areal basis for each individual cover with units of g CH_4 m^{-2} d^{-1}. The daily emissions are summed to provide annual totals for each cover and for the site as a whole (kg CH_4 yr^{-1}). The climate-related factors (meteorology and soil microclimate) are automatically accessed within CALMIM based on site location [latitude/longitude] and cover properties. The CALMIM model is intended to be user-friendly with a series of input boxes to enter basic information on the surface area and properties of each daily, intermediate, and final cover material, as well as the % surface area for each cover type with engineered gas recovery.

Unlike previous inventory models for landfill methane emissions, CALMIM does NOT rely on a multi-component first order kinetic, or first order decay (FOD), model for methane generation based on the annual quantity and composition of landfilled waste. Published literature over the last decade focusing on field measurement of landfill CH_4 emissions has indicated that, on a site-specific basis, the FOD models do not provide a scientifically-robust basis for predicting emissions due to:

- High uncertainty associated with theoretical first order kinetic models assuming homogeneous waste and hypothetical decomposition rates in heterogeneous landfill settings (IPCC, 2006);
- The complexity of methane pathways at individual sites (recovery, emissions, oxidation, lateral migration, internal storage) where modeled

generation cannot be directly and linearly related to measured emissions (Spokas et al., 2006; Spokas et al., 2011; Bogner et al., 2011).

- Lack of field validation for emissions. Previous "validation" of first order kinetic models for GHG emission inventory purposes was limited to a comparison between modeled landfill gas generation and measured landfill gas recovery (e.g., Van Zanten and Scheepers, 1994; Peer et al., 1993; Scharff and Jacobs, 2006; Thompson et al., 2009: Oonk, 2010).

CALMIM is a freely-available JAVA tool, which can be downloaded at *www.ars.usda.gov*. The original model for California was PC-based and intended to be the first step in the development of an improved science-based, field-validated model for site-specific landfill methane emissions. The development of CALMIM during 2007-2010 included a review of the technical literature; discussions with California state agencies regarding California landfill cover materials and gas recovery practices; decisions regarding the CALMIM conceptual framework including use of existing globally-validated USDA models for climate and soil microclimate (Global TempSIM, Global RainSIM, SOLARCALC, STM^2); intensive supporting laboratory studies addressing methane oxidation in California landfill cover soils; JAVA model development and revisions; intensive field validation over a 2-yr period at two California landfills (Marina and Scholl Canyon); and limited field validation at 3 additional California landfills (Lancaster, Kirby Canyon, Tri-Cities) through cooperation with an ongoing Waste Management, Inc./U.S. EPA project comparing multiple field measurement methodologies.

The original CALMIM project team consisted of

- J. Bogner, Landfills +, Inc., Wheaton, IL and Dept. of Earth & Environmental Sciences, University of Illinois at Chicago (UIC), Chicago, IL
- K. Spokas, U.S. Dept. of Agriculture(USDA)-Agricultural Research Service(ARS), St. Paul, MN
- J. Chanton, Dept. of Earth, Ocean, & Atmospheric Sciences, Florida State University, Tallahassee, FL.

The original project was supported by the California Energy Commission (CEC) Public Interest Energy Research (PIER) Program [Grant No. 500-05-039]. We gratefully acknowledge the support of Guido Franco, PIER program manager, and many individuals at the Los Angeles County Sanitation District, the Monterey Regional Waste Management District, the former California Integrated Waste Management Board (now part of Calrecycles), and the Air Resources Board (ARB) who generously shared their time, provided critical reviews, and facilitated data needs for this project. In addition, we are grateful to Waste Management, Inc. for sharing field data from their Lancaster, Kirby Canyon, and Tri-Cities Landfills. We also sincerely thank the following individuals for technical assistance with this project: Martin duSaire, Nancy Barbour, Dean Peterson, Chad Rollofson, Tia Phan, Lindsay Watson, Lianne Endo, Kia Young, Mai Song Yang, David Hamrum, Paul Roots, and Tim Badger. The final project report was approved by the CEC in late 2010.

Please refer to the following journal articles for additional details:

Journal Articles:

1. Spokas, K., Bogner J., and Chanton, J., A Process-Based Inventory Model for Landfill CH_4 Emissions Inclusive of Soil Microclimate and Seasonal Methane Oxidation, J. Geophysical Research-Biogeosciences, 116: paper G04017, 19 p. (2011).

2. Bogner, J., Spokas, K., and Chanton, J., Seasonal Greenhouse Gas Emissions (CH_4, CO_2, N_2O) from Engineered Landfills: Daily, Intermediate, and Final California Landfill Cover Soils, J. Environ. Quality 40:1010-1020 (2011).

3. Spokas, K., and Bogner, J., Limits and dynamics of methane oxidation in landfill cover soils, Waste Management 31:823-832 (2011).

In 2011-2013, the Environmental Research and Education Foundation (EREF), Raleigh, NC, supported follow-up research to improve and internationally field-validate CALMIM via financial support to the University of Illinois at Chicago (UIC) [J. Bogner, Dept. of Earth and Environmental Sciences] and the U.S. USDA-ARS, St. Paul, MN (K. Spokas). This project expanded CALMIM functionality to run on multiple platforms (PC, MAC, UNIX), decreased run times with expanded capabilities for multiple cover types, and addressed programming issues associated with broader climatic variability and soil types. The improved CALMIM model was internationally field-validated using literature and data from research groups in North America, South America, Europe, Asia, Africa, and Australia.

Two additional field projects were also completed in May and August, 2012, in collaboration with Waste Management, Inc. at their Twin Bridges Landfill near Indianapolis, IN. Because CALMIM can run either in "default" mode, using conservative boundary conditions based on literature, or "custom" mode based on site-specific data, the purpose of these projects was to understand the variability in soil gas concentrations at the base of daily and intermediate cover materials in order to recommend field protocols for determining "custom" values at specific sites. Therefore, closely-spaced, process-level field data on soil gas concentration profiles and GHG emissions for daily and intermediate cover materials were collected using a random stratified sampling design. Moreover, in collaboration with Waste Management, Inc. (Roger Green and Gary Hater) and Purdue University (Dept. of Chemistry, Drs. Maria Obiminda Cambaliza and Paul Shepson), a total of 4 different complementary field methods and CALMIM modeling were completed for the Twin Bridges site.

For the 2011-2013 project work, we are grateful to Dr. Bryan Staley (EREF) for financial support and programmatic assistance, as well as R. Green and G. Hater (Waste Management, Inc.) as well as M. Cambaliza and P. Shepson (Purdue University) as discussed above, and to Meg Corcoran (graduate student, UIC), Andrew Esser (Regional Manager, Waste Management, Inc.) and Shawn Nygen (Computer Programmer, Univ. of MN).

2.0 Installation Guide

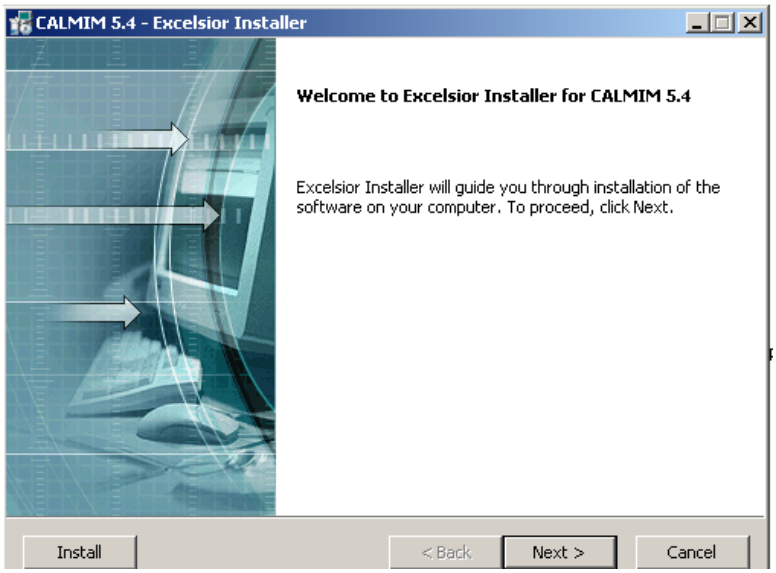
CALMIM is written entirely in JAVA, thus enabling it to run on various platforms. The installations instructions for various platforms are given in this section.

2.1.0 Installation on a Windows based computer

This section will describe the installation of the CALMIM model on a Windows™ based computer. CALMIM (for Windows) uses the Excelsior Installer from the JET family of Java pre-compiler programs. The program is distributed via a setup program (CALMIM-setup.exe) as shown below:

This program is available for download from (http://www.ars.usda.gov/services/software/download.htm?softwareid=300) or on a distribution CD available through the USDA-ARS (Send email requesting a copy to : kurt.spokas@ars.usda.gov)

When the user double-clicks the icon, the following initial window is displayed:

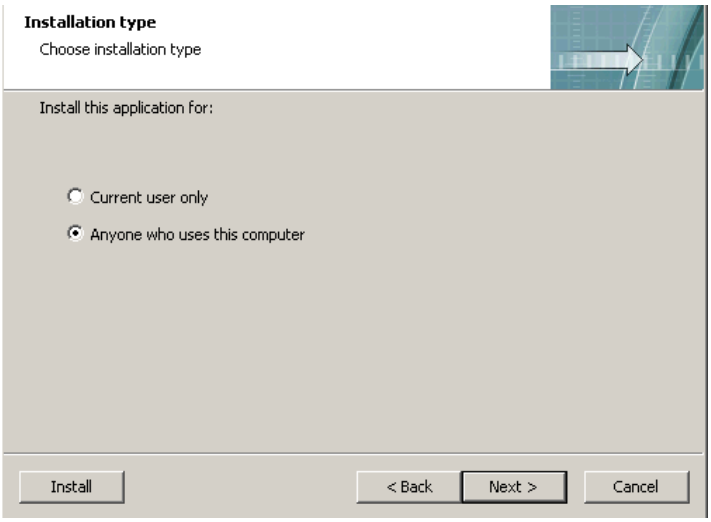


The user can use the "Install" button to use all program defaults (for file location, associations, and directories); or the user can use the Back and Next buttons to navigate through the installation wizard (as described in the next section) to customize the installation of the program.

2.1.1 Installation Type

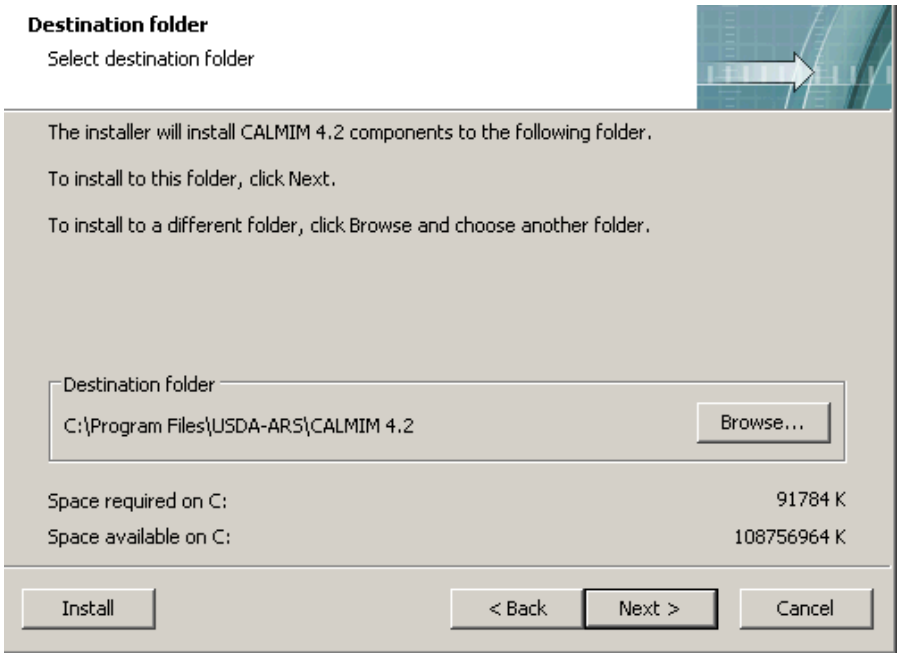
On the first screen, the user can select to install the program solely for the current user or for all the users of the computer system.

The default option is for all users to have access to this program. This option is toggled by the associated buttons on the form. Once the user has made the selection, the "Next" button should be clicked to move to the next window of the installation wizard.



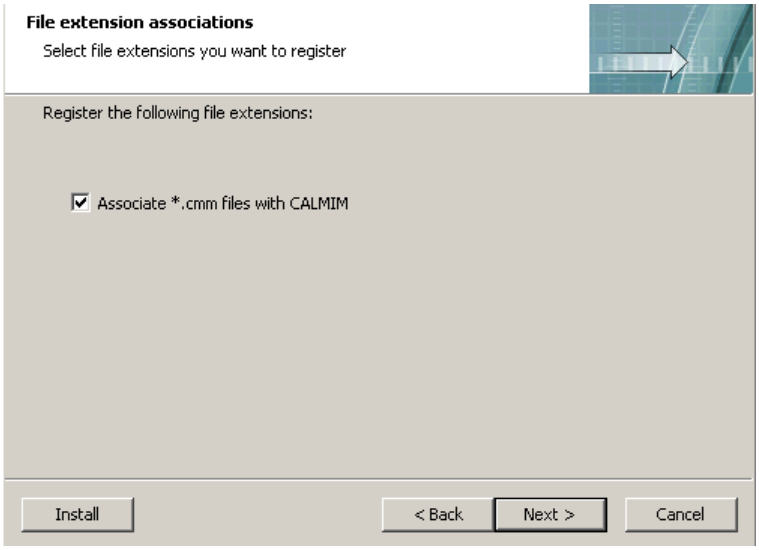
2.1.2 Program File Location

The next screen allows the user to alter the default file locations for the model directory (default is shown in the Destination folder box). The user can customize this selection by pressing the "Browse" button. After the user has selected the directory for the folder, the user should press the "Next" button for the next panel in the installation wizard.



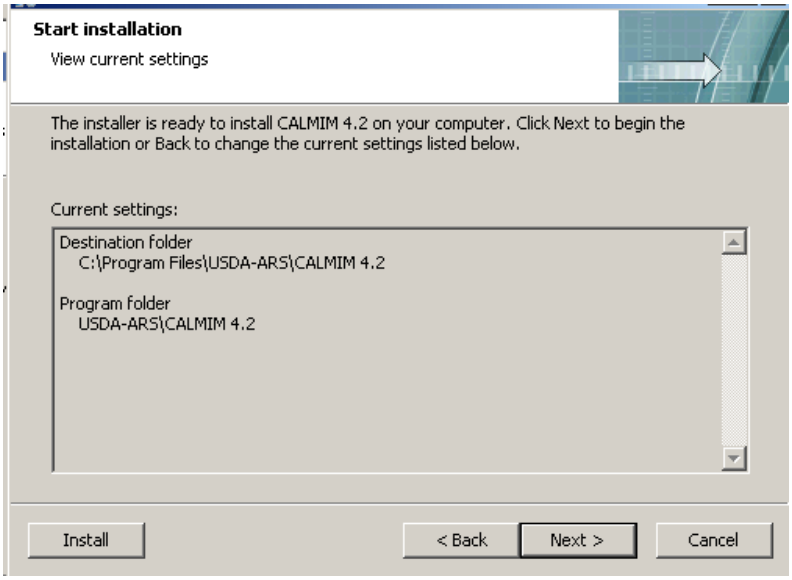
2.1.3 File Extension Association

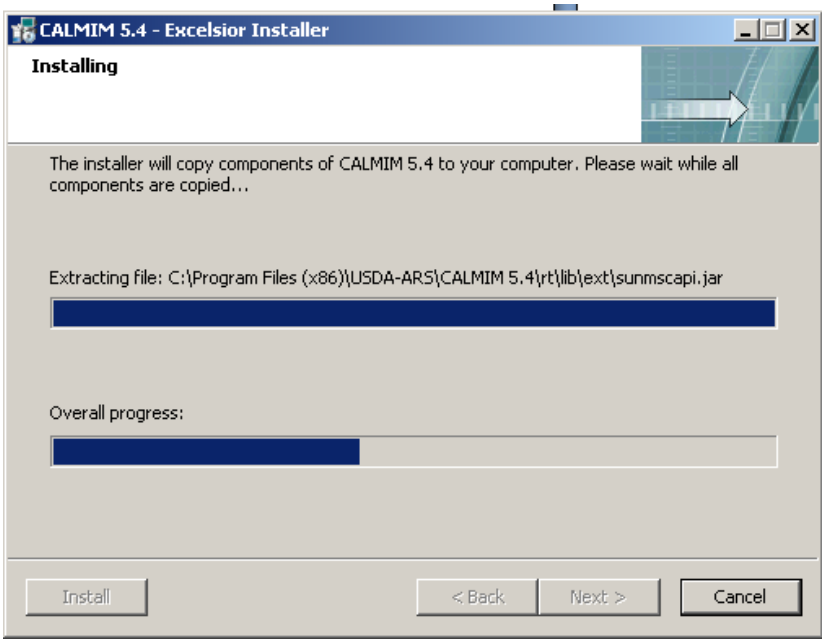
The next panel allows the user to associate the CALMIM profile filenames with the CALMIM program. This option is either enabled or disabled through the checkbox. The advantage to this association is that if the profile filename is double clicked, this will cause the computer to open the CALMIM model. Selecting "Next" takes the user to the next panel.



2.1.4 Installation Progress Window

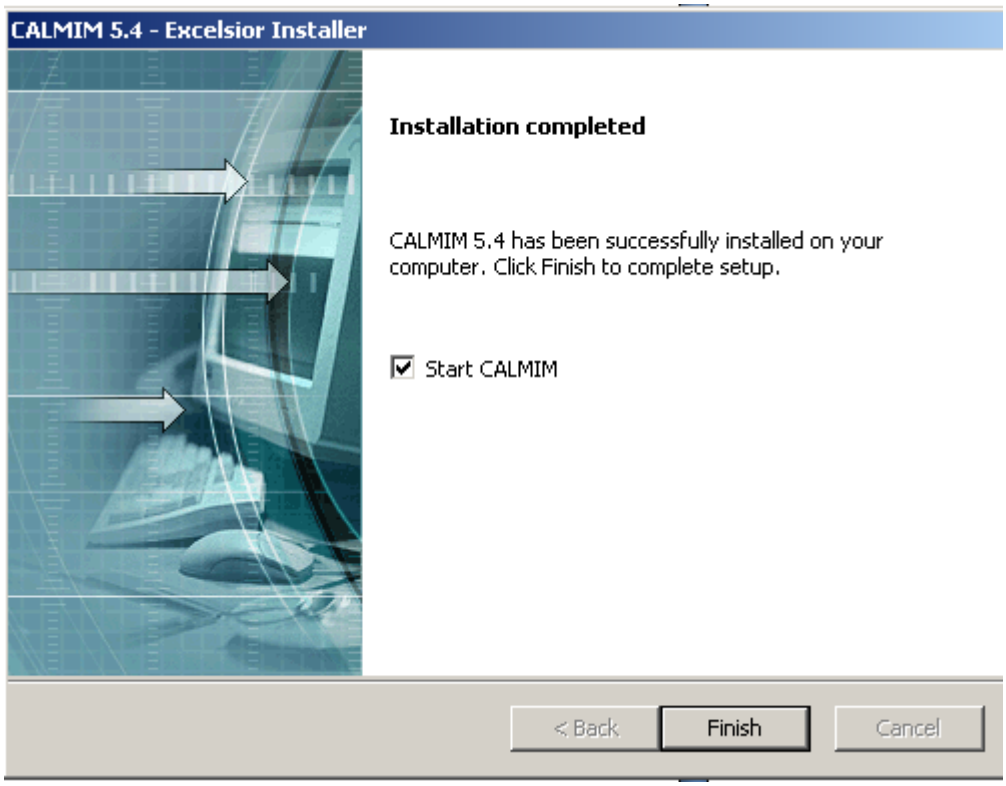
After the selections are made, the program will be installed according to the selected preferences.





2.1.5 Installation Completed

The following dialog box is shown once the installation is completed. The user can immediately start the model by leaving the checkbox enabled.



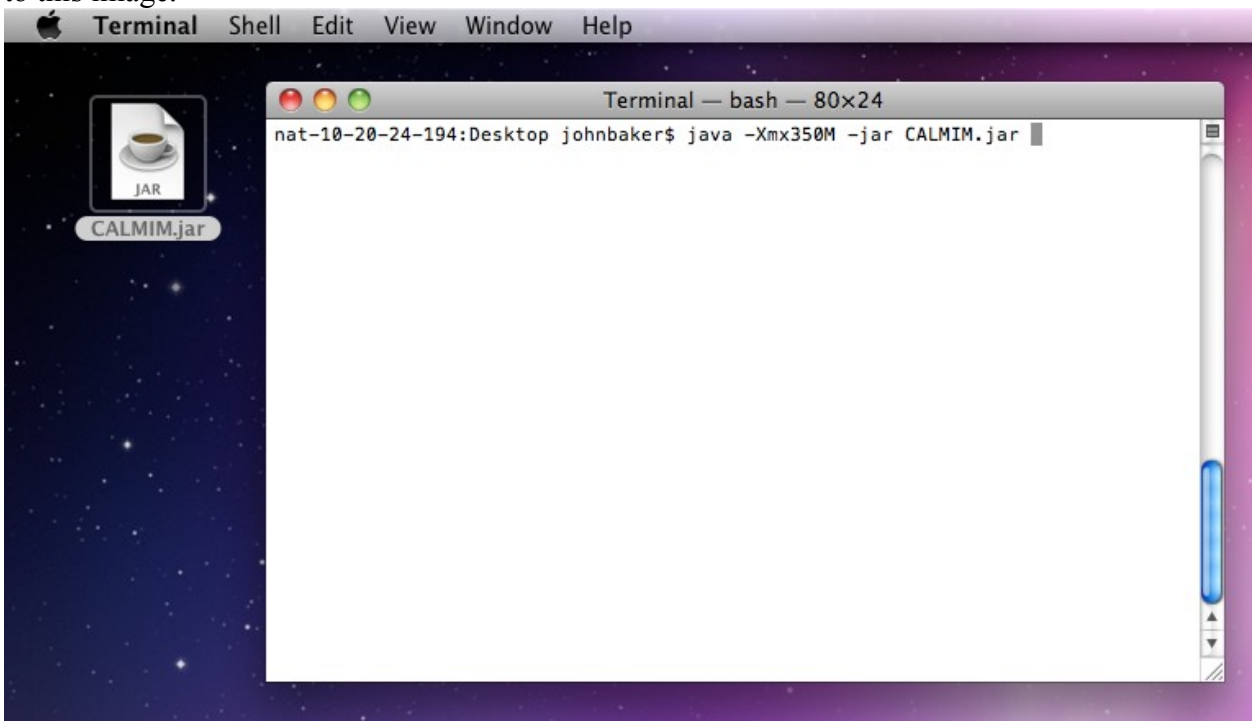
2.2 Installation on a Macintosh (Mac OSX) Computer

The alternative version of CALMIM is capable of running on Mac OS X, Linux, and Windows. Each method for running for running it is described below. Every method requires Java to be installed prior to use. Additionally, all methods use the same CALMIM file downloaded from the site, CALMIM.jar.

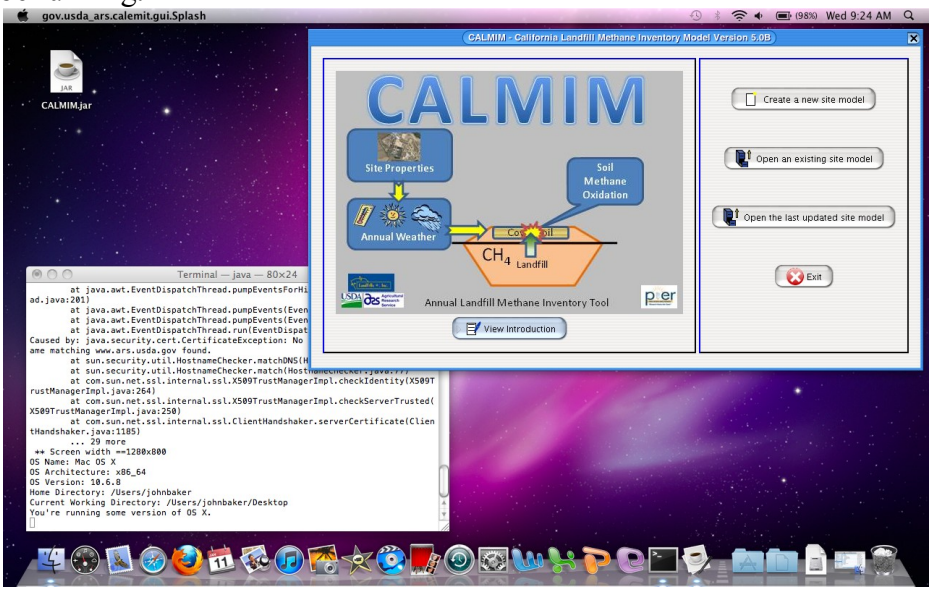
The jar version of CALMIM differs only in how it's started. The code is exactly the same in each case.

Start by noting where the CALMIM.jar file was downloaded to. This manual will assume it was downloaded to the desktop.

Open a terminal. A terminal program can be found in the Finder under Applications and Utilities. It will be a small white window with some text similar to this image.

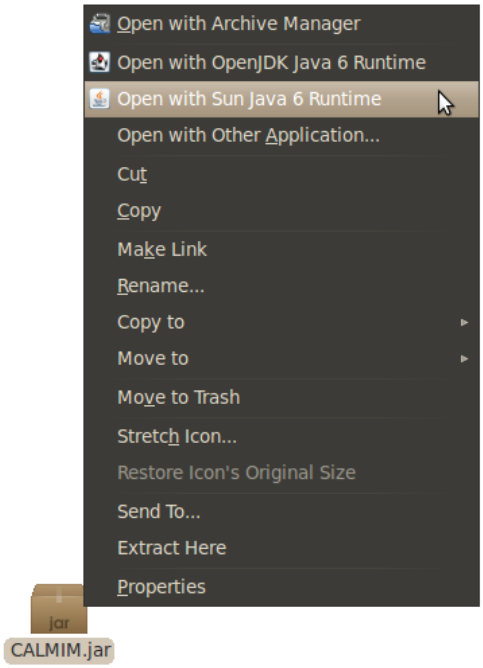


In the terminal type "*cd Desktop*" without the quotes and press enter. This changes the current directory to the desktop. Follow this command by "*java –Xmx350M –jar CALMIM.jar*", again without the quotes. CALMIM should now be running.

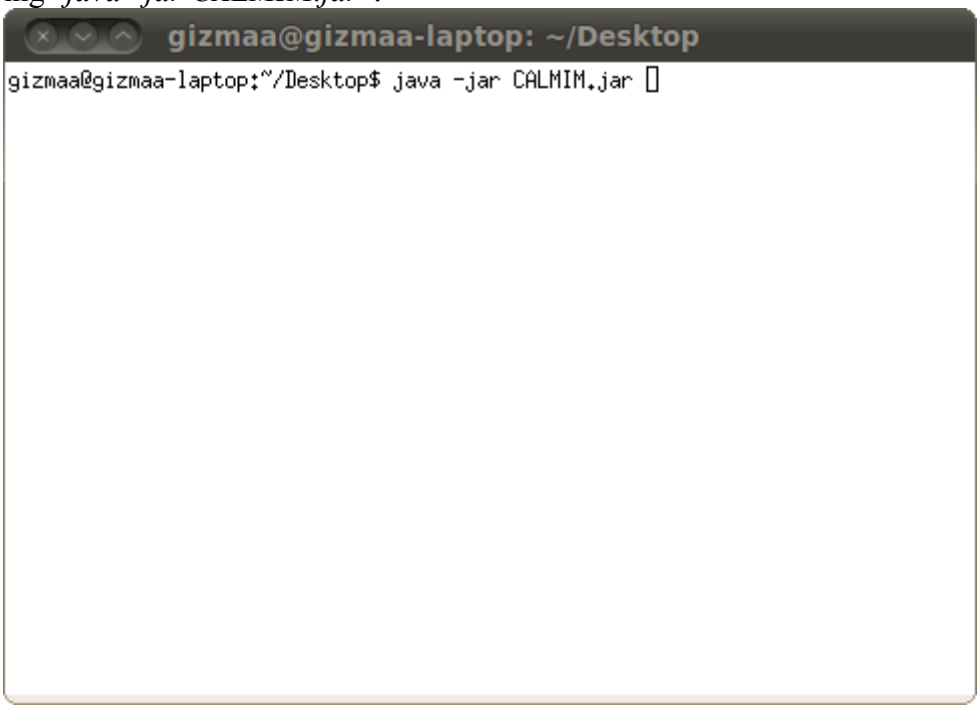


2.3 Linux

CALMIM has been tested on Ubuntu 10.04 Lucid Lynx 64-bit but should work on any Linux distribution which has Java installed. The simplest way of running CALMIM is to right click the CALMIM.jar file and click "Open with Sun Java 6 Runtime".

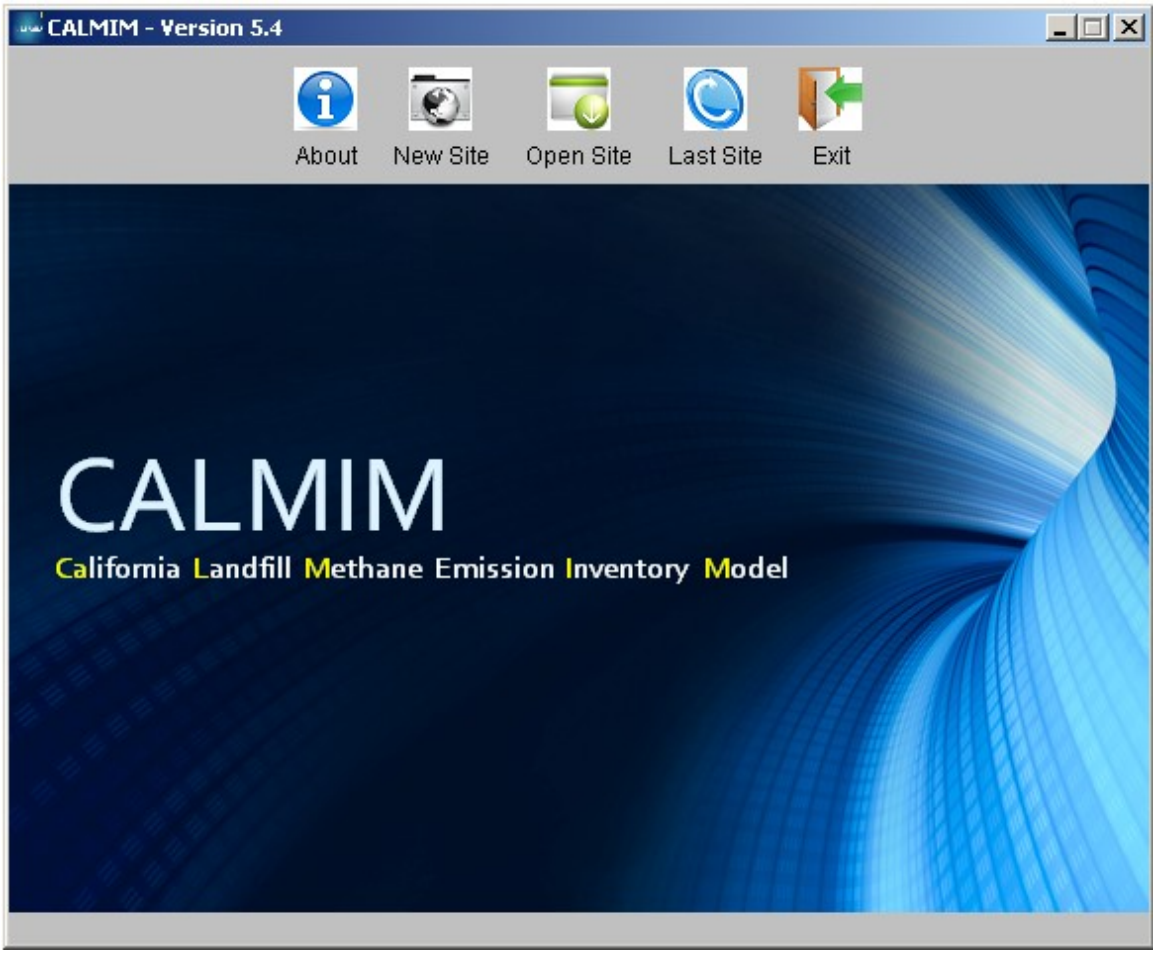


Alternatively, it can be run from the command line. Open your terminal of preference and navigate to the directory where CALMIM resides. Execute it by typing "*java –jar CALMIM.jar*".



If the terminal displays errors about exceeding the heap size try executing CALMIM with "*java –Xmx350M –jar CALMIM.jar*" to give CALMIM a bit more memory.

3.0 Main Screen



The main screen has five available options:

1. **About** 

   This button will access a brief overview of the CALMIM model (less detailed than Chapter 1 of this manual and references cited therein).

2. **Create a new site model** 

   This button launches a new input wizard to collect information on the landfill site to be modeled. This is the starting point for new sites and new users without previously saved profiles.

3. **Open an existing site model** 

   This button opens a previous saved file

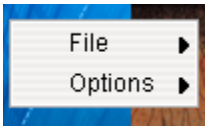
4. **Open the last updated site model** 

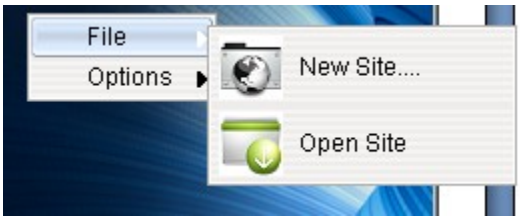
   This button opens the last modeled site (last run) of the CALMIM model.
   NOTE: Either option 3 or 4 is recommended for multiple runs for the same site, as these options will preserve the *same* randomizations for monthly meteorological data.

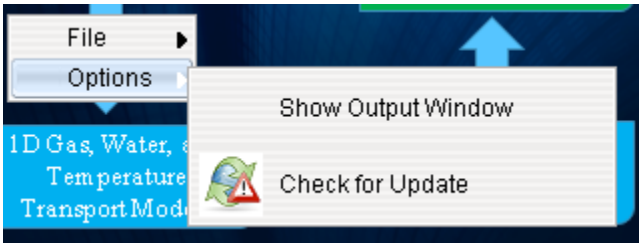
5. **Exit** 

   This button will exit the program.

These options are also available in a pop-up menu (pressing the right mouse button):



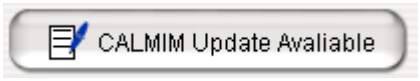




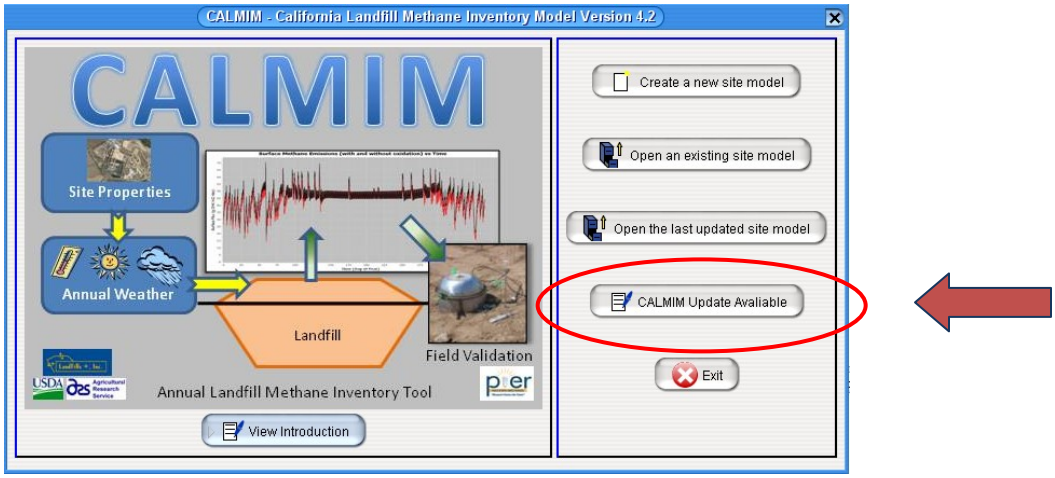
The SHOW output window is an advanced feature allowing you to see more of the modeling output. This is left as a feature for future debugging needs.

The Check for Update – forces the computer to check for an update now.

3.1 Update availability



If the user has a connection to the internet, an automatic check will be run each time CALMIM starts to determine if there is an update available. If there is an update available, an additional button will be displayed on the main menu as shown below:

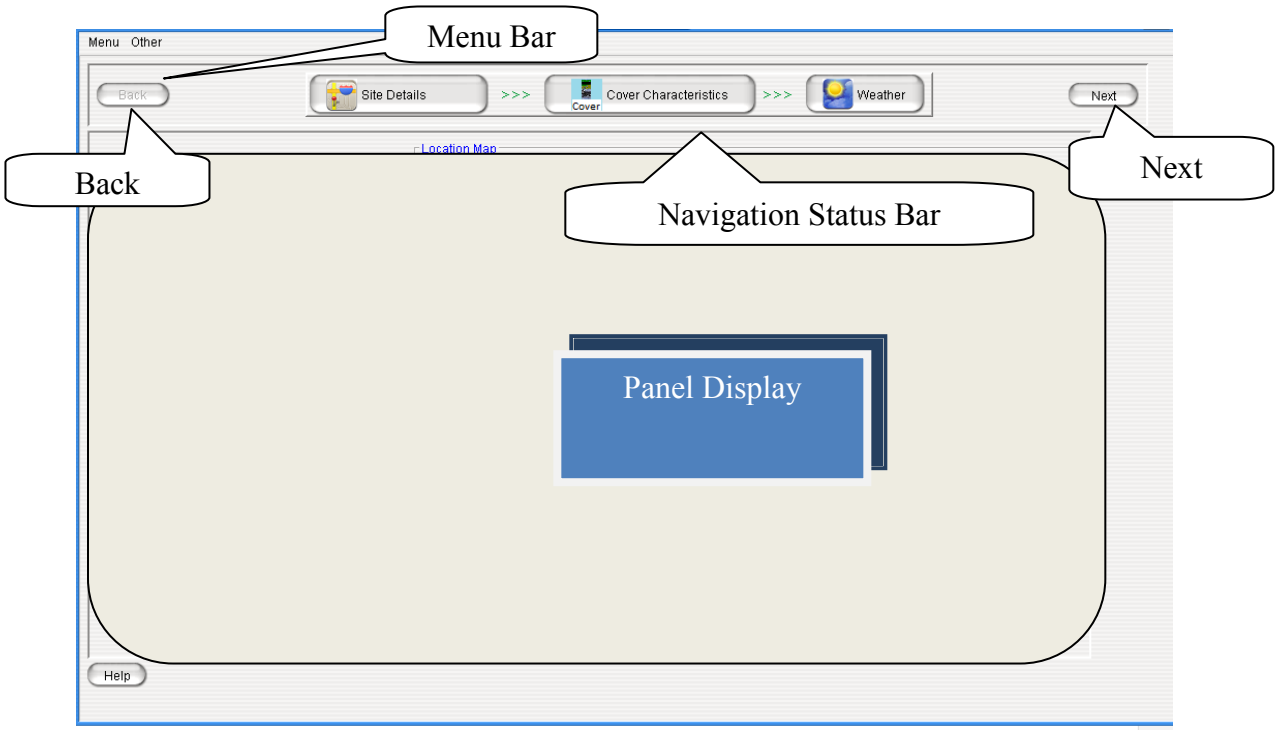


When the user selects this button, you will be taken to the main webpage for CALMIM distribution, where the user can download and install the updated version.

Note:
IMPORTANT! Please remove (uninstall) the current version before installing any updates.
This warning will also be displayed by the installer program.
[Please see ***Installation Guide (Section 2)*** for further information]

4.0 Site Location/Maps & Total Area Screens

4.1 Structural overview of main model window



Menu – displays the menu for the program, which is described on the next page.

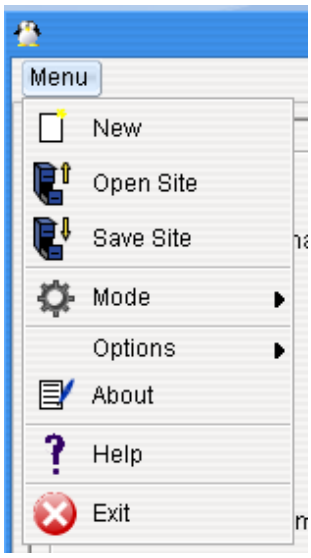
Back button – Allows the user to navigate backwards in the wizard screens. This button is enabled once the user has advanced to the next panel (Cover Editor).

Next button – Allows the user to move to the next panel in the wizard screens.

Navigation status bar – Displays the current page of the wizard (in red) as well as where the user is in the panel order.

Help – Displays on-line help information for current panel displayed.

4.1.1 Menu:



4.1.2. Menu Options:

New –

Opens a new site

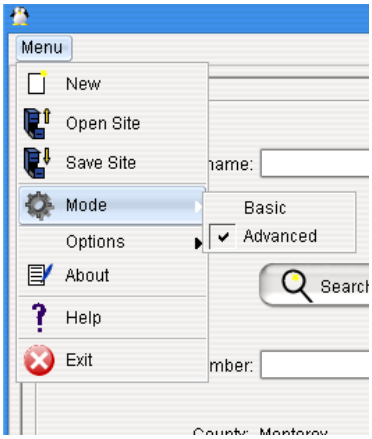
Open Site –

Opens dialog box to open a previously saved site. The CALMIM profile files are saved with a *.CMM extension.

Save Site –

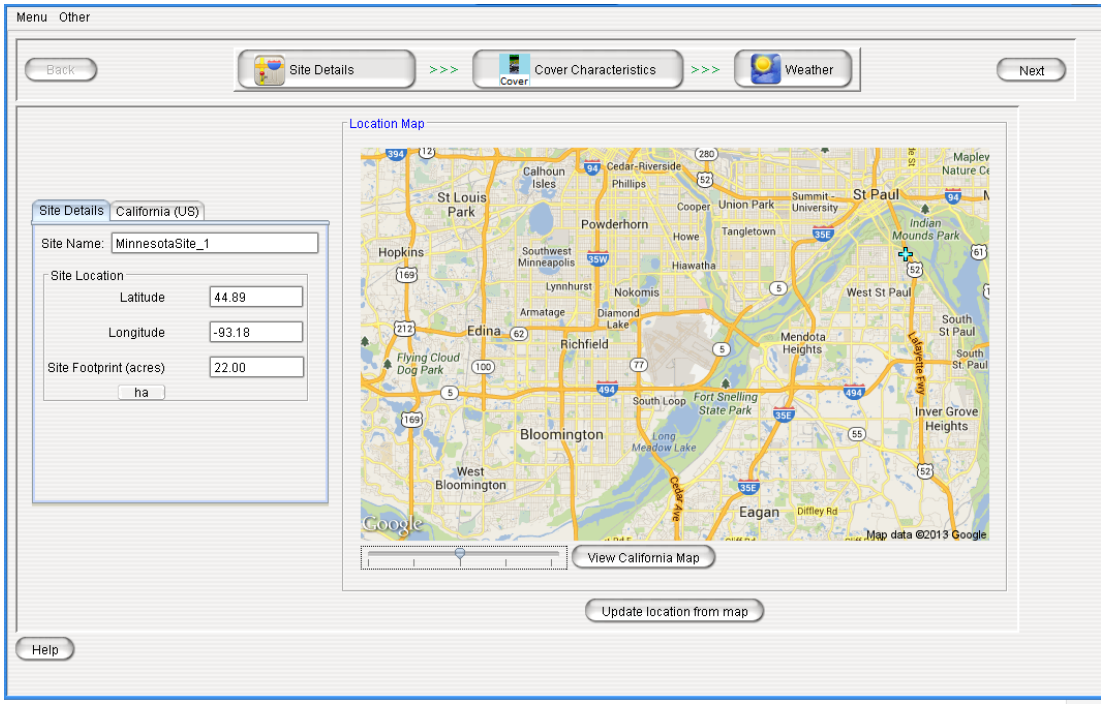
Opens dialog box to save current site profile file (.CMM).

Mode –



This option allows the user to select the basic or advanced user levels. The advanced mode is used to toggle whether the irrigation editor is displayed in the Weather display panel (see Section 7). This is the sole feature that is automatically enabled or disabled with this option. Other advanced options are discussed in Section 6. The advanced toggle only works while on the weather screen.

5.0 Site Properties Panel



Required information about the landfill site to be modeled is entered on this panel. Inputs include a site name, its latitude & longitude, and the area of the waste footprint. All of this input information is required for each site.

5.0.1 *Latitude*

The latitude of the site is entered in this text box. The latitude is positive for North of the equator and negative for locations South of the equator. For example, the latitude for Sydney Australia (33^{o} 55' South) would be entered as -33.92 and for Chicago, IL (USA; 41^{o} 51' North) would be +42.85.

5.0.2. *Longitude*

The longitude of the site is entered in this textbox. East is entered as positive values and West longitudes are negative values. For example, the longitude for Sydney, Australia (151^{o} 17' East) would be entered as +151.28 and for Chicago, IL (USA; 87^{o} 41' West) would be -87.68.

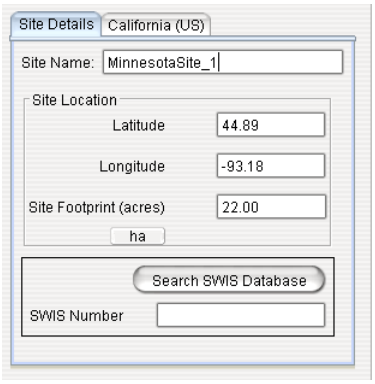
5.0.3. *Site Waste Footprint*

This is the total area of the waste footprint in acres, which represents the area of the site where waste is currently or has been historically deposited. This is NOT the total size or permitted area of the landfill site.

5. 1 California Options

To enable California SWIS search options – Select the tab ("Caifornia(US)") and enable the option checkbox (shown above).

After this check box is enabled, the screen on the previous menu will change to the following:



By entering a part of the name in the site name box and then by pressing the "Search SWIS Database" button, the program will attempt to locate the site in the California SWIS (Solid Waste Information System) database included with the CALMIM model (see http://www.calrecycle.ca.gov/SWFAcilities/Directory/ for additional information regarding the SWIS system).

The model will display a pop up box with the sites located:

The user can select the site from the pull-down box and then click on the "Select Site" button 

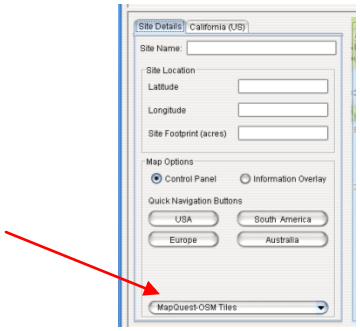
. The program will automatically populate the corresponding text boxes with the latitude, longitude, and waste footprint (if available in SWIS records). The user will then be returned to the main wizard.

If none of the listed sites are the desired site, please select "Cancel" and the program will return to the wizard. At this point, the user could either modify the search or continue by manually entering the required data.

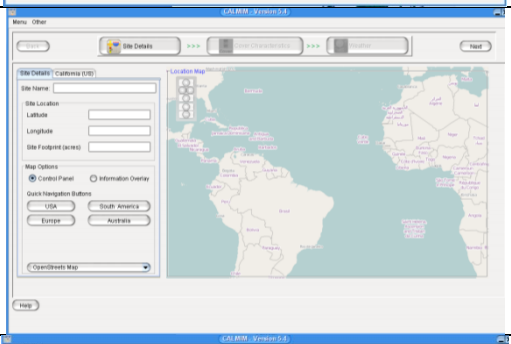
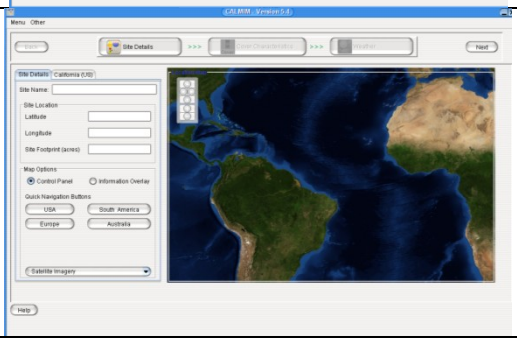
If the site is not found, the model will display a warning box notifying the user that the site was not located in the database.

5.2 Map Options - *Map Tile Servers*

This button is located at the bottom of the Location Map panel as shown below.

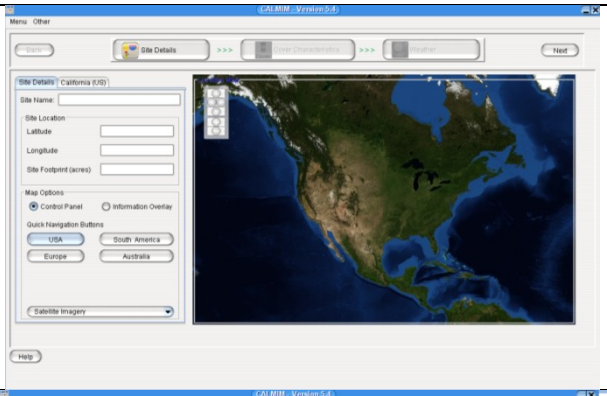
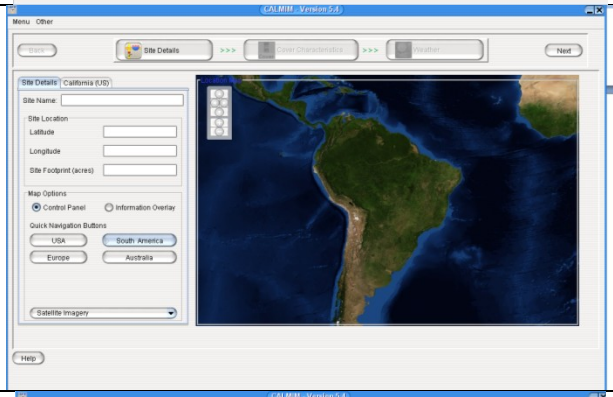
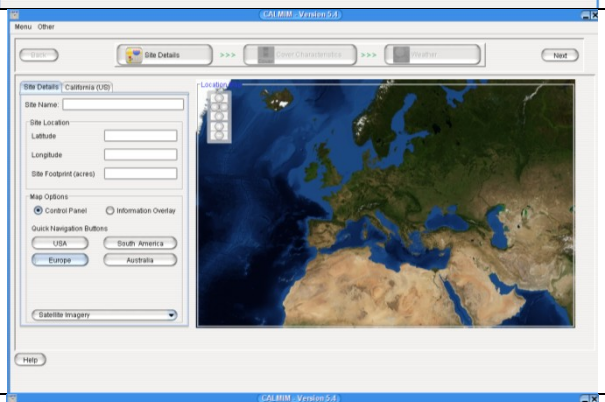
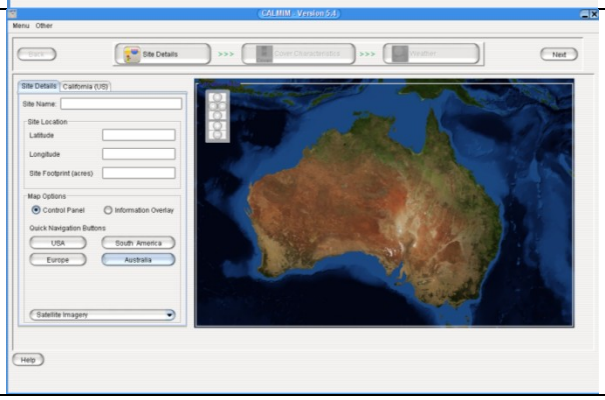


If this button is selected, the model will change the map tile server, thus changing the view of the map.

MapQuest OSM TileServer	
OpenStreets Tile Server	
Satellite Imagery Tile Server	

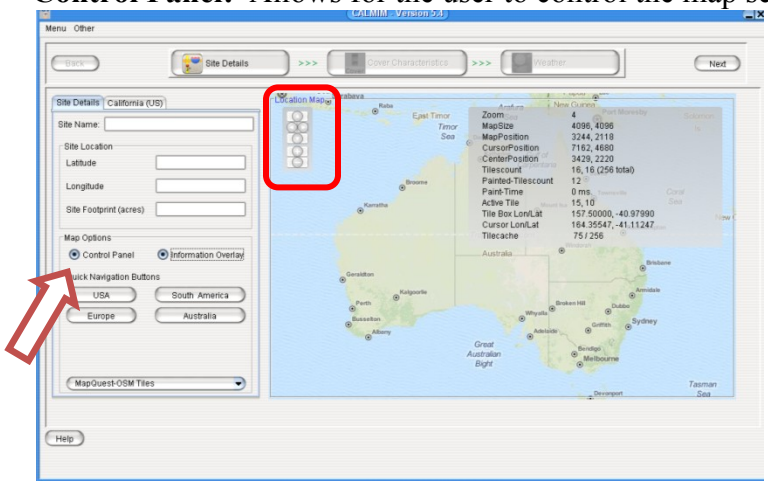
5.2 Map Options – *Quick Select Buttons*

There are 4 quick select buttons that will change the world map to the following views:

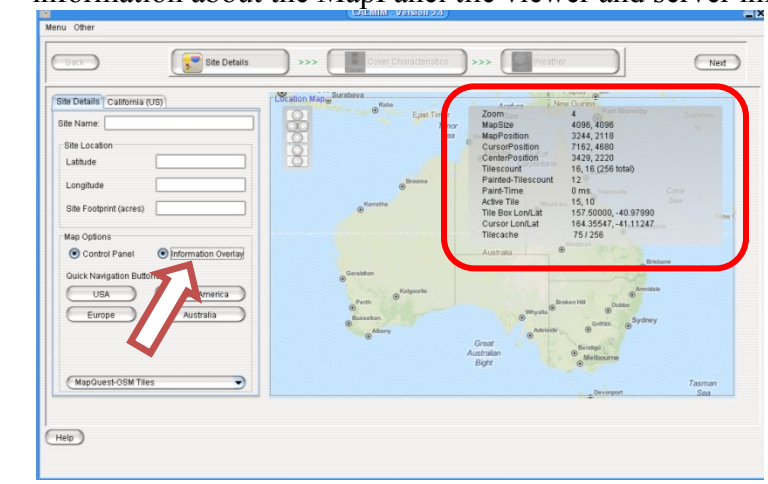
US	
South America	
Europe	
Australia	

5.2.2 Map Options - *Control Panel and Information Overlay*

Control Panel: Allows for the user to control the map scrolling and zoom level.



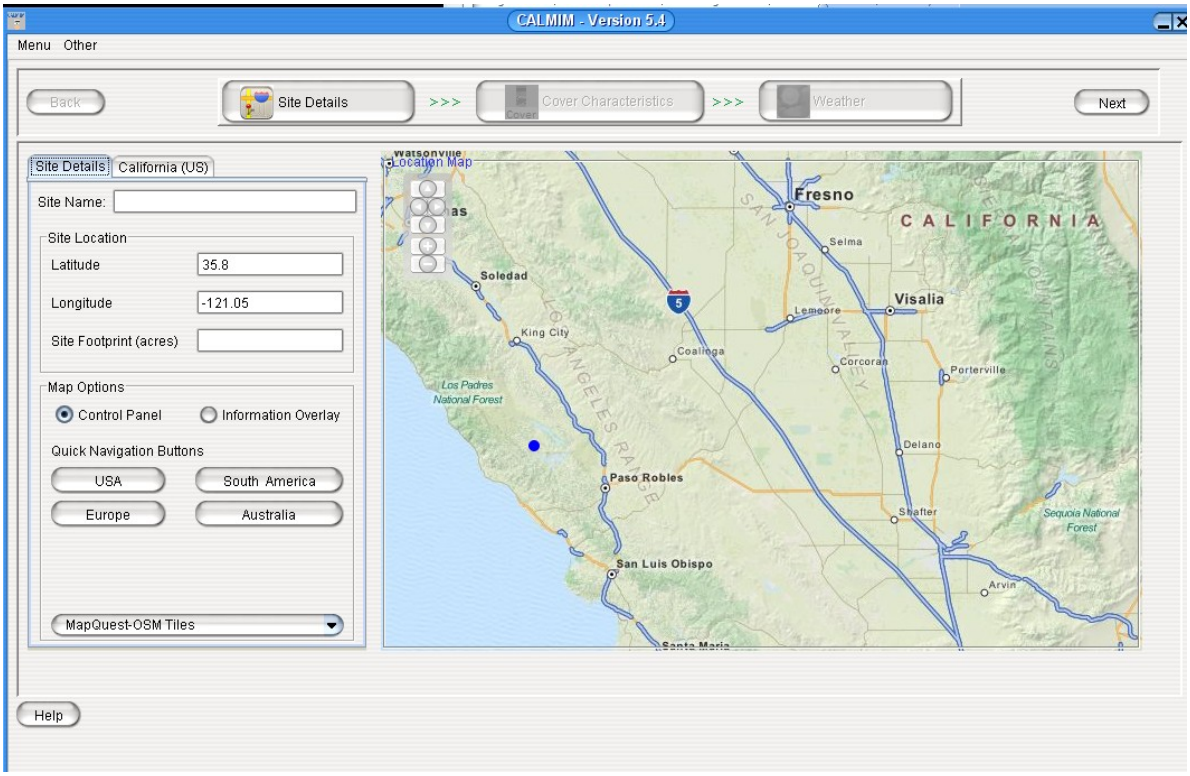
Information Overlay: Selecting the information overlay button the model will display information about the MapPanel tile viewer and server information.



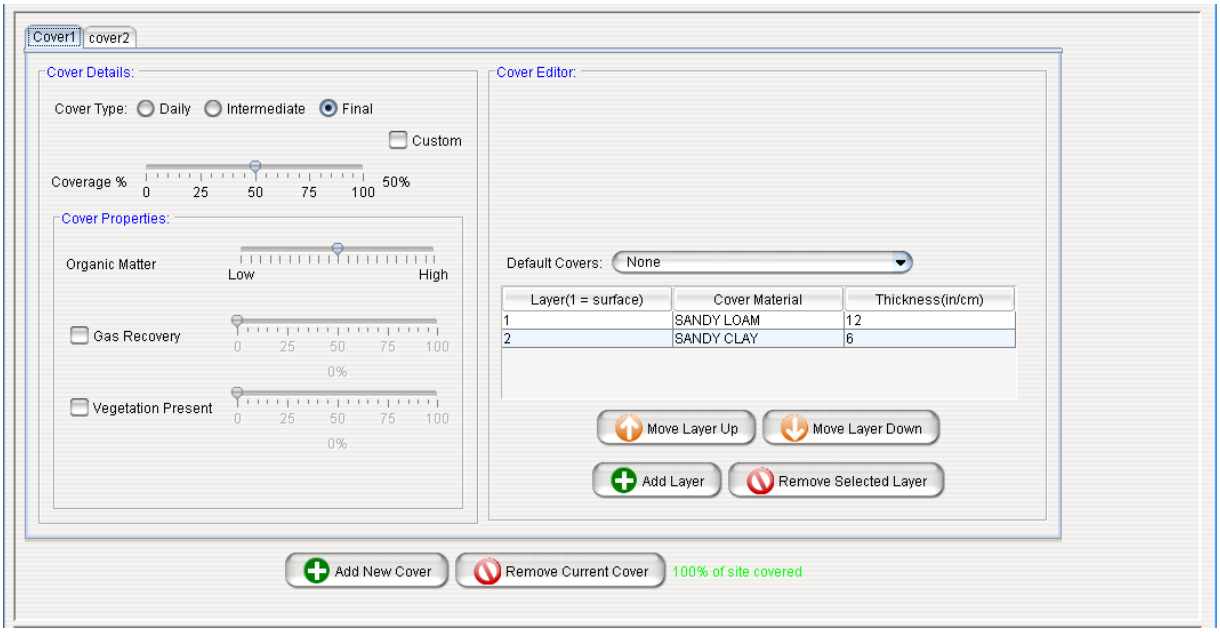
These features were part of the MapPanel class and were not modified.
See http://mappanel.sourceforge.net/ for additional information.

5.2.1 Location Selection from Maps

By clicking any location on the map, the model will automatically select that location (latitude and longitude) and enter them into the dialog box on the screen. The location will be shown with a blue circular dot.



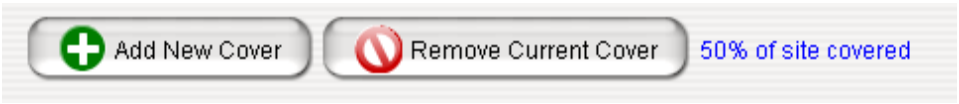
6.0 Cover Editor Panel



This panel allows the user to customize up to 10 different cover configurations for the site.

6.1 Cover Tabs

There are two main buttons to add or delete covers from the model:



1. ***Add New Cover button*** 

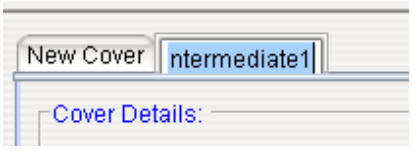
The user should use this button to add a new cover to the model. Up to 10 different cover designs can be entered per site within a single model run. If additional cover designs are at the site, additional model runs would be necessary.
The program will prompt the user for a name for the cover as shown below:

The name should be descriptive enough for the user to identify the cover in the output, for example “Intermediate1” or similar. This new cover will then appear as a tab as shown in the figure below.

The user can switch between cover types by clicking on the respective tabs for the various covers.

Renaming Cover Tabs

By double clicking on the tabs, the user can rename the various cover tabs. This will highlight the tab to allow a new cover name to be entered.

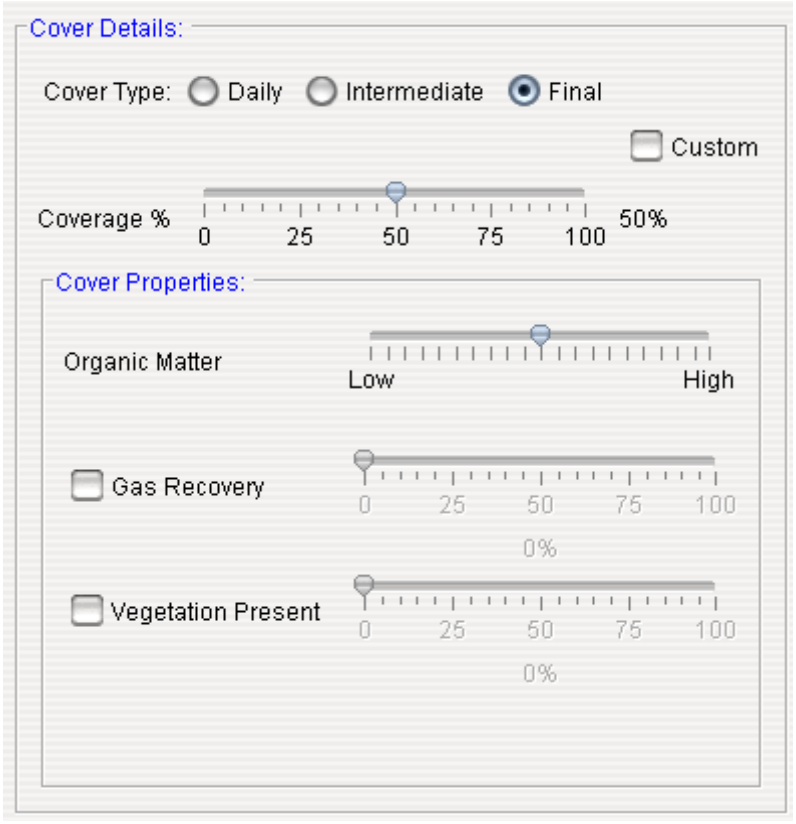


2. ***Remove Current Cover*** 

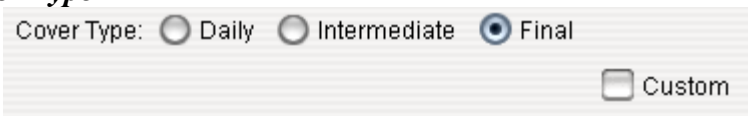
This button will remove the currently selected cover tab. The model will not allow the user to delete the last tab as one model tab is required for the model to run. Before deleting any cover, the model will confirm the delete with the user using the dialog box shown below:

The name of the selected cover will appear in the dialog box in place of **Interemdiate1** in the example dialog above.

6.2 "Cover Details" Section of Panel

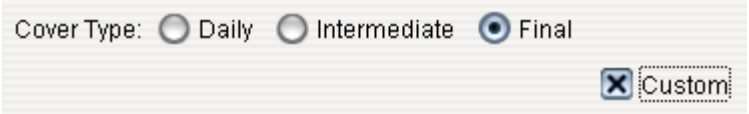


6.1.1 *Cover Type*

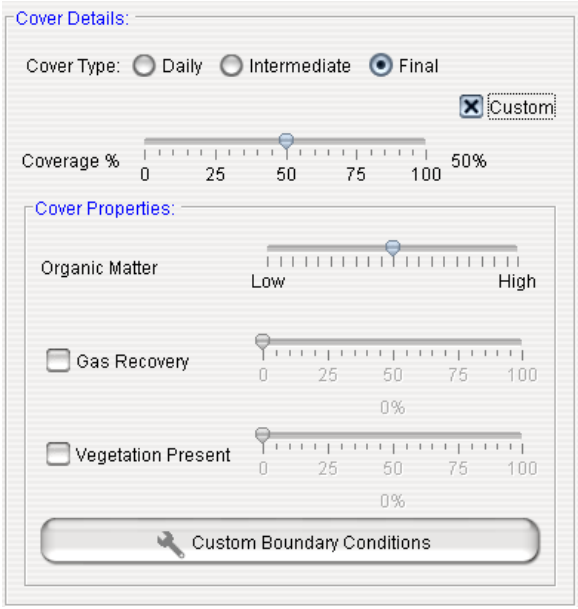


These 3 buttons allow the user to select the basic cover type. Please note that this selection determines default boundary gas concentrations, default temperature profiles, and maximum methane oxidation rate for each cover type (See Appendix A).

There is also the selection for a "Custom" cover type, which is selected by checking the Custom checkbox:

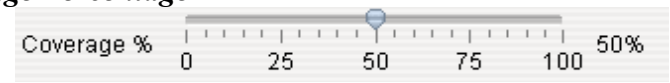


When the custom cover type is selected the model displays the "Custom boundary conditions" button:

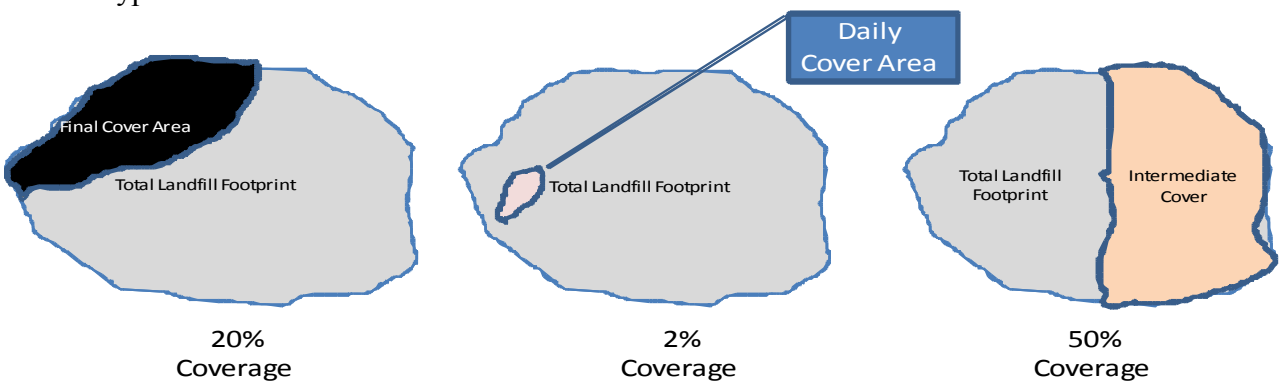


The features of this button are described later (section 6.5)

6.1.2 *Coverage Percentage*



This slider bar allows the user to specify the percentage of the waste footprint that this cover represents. For example, as shown in the figure below, the percent coverage for different representative areas of the hypothetical landfill:

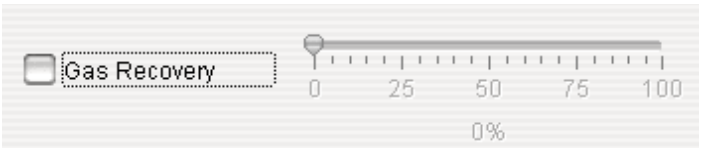


6.1.1 *Cover Properties*

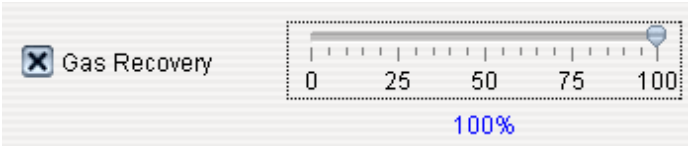
a. Organic matter (slider bar)

This selection controls the amount of organic material that the model uses for calculation of the soil properties (see below). High Organic material cover materials would be those amended with sewage sludge, compost, wood chips, or other organic wastes. This slider bar from Low to High represents a range of 0 to 5% organic matter.

b. Gas Recovery System Information

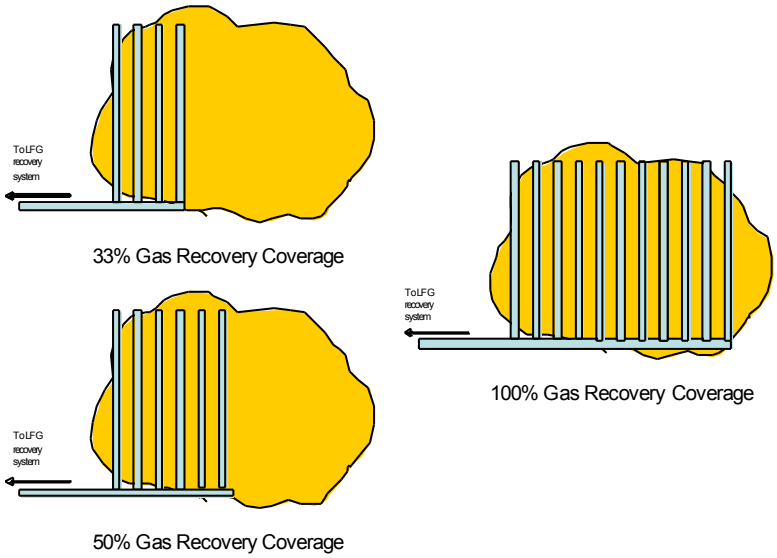


If a gas recovery system is present, the user should select the **Gas Recovery checkbox**, which will enable the gas recovery slider bar as shown below:



NOTE: This percentage is NOT the estimated efficiency of the gas recovery system.
Instead, this percentage represents only the areal coverage of any gas recovery system
for a particular cover type.

The user should select the percent of the area for this cover type which has a gas recovery system in place (vertical wells, horizontal collectors, or combination). Some examples are given below.



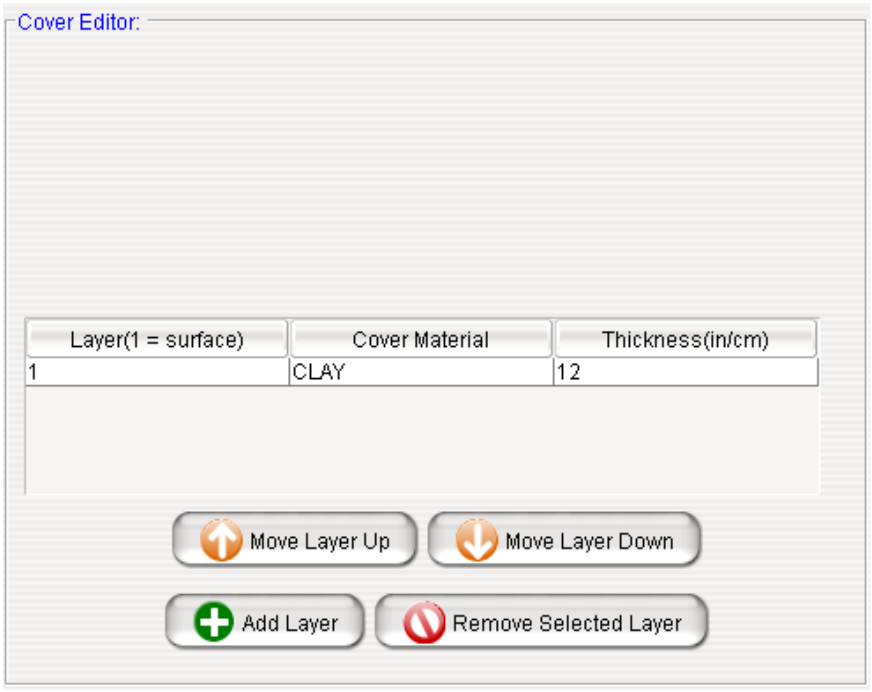
c. Vegetation Present

Similar to the gas recovery system coverage, the user is requested to enter the % vegetation cover.

If there is vegetation present on the cover type, then the user should select the "Vegetation Present" checkbox, which will enable the vegetation present scroll bar.

The user should use the scroll bar to enter the approximate average annual vegetation coverage for this cover type. This is an estimate of the percentage of the surface area which is typically covered by vegetation.

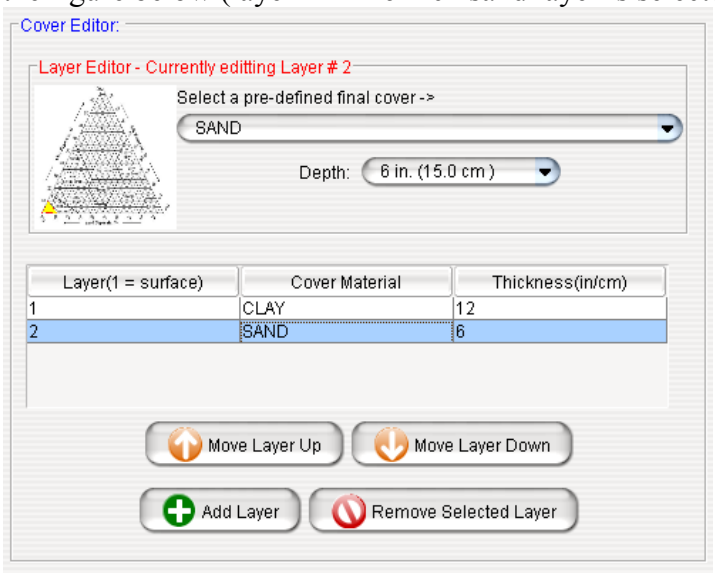
6.2 Cover Editor



6.2.1 Highlighting a layer in the cover editor

To highlight a layer:

Position the mouse over any element (layer number, cover material, or thickness) and press the mouse button. The selected layer will be highlighted in blue as shown in the figure below (layer #2 → 6 inch sand layer is selected):



1. **Move Layer Up** 

This option is only functional with two or more layers.

This button moves the selected layer closer to the surface (up).

2. Move Layer Down 

This option is only functional with two or more layers.
This button moves the selected layer closer to the base of the cover (down).

3. Add Layer 

This option adds a new layer (default layer is 6 inches of clay).

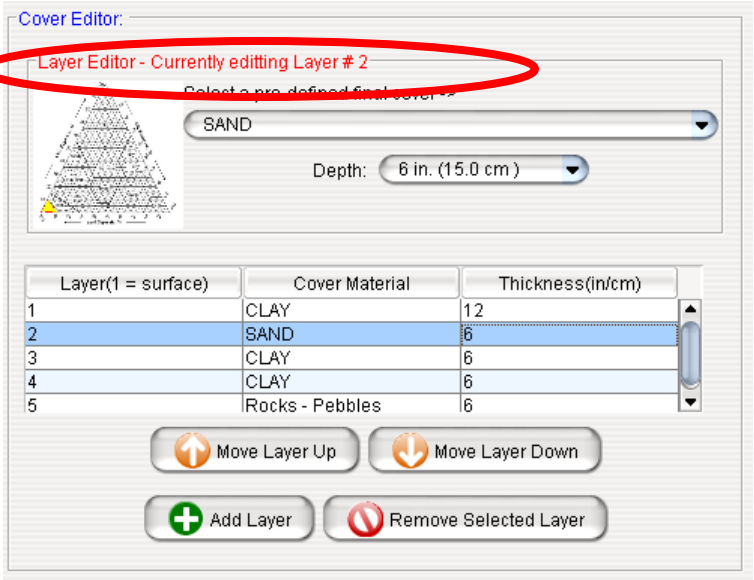
4. Remove Selected Layer 

This button removes the selected (highlighted) layer in the cover editor.

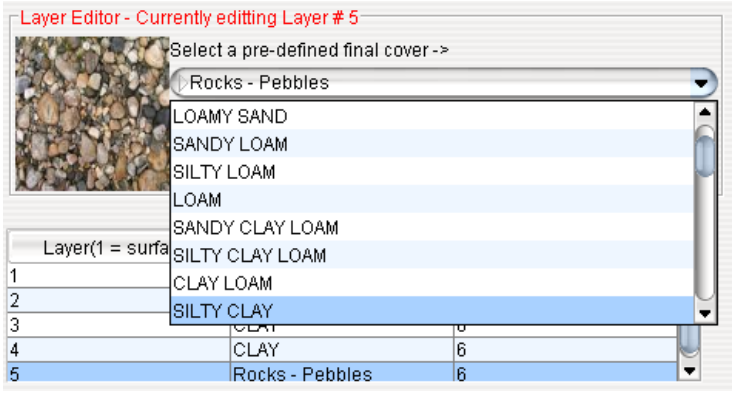
6.2.2 *Cover Layer Editor*

Once a layer is highlighted (see Section 4.2.1), the layer editor becomes visible for that respective layer.

Note: the title bar of the editor indicates which layer you are currently editing. See circled area in figure below.

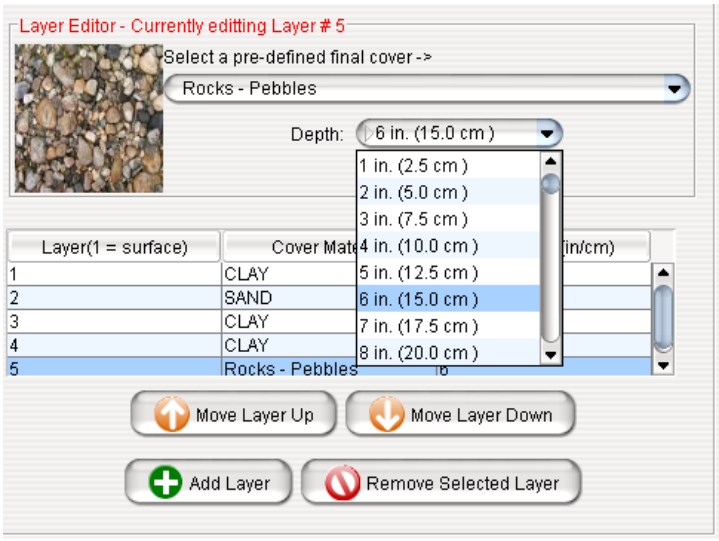


Once the layer editor is enabled by highlighting the respective layer, the user makes a selection among the 12 USDA soil texture classifications or among 21 other alternative choices through the pull-down combo box. The alternative choices are alternative daily cover (ADC) materials and non-soil materials, including geomembranes. The model will display either the section of the textual triangle selected (USDA soil types) or a representative picture of the cover material selected. See Appendix A for the physical properties (default values) for the various materials.



(Combo box for material selection is shown expanded)

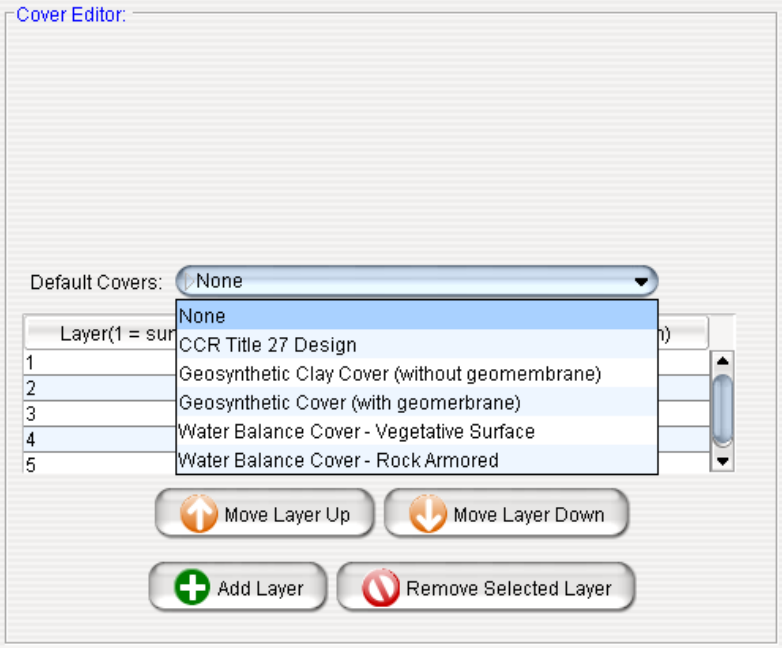
After the material is selected for a particular layer, the thickness of the layer should be specified with the pull-down combo box as shown in the figure below. The maximum thickness for an individual layer is 100 inches (254 cm). Some of the specialized materials have a fixed thickness which cannot be changed by the user (e.g. geomembrane).



(Combo box for thickness selection is shown expanded)

6.4 Default California final cover types (only for Final Cover).

When the user selects the "Final cover" type, an additional pull-down combo box is displayed with the 5 default California final cover types.



Details for these final cover types are given in Table 6.1 below. If the cover conditions deviate from these values, each layer should be entered individually as discussed above, rather than selecting the default design.

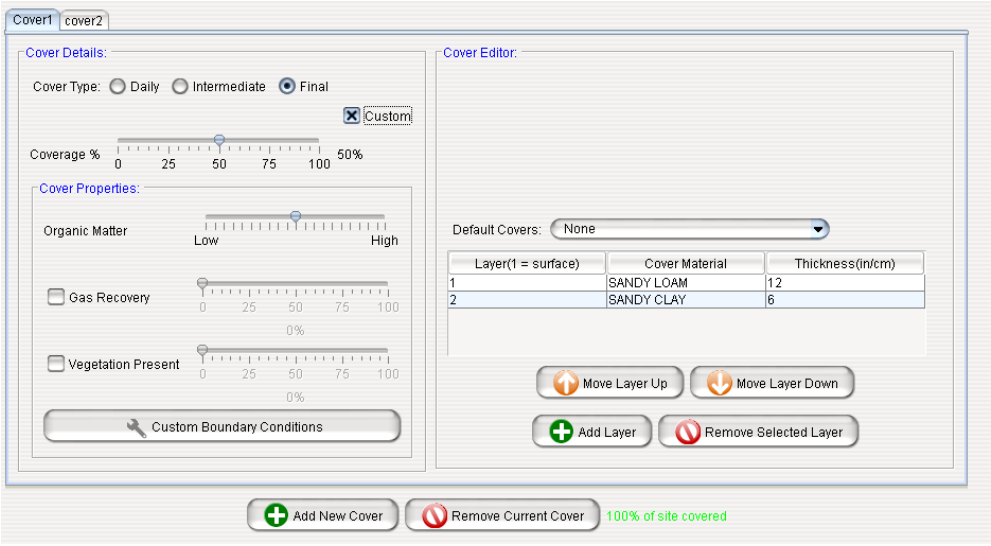
Table 6.1. Settings for Default Final Cover Types

Layer	*CCR Title 27*	*Geosynthetic Clay (without geomembrane)*	*Geosynthetic Cover (with geomembrane)*	*Water Balance (Vegetation Surface)*	*Water Balance (rock armored)*
1	Loam (12 inches)	Loam (12 inches)	Loam (12 inches)	Loam (12 inches)	Rocks/Boulders (6 inches)
2	Clay (12 inches)	Clay (40 inches)	HDPE geomembrane (1 inch*)	Silty Clay Loam (36 inches)	Loam (12 inches)
3	Silty Clay Loam (24 inches)	Silty Clay Loam (12 inches)	Silty Clay Loam (24 inches)		Silty Clay Loam (36 inches)
Vegetation (%)	50	50	50	50	0

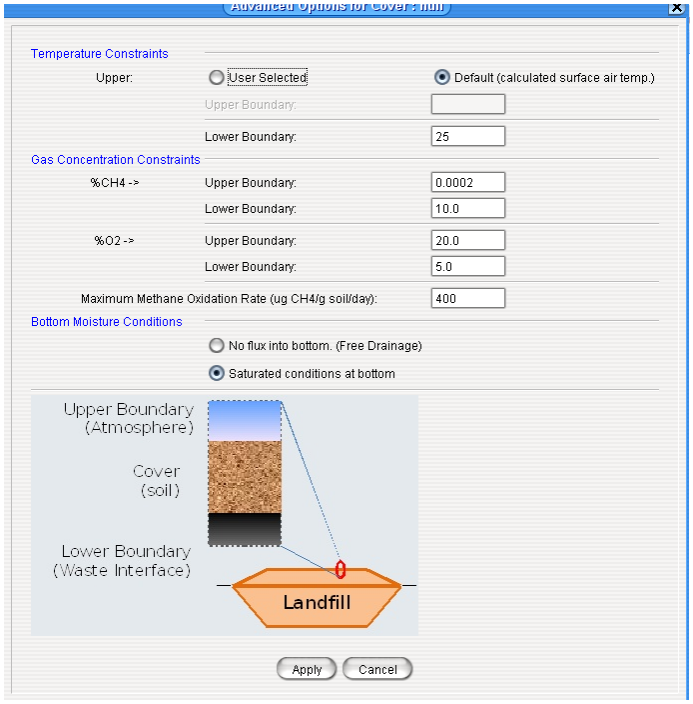
Notes:
* -indicates required minimum thickness for CALMIM for a soil layer (1" – 2.5 cm)

6.5 *Custom boundary conditions*

If the "Custom" checkbox is selected, the user can override the existing default boundary conditions for a given cover type (daily, intermediate, or final; See Appendix 1). The "**Custom Boundary Conditions**" button will be displayed in the cover editor panel as shown below:



When the user clicks on the "Custom Boundary Conditions" button, the dialog box below is displayed.



These options allow the user to change the boundary conditions for the modeling, including:

- Temperature profile (upper and lower temperatures)
  - Atmospheric temperature (Air temperature)
    - Fixed or simulated air temperature
  - Temperature at Cover/Waste interface (at top of refuse beneath the cover)

- Gas concentration profiles for methane (CH_4):
  - CH_4 concentration in air at ground surface (atmospheric CH_4)
  - Soil gas CH_4 concentration at Cover/Waste interface (at top of refuse beneath the cover)

- Gas concentration profile for oxygen (O_2):
  - O_2 concentration in air at ground surface (atmospheric O_2)
  - Soil gas O_2 concentration at Cover/Waste interface (at top of refuse beneath the cover)

- Maximum CH_4 oxidation rate

- Bottom moisture conditions
  - Saturated or free drainage

Temperature profile (upper and lower temperatures)

The upper limit can be a user-selected constant value ("User Selected") or the variable air temperature from the weather simulation. The latter is recommended.

The lower boundary is held constant at the designated set point.

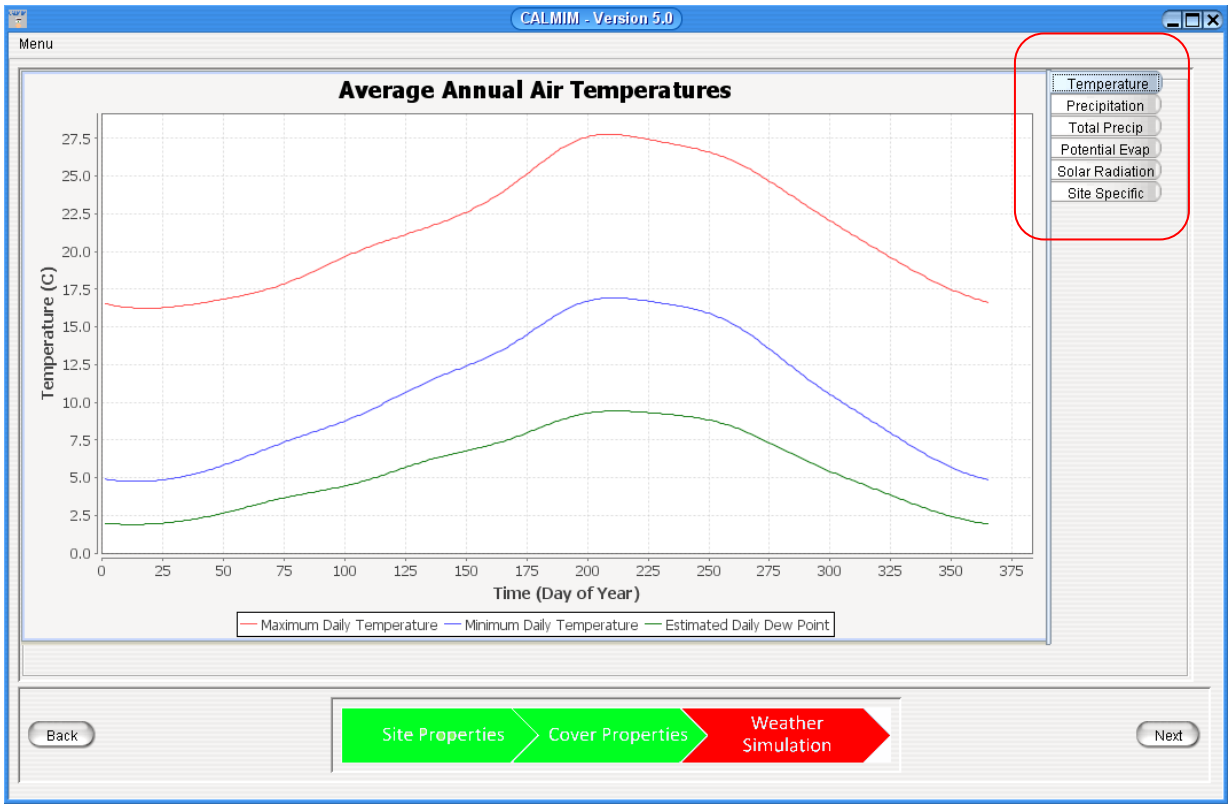
Gas Concentrations:

The concentrations of methane and oxygen are both specified (in percent by volume) for the upper boundary (concentration in atmosphere) and the lower boundary (soil gas concentration at the base of cover – the cover/waste interface)

Bottom Moisture Conditions:

The saturated condition at the bottom of the cover is the default boundary condition, since the field state for the waste/soil interface is typically saturated due to the high humidity of the landfill gas. However, the user could change this to a free drainage condition. The upper moisture condition is controlled by the simulated weather (either evaporation or precipitation) and cannot be changed by the user.

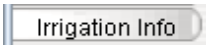
7.0 Weather Simulation Screen

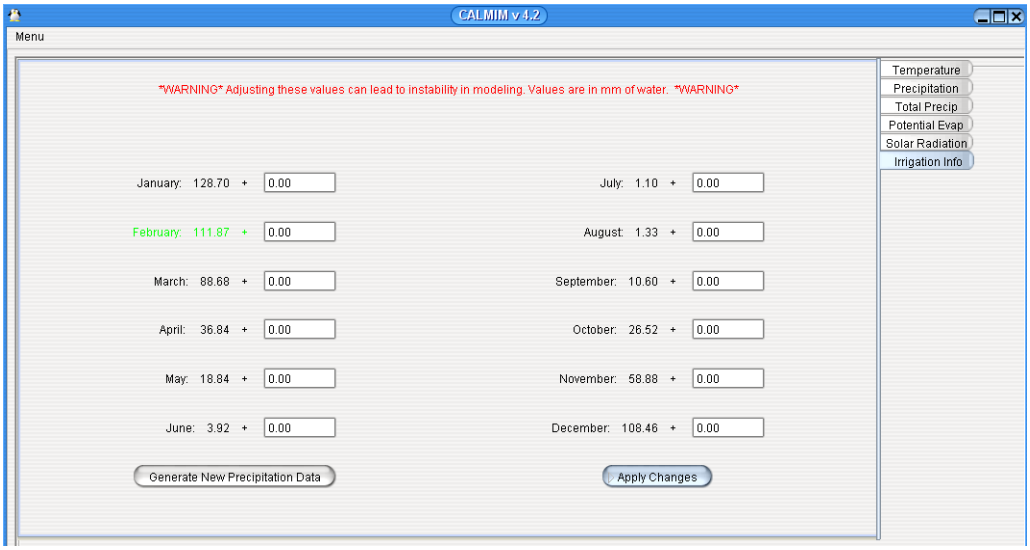


The weather simulation panel displays the results of the weather simulation for the site as individual graphs. Each graph can be viewed by selecting the respective tab at the upper right side of the screen (see circled tabs above).

The graphical libraries used in this program are from JFreeChart
(http://www.jfree.org/index.html)
and the user is encouraged to visit the webpage
(http://www.jfree.org/jfreechart/api/javadoc/index.html)
for further information on the available graph options.

7.1 *Irrigation Info Tab (Advanced Mode Only)*

The ”Irrigation Info”  is only displayed when the user selects “Advanced” mode (See Menu Options – Section 4). The irrigation tab allows the user to enter monthly irrigation totals (in mm of water) for sites where irrigation is practiced:

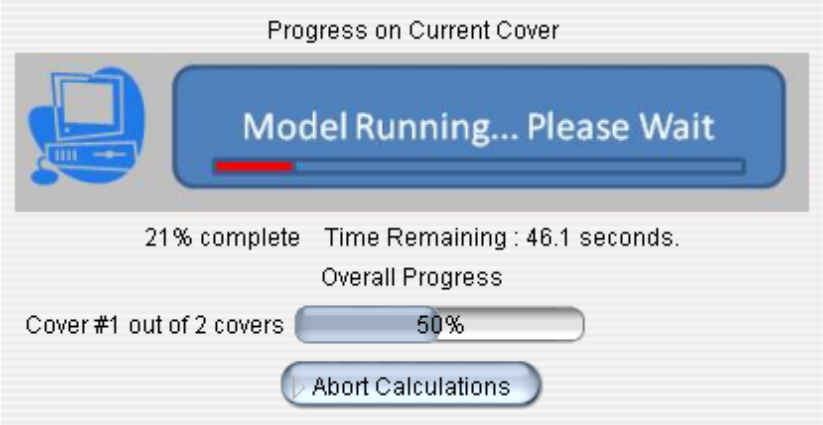


The user should input the total monthly amounts of irrigation water (in mm of water) for the month in the respective textbox, and then select “Apply Changes” to apply the new irrigation amounts. The model will display the new monthly totals and highlight (in green) those which were updated.

The other button (“Generate New Precipitation Data”) will erase the previous irrigation data so that the user can generate a new set of precipitation data. This should be selected if the user made a serious mistake in entering data and wants to start over.

8.0 Model Calculation Screen

While the model is calculating the following screen is displayed:

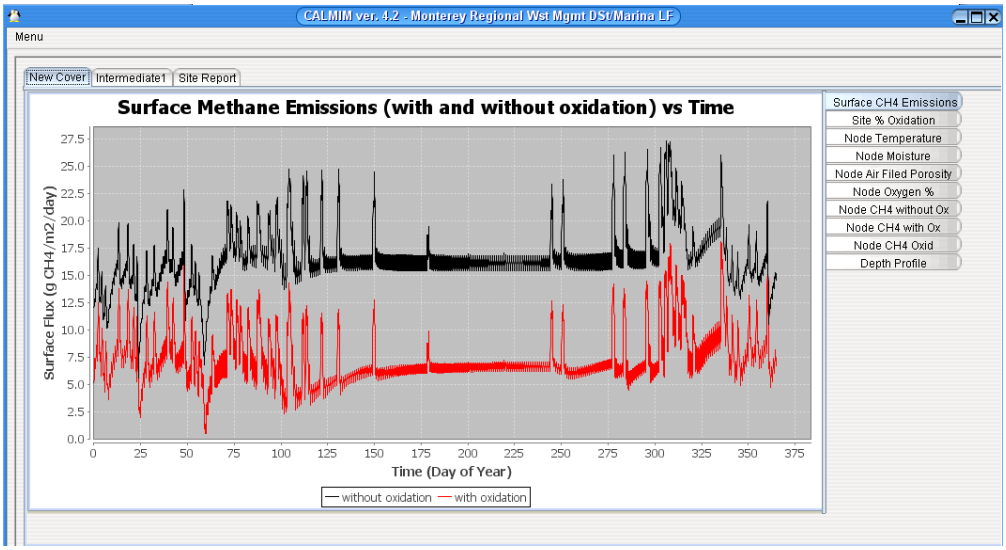


This dialog box displays progress for model calculations for the current cover, along with the estimated time remaining for that cover. It is important to note that the time remaining only applies to the current cover and not to the entire model run.

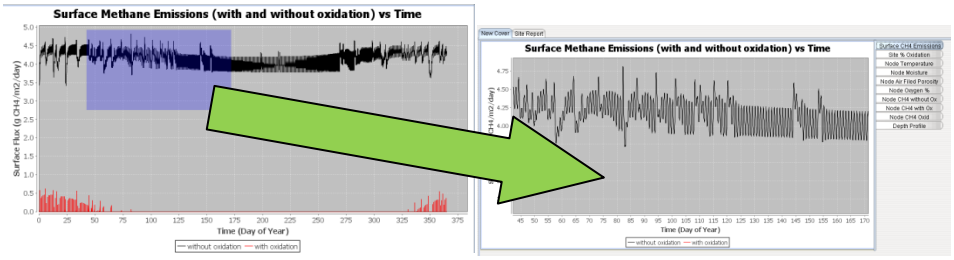
The progress bar at the top indicates model progress for the total number of covers entered by the user. The abort calculation button allows you to abort the run and exit the program. No intermediate data from the calculations are stored. The model could be restarted by using the "**Open the last updated site model"** (See Section 3) to restart the model.

9.0 Final Results Screen

After the model has completed the calculations, the final screen is displayed:

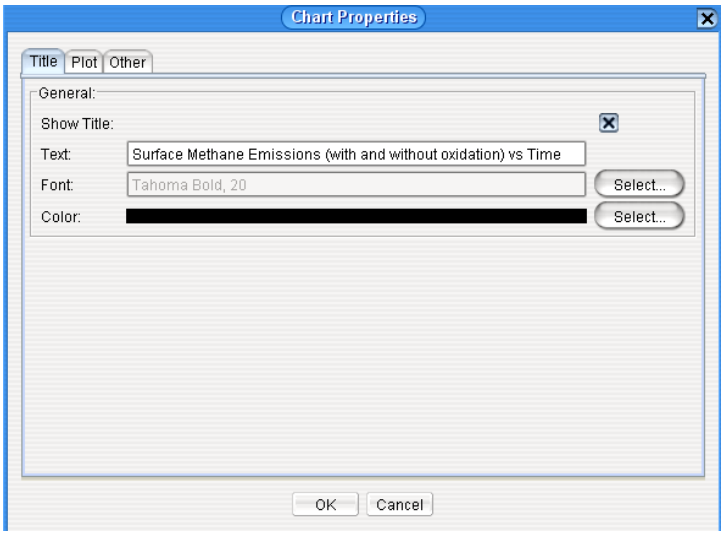


A number of different graphs can be individually viewed for each cover type by selecting the tabs at the upper right side of the screen. Each of these graphs will be described individually in the following pages. The user can navigate through the various cover types by selecting the corresponding tab along the top of the screen panel. In addition, there is a "Site Report" tab, which summarizes the results for the site.
In addition, the left mouse button can be used to click and drag in order to zoom-in on an area of interest as shown below: here the highlighted region (purple/blue) is being zoomed to the size of the graph at the right after release of the left mouse button.



For each of the graphs, when the mouse is on the graph, the user can press the right mouse button to display an option menu for the figure :

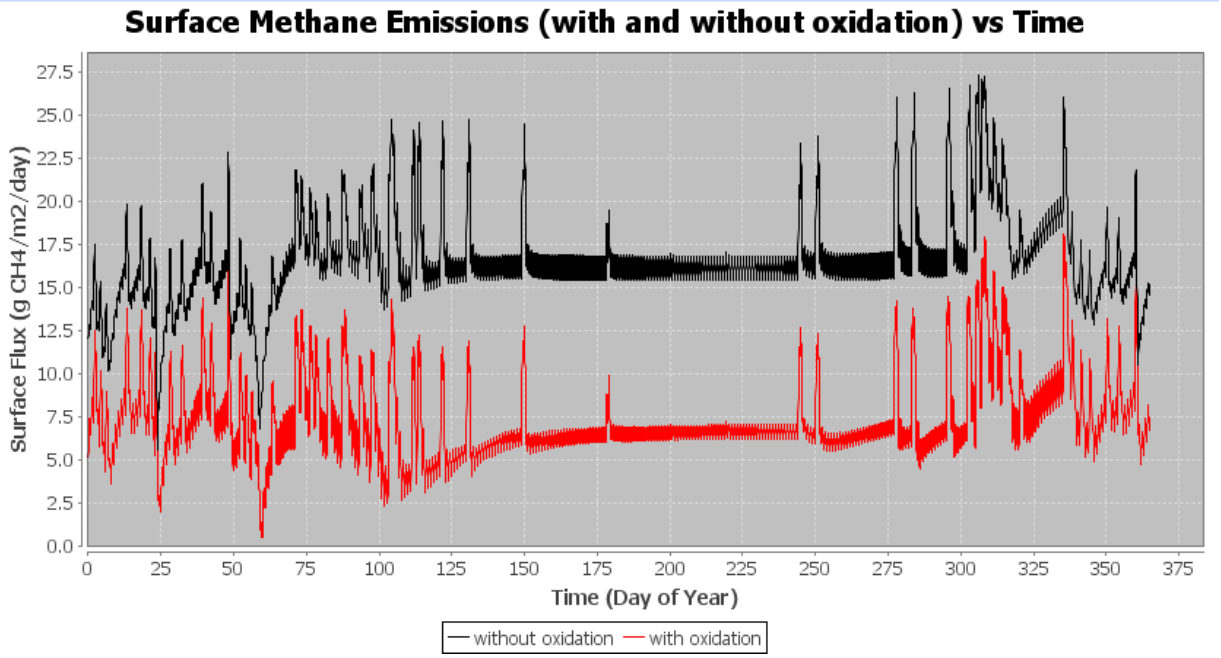
Selecting "Properties…" brings up the properties screen, where the user can change and alter the appearance of the graphs.



The "Save as" and "Print" functions will allow any particular graph to be saved or printed for future reference.

The graphical libraries used in this program are from JFreeChart
(http://www.jfree.org/index.html)
and the user is encouraged to visit the webpage
(http://www.jfree.org/jfreechart/api/javadoc/index.html)
for further information on the available graph options.

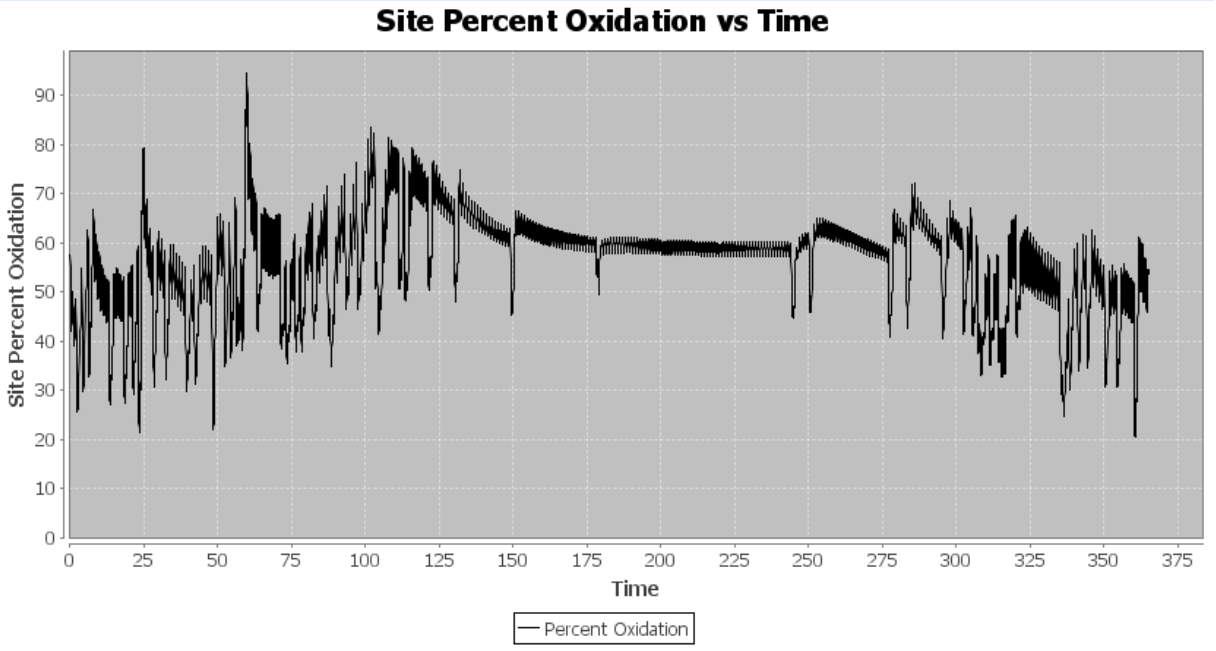
Surface CH4 Emissions *-Predicted Surface Methane Emissions for a Selected Cover*



This graph displays the variable surface emissions (10-min. time steps) for a typical annual cycle (365 days) both without methanotrophic methane oxidation (black line) and with methane oxidation (red line) included in the calculations. CALMIM calculates these separately so that the effect of oxidation (difference between the two plots) can be readily seen on this graph.

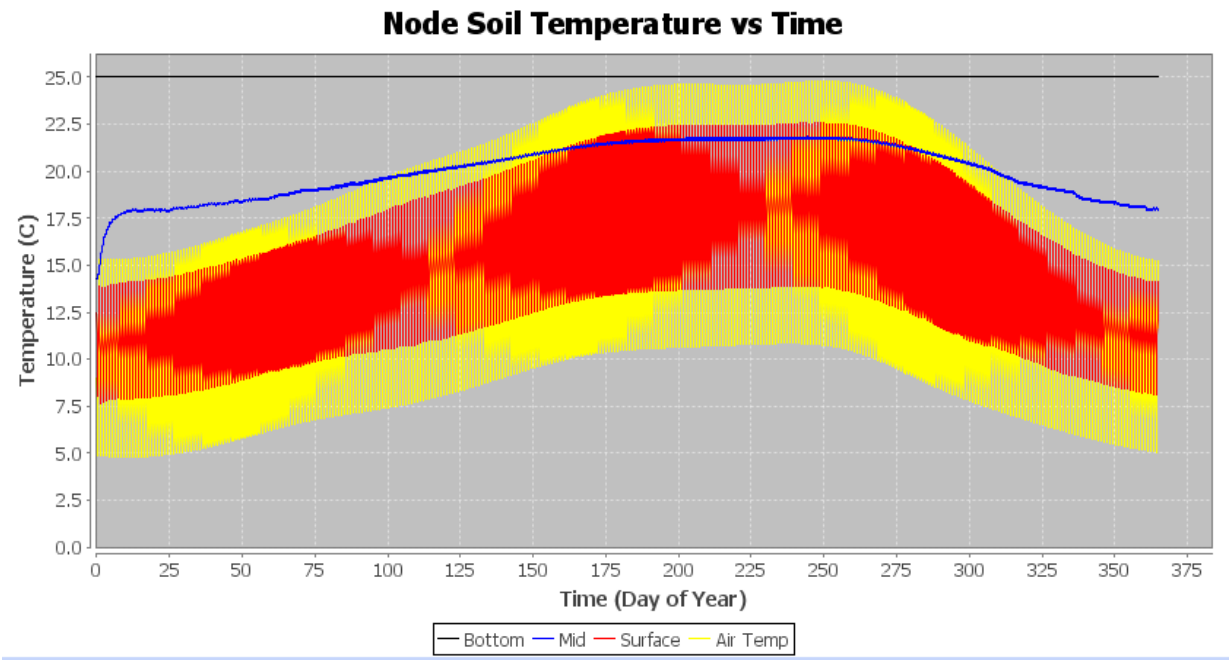
This graph clearly shows the high variability in emissions calculated by the model as a result of the variable soil moisture and temperature within the cover soil which affects both gaseous diffusion and microbial methane oxidation. The other output graphs provide additional information as discussed below.

Site % Oxidation ***-Predicted Percent Oxidation for this Particular Cover***



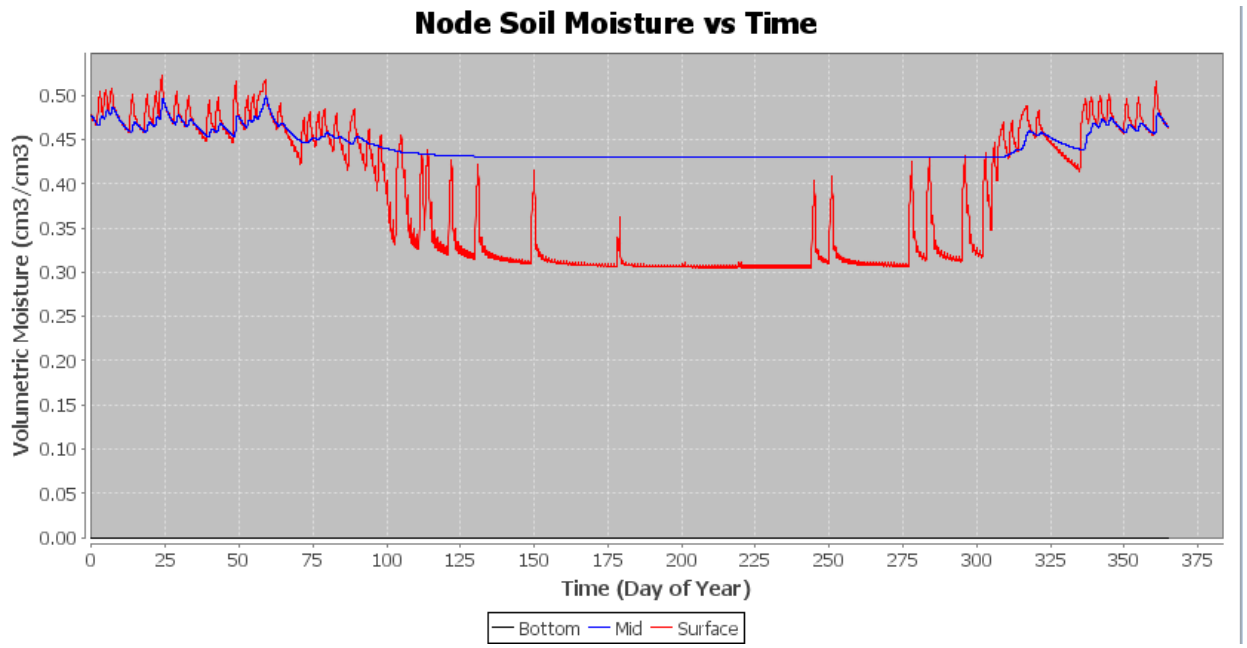
This graph illustrates the calculated percent oxidation as a result of the variable temperature and soil moisture conditions in the landfill cover materials. The percent oxidation is calculated from the difference between the two methane emission plots (with and without oxidation) shown above. This graph plots the percent of emissions at each time step "without oxidation" which is represented by the emissions at that time step "with oxidation." Thus, this graph shows the net total effect of comparing surface emission values with and without oxidation.

Node Temperature ***-Predicted Temperature of each Node***



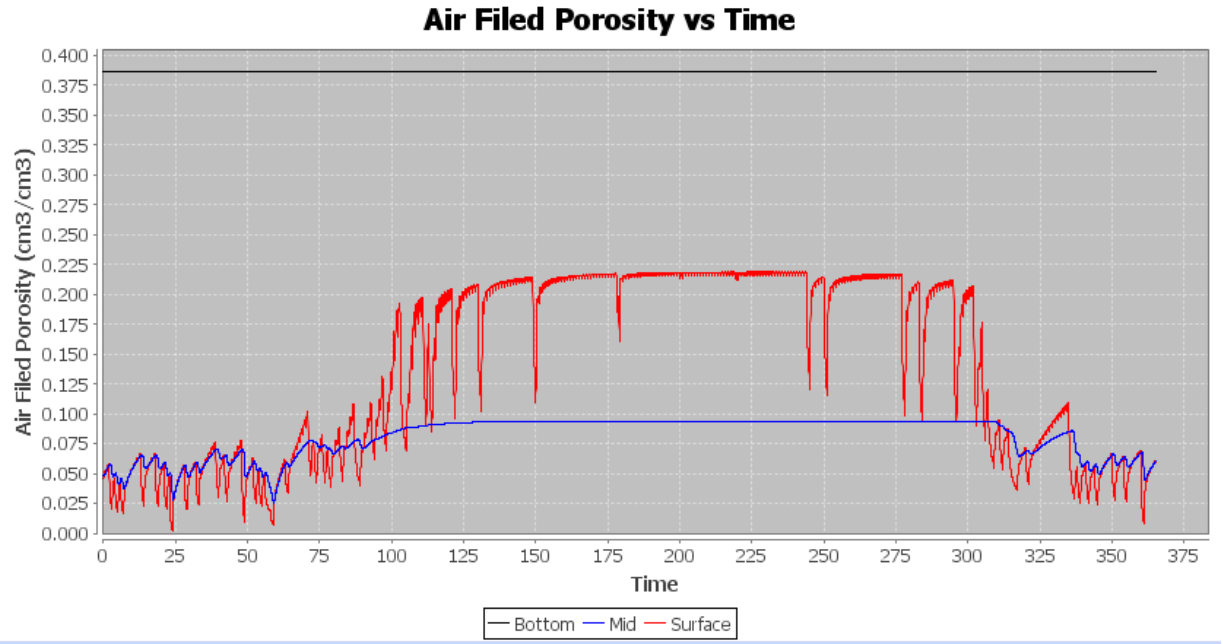
This graph illustrates the surface, mid and bottom node soil temperatures at these 3 respective depths for the selected cover.

Node Moisture ***-Predicted Soil Moisture (volumetric) of each Node***



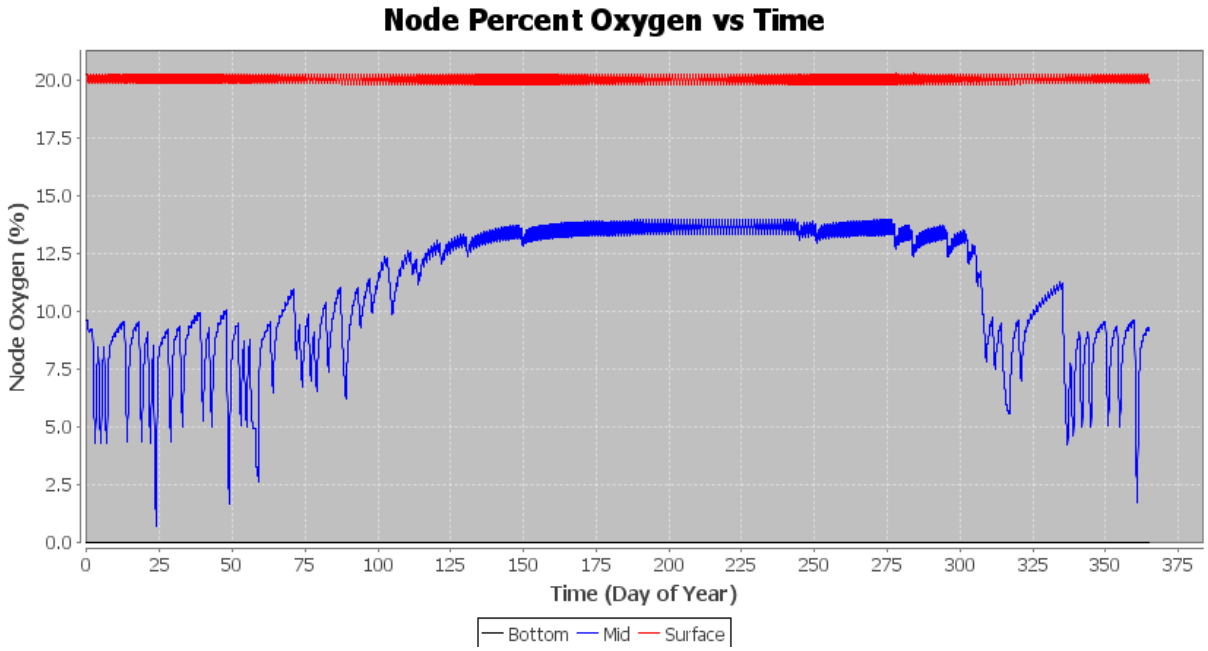
This graph display the surface, mid and bottom node results for volumetric soil moisture at these 3 respective depths for the selected cover.

Node Air Filed Porosity ***-Predicted Air-Filled Porosity of each Node***



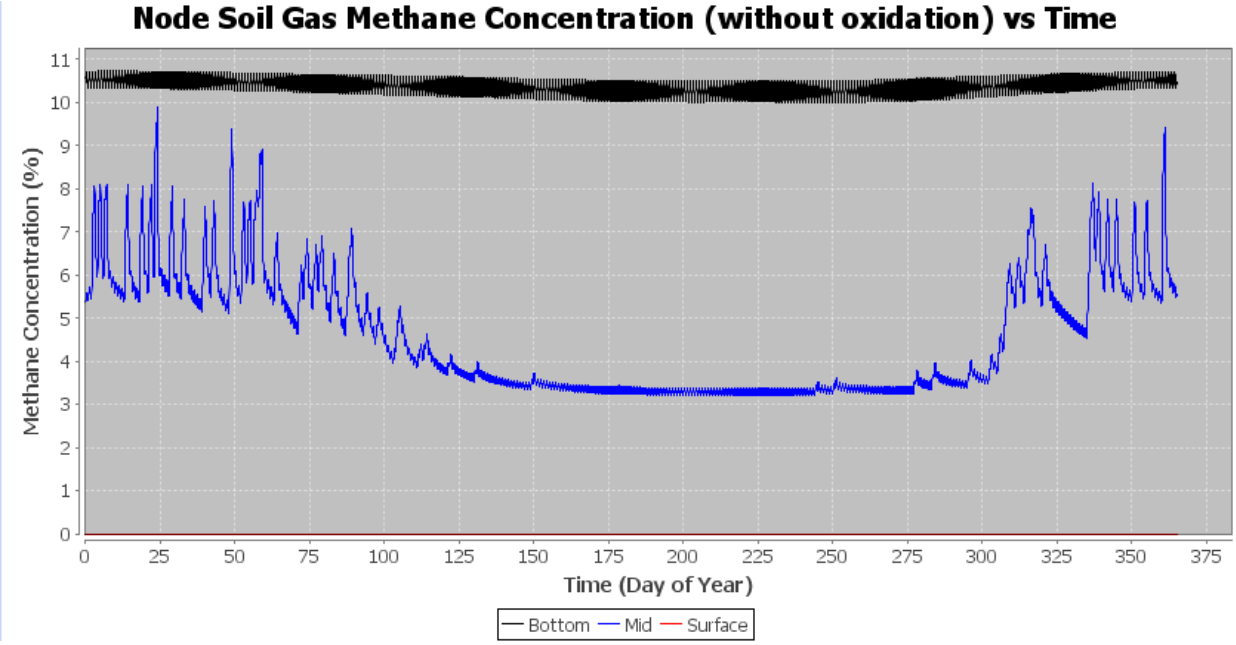
This graph illustrates the surface, mid and bottom node alterations in air-filled porosity at 3 depths for the selected cover. Air-filled porosity changes as a function of the fluctuating soil moisture conditions.

Node Oxygen % ***- Oxygen Concentration within each Node***



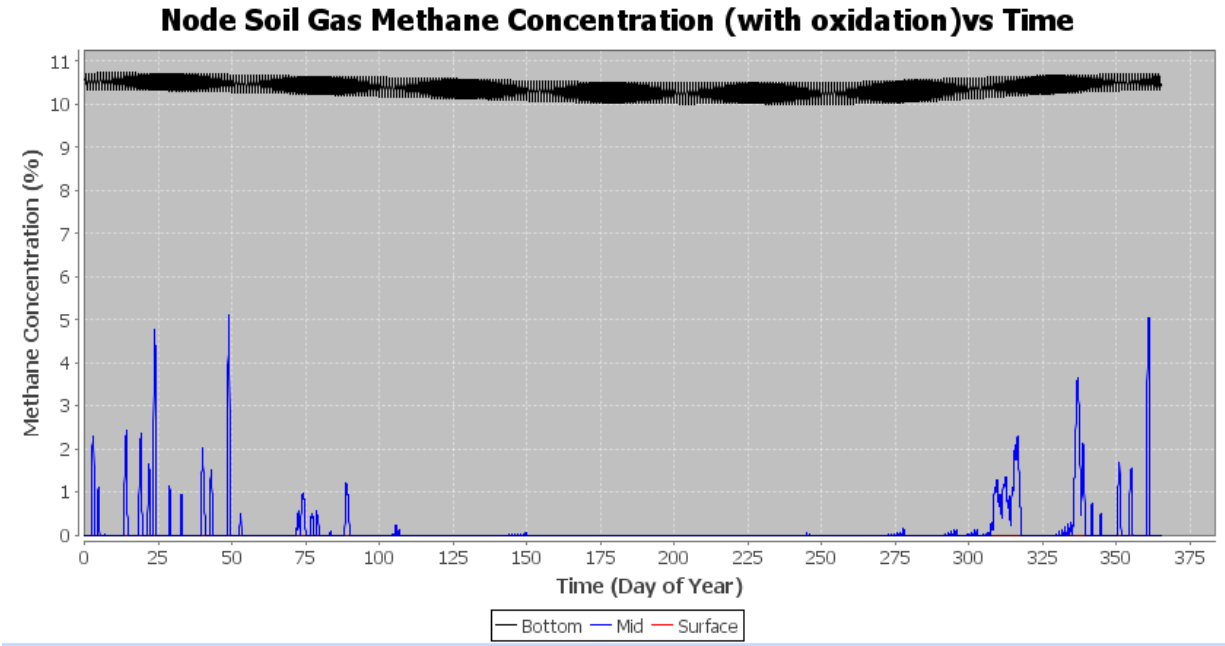
This graph illustrates the surface, mid and bottom node results for soil gas oxygen concentrations (V%) at these 3 respective depths for the selected cover. This value is an indication of the aeration status of the cover soil.

Node CH4 without Ox ***- Methane Concentration within each Node without Methane Oxidation***



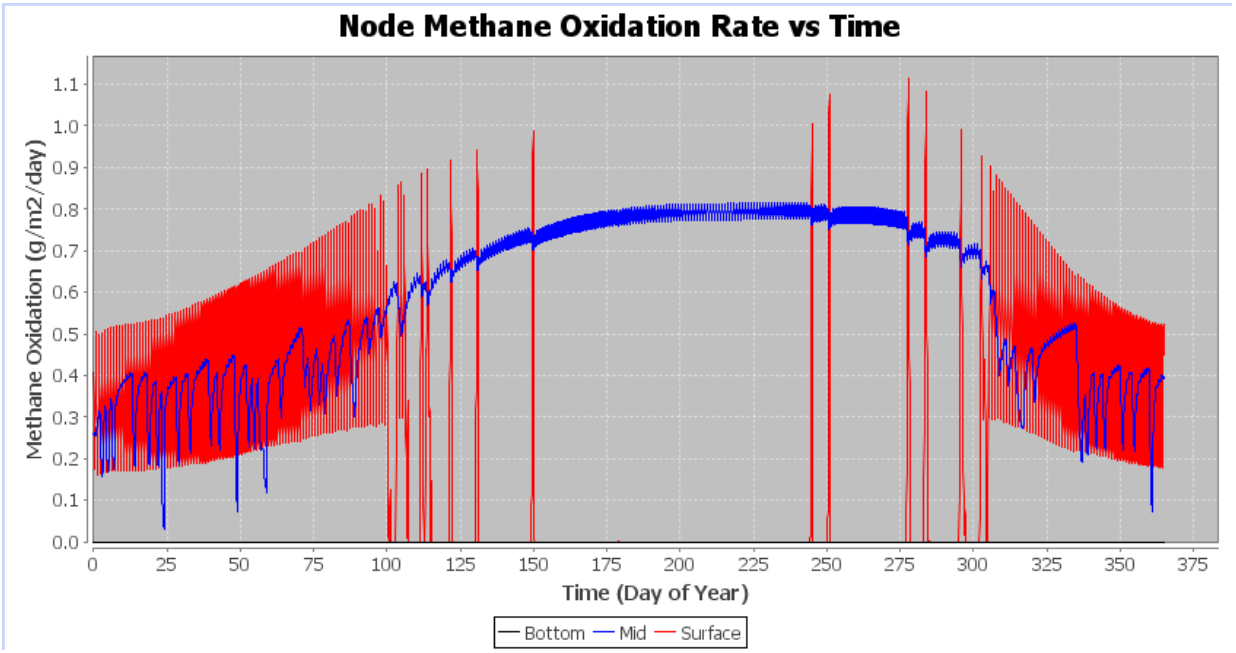
This graph illustrates the surface, mid and bottom node results for soil gas methane concentration (V%) without methane oxidation at these 3 respective depths for the selected cover.

Node CH4 with Ox ***- Methane Concentration within each Node with Methane Oxidation***



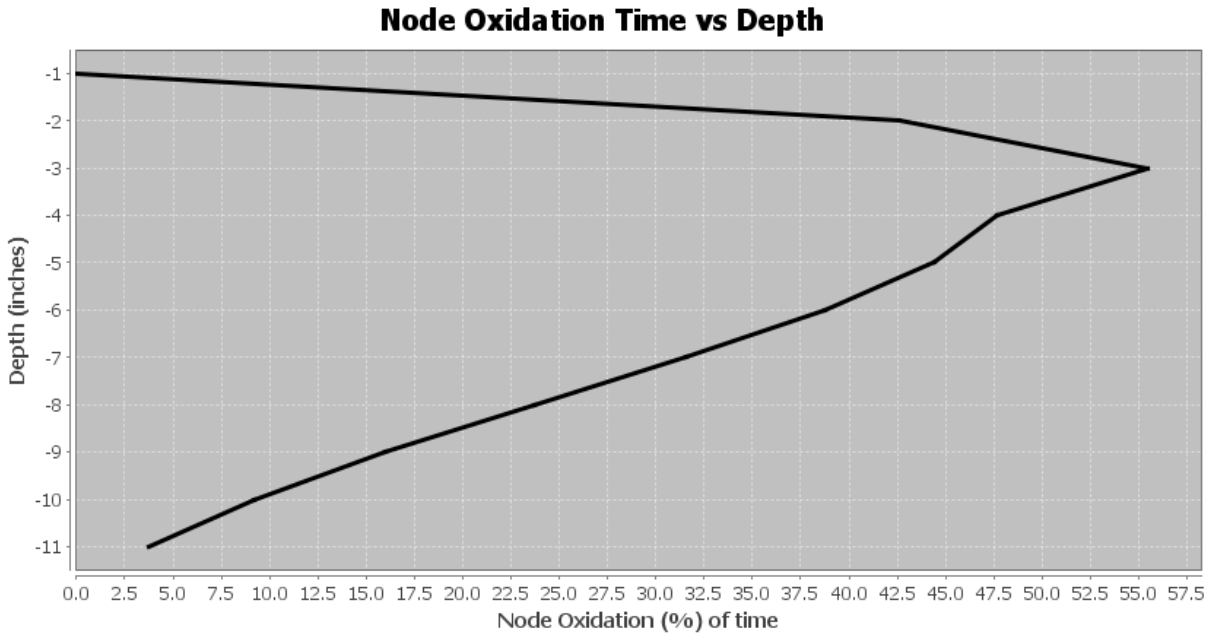
This graph illustrates the surface, mid and bottom node results for soil gas methane concentration (V%) with methane oxidation at these 3 respective depths for the selected cover. methane concentrations with methane oxidation. Note the drastic difference in methane concentrations between the "with" and "without" methane oxidation scenarios. Also note the highly variable methane concentration in the middle layer of this particular cover.

Node CH4 Oxid ***- Percent Oxidation within each Node***



This graph illustrates the total methane oxidation rate per node (in units of g CH_4 m^{-2} day^{-1}) at the same 3 respective depths for the selected cover. Note that this is calculated separately for each node and is NOT the methane surface emissions.

Depth Profile - ***Depth Profile of Methane Oxidation***



This graph illustrates the percentage of time (over an annual cycle) that each node over the total depth of a selected cover is capable of oxidizing methane.

10.0 Change Log

Version 5.0A ::

- 100” per cover limitation removed
  - The only cover thickness limit now is how much hard drive space is available.
  - 1000” (one thousand inches, all layers summed) equates to about 1200 MB of data.
- File management changed
  - Overview.xls – Contains run setup information, plots, and Daily Weather data
  - HourlySurfaceEmissions.csv – Unchanged
  - All other sets of data are now stored in their own files, not as sheets in Overview.xls
  - Data files – If the sum of all layers in a cover exceeds 254 inches the data files will be saved as CSV files instead of XLS files. This is a limit of the XLS format.
  - New directory structure: **CALMIM-DataOutput\SiteName\ Cover_Dec-19-2011_1609**
    - The time stamp is the date and time when the simulation was started
    - Following the date is a time string 1609 = 4:09 pm
- Custom weather files can now be used (more changes after the images)

Version 5.0B

- Directory fix for Windows Vista/7, no effect on the output
- Added weather data source to the overview file
- Fixed the advanced menu option, the Irrigation tab on the Weather Panel will now consistently show up

Version 5.0C

- Fixed typo, "Air Filled" was spelt "Air Filed"
- Added units to the upper and lower labels, °C
- Automatically saves the current run's settings to …\My Documents\CALMIM-DataOutput\Run_MMM-DD-YYYY_HHmm.CMM
- Corrected an error in the simulated data, data early at the beginning of the year was significantly off and took some time to equilibrate
- Runs with multiple covers will generate a single overview file in addition to all other files normally generated. This file contains the general information from each Overview.xls file and is located in …\My Documents\CALMIM-DataOutput\<Site Name>\<Cover1 Name>.xls.

Version 5.1

- Added Google maps as an option to select the latitude and longitude. Google maps will be unavailable when no internet connection is present.
    - Click to place the location cursor
    - Double click to center the map about that point
    - Use the scroll wheel to zoom in and out

Version 5.2

Fixed installer program bug.

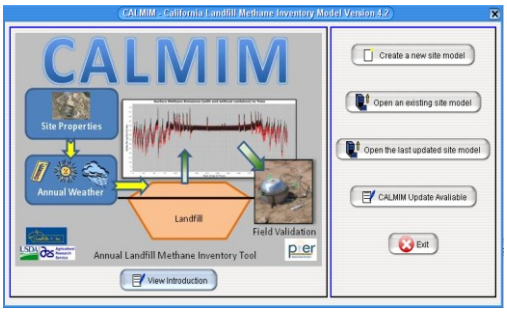
Version 5.3

First implementation of the map tile server for the location selection.

Version 5.4

Numerous structural/cosmetic improvements, additional computation capabilities, graphical interfaces, and other upgrades have been added to CALMIM during this project. Below is a listing of the most significant improvements:

- Improved main menu graphics and menu structures as shown in Figure.



Old Version

New Version

- Improved model performance through decreased run times. A major emphasis of this project was to reduce run-times. This has been accomplished: Currently, a 1.5 m cover takes about 6 minutes on a typical dual core (Intel i3 – 1.8GHz) processor.

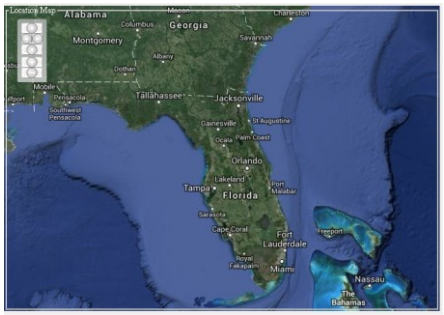
- Corrected minor bugs in the calculation modules to reduce memory leaks during program execution.

- Improved multi-platform capability (PC, MAC O/S, UNIX)

- Download section on ARS website now includes a specific MAC version with standard Mac O/S Installer

- Expanded ability to run 10 different covers concurrently for one site using 30 available materials (standard soil textures and alternative cover materials) for layered cover soils specified by user. Total cover thickness is limited by local computer resources (e.g., cover thickness >2.5 m requires 4+ GB memory)

- These include improved graphical interfaces, expanded automatic generation of output files and graphs, and more user-friendly features. Also included is the modernization of the GUI interface to the new JAVA standards. For example, the improved on-line map feature for site selection is shown in Figure.

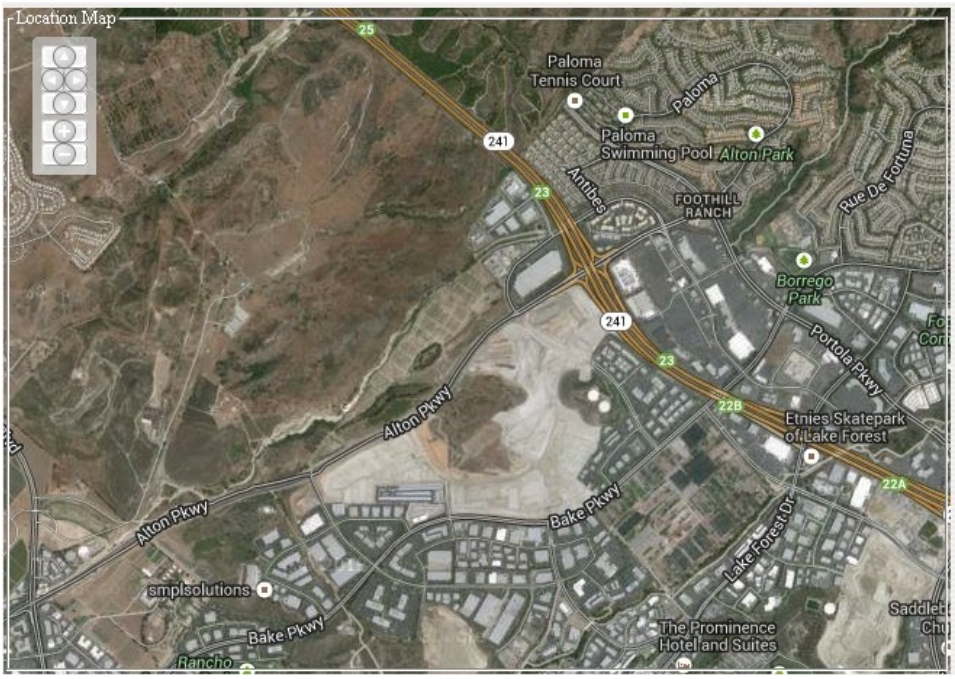


Old Version
(non-scrollable; non-zoomable)

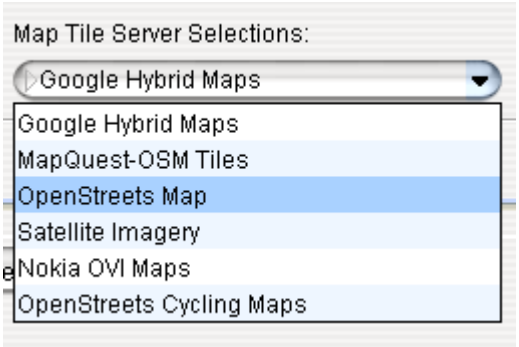
⇨

New Version
(Full zoom/scale operations)

- Satellite imagery is also provided through Google Hybrid Maps and OpenMapStreet sources for improving landfill site selection.



- Other map tile server possibilities were also added to the program (Figure 14), to give the user additional options for the level of detail in the displayed map.



With the exception of the Google Hybrid Maps, these map tile features are based on OpenStreetMap.

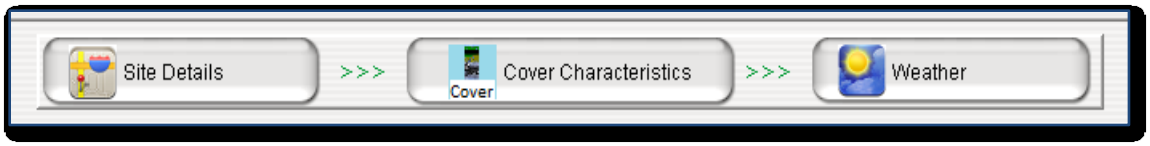
OpenStreetMap is *open data*, licensed under the Open Data Commons Open Database License (ODbL). The cartography in our map tiles, and our documentation, are licensed under the Creative Commons Attribution-ShareAlike 2.0 license (CC BY-SA). OpenStreetMap is "© OpenStreetMap contributors". Map data is available under the Open Database License, and if using our map tiles, that the cartography is licensed as CC BY-SA. (see this copyright page). Although OpenStreetMap is open data, we cannot provide a free-of-charge map API for third-party developers. See their API Usage Policy, Tile Usage Policy and Nominatim Usage Policy. Contributors to OpenStreetMap include thousands of individuals.

We also include openly-licensed data from national mapping agencies and other sources, including:

Austria: Contains data from Stadt Wien (under CC BY), Land Vorarlberg and Land Tirol (under CC BY AT with amendments).
Canada: Contains data from GeoBase®, GeoGratis (© Department of Natural Resources Canada), CanVec (© Department of Natural Resources Canada), and StatCan (Geography Division, Statistics Canada).
France: Contains data sourced from Direction Générale des Impôts.
Netherlands: Contains © AND data, 2007 (www.and.com)
New Zealand: Contains data sourced from Land Information New Zealand. Crown Copyright reserved.
South Africa: Contains data sourced from Chief Directorate: National Geo-Spatial Information, State copyright reserved.
United Kingdom: Contains Ordnance Survey data © Crown copyright and database right 2010-12.

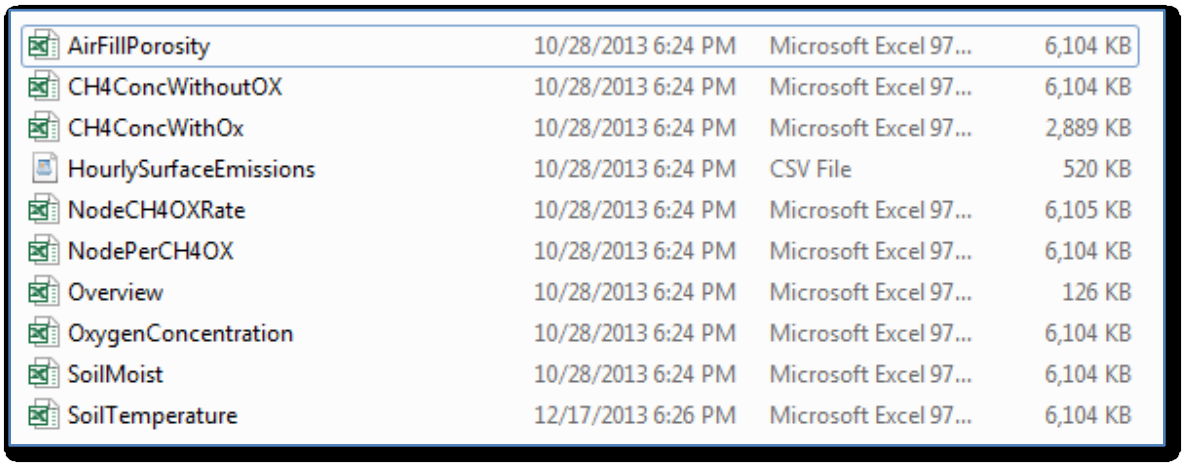
For further details of these, and other sources that have been used to help improve OpenStreetMap, please see the Contributors page on the OpenStreetMap Wiki. Inclusion of data in OpenStreetMap does not imply that the original data provider endorses OpenStreetMap, CALMIM or provides any warranty, or accepts any liability.

- Other new features include the following:
  - Added embedded unit conversions for metric system (i.e., site area in hectares).
  - Improved graphical buttons for quick positioning within the site wizard screens as shown in Figure 15.



- Improved data output directly into Microsoft Excel® compatible workbooks.

- Output directory format established to ensure ease of user data retrieval.
- Added generation of an "Overview" Excel file, which contains the pertinent information for each model run (Figure 16).



AirFillPorosity	10/28/2013 6:24 PM	Microsoft Excel 97...	6,104 KB
CH4ConcWithoutOX	10/28/2013 6:24 PM	Microsoft Excel 97...	6,104 KB
CH4ConcWithOx	10/28/2013 6:24 PM	Microsoft Excel 97...	2,889 KB
HourlySurfaceEmissions	10/28/2013 6:24 PM	CSV File	520 KB
NodeCH4OXRate	10/28/2013 6:24 PM	Microsoft Excel 97...	6,105 KB
NodePerCH4OX	10/28/2013 6:24 PM	Microsoft Excel 97...	6,104 KB
Overview	10/28/2013 6:24 PM	Microsoft Excel 97...	126 KB
OxygenConcentration	10/28/2013 6:24 PM	Microsoft Excel 97...	6,104 KB
SoilMoist	10/28/2013 6:24 PM	Microsoft Excel 97...	6,104 KB
SoilTemperature	12/17/2013 6:26 PM	Microsoft Excel 97...	6,104 KB

- Added on-line help (Microsoft based HELP file), which allows searches and improved linking with the program interface as shown in Figure 17.

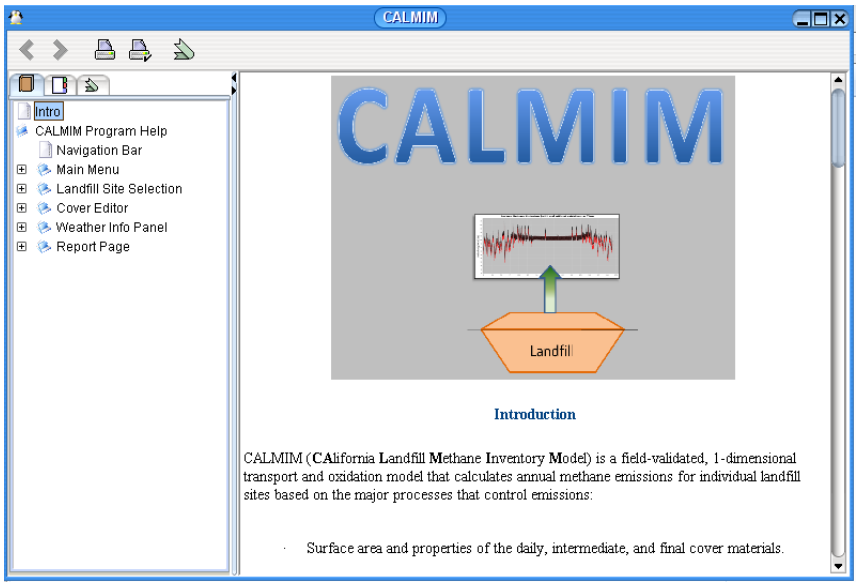


Figure 60. Illustration of CALMIM on-line help system.

- Improved soil profile initialization step to minimize numeric error due to model initialization.

- For numerical modeling, particularly for seasonal climatic effects, consistent initialization of differential algebraic equations (DAEs) is often very difficult to obtain (Ascher and Petzold, 1998). This stems from the fact that the model starts out uninitialized (in other words all variables are 0 [zero]). However, our starting conditions do vary from year-to-year as well as site-to-site. Adding further complication is the requirement that there are fixed algebraic constraints in the numeric solutions for the DAEs that are often difficult to satisfy with unknown initial starting values. In order to keep the number of required model input parameters to a minimum, a solution was needed for model initialization.

- However, discrete initialization steps can and do have drawbacks. Initialization steps in a numeric model can place a large burden on the computation time, often limiting the real-time simulation that can be performed (Tummescheit and Eborn, 2002). In order to prevent the doubling of computation time, a pre-initialization run of the CALMIM model is performed where the model uses hourly time steps (60 minutes) to simulate the soil temperature, moisture, and gas transport through the various soil covers over a typical annual cycle. This initialization run then retains the ending values to re-initialize the model for the "real" calculations using the model conditions at the end of the initialization year as the starting values for the new start of the year.

- This initialization method saved computation time, while improving initialization of the numeric model with minimal data for initial conditions (e.g., temperature and soil moisture profile data). When we expanded CALMIM applications after

2010 to landfill sites outside of California for the current EREF project, initialization errors were a particular issue for (northern latitude) cold climatic regions with freezing soil temperatures.

- Improved modeling of site-specific boundary conditions.

- We fixed a bug which ignored user-entered boundary conditions if the stability criterion for the numerical modeling was violated. The remedy for this issue was also aided by the pre-initialization runs discussed above.

- Fixed bug in oxygen transport routines, which instead of allowing bidirectional transport, was formerly only allowing downward diffusion of oxygen and not upward oxygen diffusion. This has been fixed in Version 5.4.

Versioning Scheme

The version number consists of three components, two numbers separated by a decimal followed by a letter. A change in the first number denotes a major change in functionality or layout.

The second number indicates a significant change. If this or the first number change the update button will appear on the first window with buttons.

The letter at the end signifies a minor change. An increment in the letter will not cause the update button to appear so please check the website if minor updates are necessary.

Appendix B. Reprint of :

Spokas, K, J Bogner, and J Chanton. "A Process- Based Inventory Model for Landfill Ch4 Emissions Inclusive of Seasonal Soil Microclimate and Ch4 Oxidation." *Journal of Geophysical Research: Biogeosciences* (2005–2012) 116, no. G4 (2011).

A process-based inventory model for landfill CH_4 emissions inclusive of seasonal soil microclimate and CH_4 oxidation

K. Spokas [1*], J. Bogner [2], and J. Chanton [3]

1- USDA-Agricultural Research Service, Soil and Water Management, St. Paul, MN. 55108 and Adjunct Professor, University of Minnesota, Dept. of Soil, Water and Climate, St. Paul, MN. 55108

2- Landfills+, Inc, Wheaton, IL and Research Professor, University of Illinois at Chicago, Dept. of Earth and Environmental Sciences, Chicago, IL

3- Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL USA 32306-4320.

* Corresponding Author:

Kurt Spokas

USDA-ARS

1991 Upper Buford Circle – 439 Borlaug Hall

St. Paul, MN 55108

Phone : (612) 626-2834

Fax: (651) 649-5175

Email: kurt.spokas@ars.usda.gov

Abstract

We have developed and field-validated an annual inventory model for California landfill CH_4 emissions that incorporates both site-specific soil properties and soil microclimate modeling coupled to 0.5^o scale global climatic models. Based on 1-D diffusion, CALMIM (California Landfill Methane Inventory Model) is a freely-available JAVA tool which models a typical annual cycle for CH_4 emissions from site-specific daily, intermediate, and final landfill cover designs. Literature over the last decade has emphasized that the major factors controlling emissions in these highly-managed soil systems are the presence or absence of engineered gas extraction, gaseous transport rates as affected by the thickness and physical properties of cover soils, and methanotrophic CH_4 oxidation in cover materials as a function of seasonal soil microclimate. Moreover, current IPCC national inventory models for landfill CH_4 emissions based on theoretical gas generation have high uncertainties and lack comprehensive field validation. This new approach, which is compliant with IPCC "Tier III" criteria, has been field-validated at two California sites (Monterey County; Los Angeles County), with limited field validation at three additional California sites. CALMIM accurately predicts soil temperature and moisture trends with emission predictions within the same order of magnitude as field measurements, indicating an acceptable initial model comparison in the context of published literature on measured CH_4 emissions spanning 7 orders of magnitude. In addition to regional defaults for inventory purposes, CALMIM permits user-selectable parameters and boundary conditions for more rigorous site-specific applications where detailed CH_4 emissions, meteorological, and soil microclimate data exist.

1. Introduction and Background

In addition to natural wetlands, atmospheric methane (CH_4) has multiple anthropogenic sources with high uncertainties [*Bousquet et al.,* 2006], including rice production, ruminant animals, natural gas leakages, biomass burning, and landfills. With a 100-year global warming potential (GWP) that is 25 times higher than CO_2 and a short atmospheric lifetime of about 12 years [*Forster et al*., 2007], reductions in CH_4 emissions from specific sources such as landfills can positively impact atmospheric concentrations within decadal timeframes. According to global estimates summarized in the IPCC 4th Assessment Report, annual landfill CH_4 emissions of approximately 600-700 Mt CO_2 equivalent yr^{-1} constitute half the total emissions from the waste sector, or between 1 and 2% of total anthropogenic GHG emissions of about 49 Gt CO_2 eq. [*Bogner et al.,* 2007; *Rogner et al.,* 2007]. Landfill gas, as generated, contains 50-60 % CH_4 (v/v). In the absence of controls (such as engineered gas recovery and well-maintained cover materials), landfills can be potent local sources of atmospheric CH_4. Moreover, in both developed and developing countries with a history of landfilling, inventory estimates indicate that landfills can be nationally significant sources of atmospheric CH_4—for example, in the U.S., landfills are currently the third largest anthropogenic source of CH_4, after natural gas systems and ruminant animals [*U.S. EPA*, 2011].

Compared to other CH_4 sources, current global estimates for annual landfill CH_4 emissions are especially problematical with high estimated uncertainties up to > 200% [*IPCC,* 2006]. For national inventory reporting to the UNFCCC (United Nations Framework Convention on Climate Change), emissions are estimated using IPCC Tier I & II methodologies [*IPCC*, 2006] based on a first order kinetic equation for landfill CH_4

generation, termed a first order decay (FOD) model. The estimated mass of CH_4 generated in a particular year is based on the waste landfilled in that year summed with the predicted CH_4 generated from waste landfilled in previous years. Thus CH_4 generation relies on the annual mass of landfilled waste, assumed or reported waste composition, a CH_4 generation potential ($m\ m^{-1}$), and a kinetic constant (t^{-1}) for each biodegradable waste component which is assumed to differ with climate (e.g., wet/dry; tropical/temperate). As appropriate for specific countries, two subtractions can also be applied to yield the CH_4 emitted—these are the annual CH_4 recovery from engineered landfill gas recovery projects and a further 10% reduction for methanotrophic CH_4 oxidation in cover materials, based on one older study, *Czepiel et al.* [1996]. Some of the questionable assumptions of the current methodology include the application of a kinetic equation suitable for homogeneous waste decomposition, omission of the physical effect of cover soils on emissions, the use of a single [10%] oxidation factor, the assumption that modeled generation is related to residual emissions at sites with high rates of gas recovery, and the assumption that reliable annual waste data exist for model input [*IPCC*, 2006; *Bogner et al.*, 2007; *Scheutz et al.*, 2009].

Addressing the waste data first, current approaches include: (a) use of data with variable quality and quantity from national waste statistics, surveys, or IPCC guidance documents [*IPCC* 1996, 2006]; (b) estimates based on population alone [e.g., *Nakicenovic et al.*, 2000]; and (c) because waste generation is related to affluence as well as population, the use of surrogate variables linked to demographic or economic indicators for which national data are annually collected, including per capita gross domestic product (GDP) per capita, energy consumption, or private final consumption

[e.g. *Richards,* 1989; *Bogner and Matthews*, 2003; *Mertins et al.,* 1999]. More realistically, annual waste mass and composition data are lacking for many countries and regions, data quality is variable, national definitions are not uniform, and inter-annual as well as site-by-site variability is often not well quantified [*Bogner et al.,* 2007].

Importantly, neither the existing IPCC multicomponent FOD methodology for landfill CH_4 emissions [*IPCC*, 2006] nor the single component LANDGEM methodology used in the U.S. [*US EPA*, 2005] were ever field-validated for surface CH_4 emissions. Rather, historic model validation consisted of comparing modeled generation to measured gas recovery [e.g., *Peer et al.,* 1993; *Van Zanten and Scheepers*, 1994; *Scharff and Jacobs,* 2006; *Thompson et al.,* 2009]. This approach was consistent with the original intended purpose of these models for predicting gas recovery for commercial landfill gas utilization projects. Moreover, when these models began to be applied to emissions more than a decade ago [*IPCC* 1996, 2006, *Czepiel et al.*, 1996 a, b], comprehensive field measurement programs for landfill CH_4 emissions were just beginning. At the site-specific level, use of the first order models as the starting point for emissions estimates becomes especially problematic as there can be large discrepancies between modeled and measured CH_4 pathways. Indeed, the application of the current IPCC model to the two main field validation sites for this project indicated that modeled CH_4 generation (IPCC 2006), using site-specific disposal data and regional California waste composition data, was only a fraction of the currently-measured CH_4 recovery.

In general, field and laboratory data over the last decade have demonstrated that both landfill CH_4 emission and oxidation rates can vary by several orders of magnitude in

field settings with measured emissions related to the implementation of engineered gas extraction as well as the seasonal properties of site-specific cover materials to retard gaseous emissions and promote methanotrophic oxidation [e.g., *Scheutz et al.,* 2009]. In particular, detailed CH_4 mass balance studies at field scale (7 cells at 3 landfill sites) showed that, while CH_4 recovery could be generally correlated to FOD-modeled generation at sites where waste inputs were well-quantified, there was no correlation between modeled generation and measured emissions, which varied over about 6 orders of magnitude [*Spokas et al.,* 2003; *Bogner and Spokas,* 2010]. Moreover, the 10% default value for CH_4 oxidation value is derived solely from the first study in the literature to quantify annual CH_4 oxidation [*Czepiel et al.*, 1996b]. This assessment relied on field measurement of emissions, supporting laboratory oxidation studies, and the application of a seasonal climatic model for a single small U.S. landfill (Nashua, New Hampshire) which did not have engineered gas recovery. A recent review summarizing a variety of lab and field investigations for landfill CH_4 oxidation indicated an average of $35 \pm 6\%$ for landfill cover soils with differing characteristics and seasonal variability [*Chanton et al.,* 2009]. Recent literature has emphasized the dependency of emissions of cover soil thickness and texture, as well as microbial oxidation rates which vary spatially and temporally with seasonal climatic trends [*Jones and Nedwell*, 1990; *Kightley et al.,* 1995; *Bogner et al.,* 1997b; *Klusman and Dick,* 2000; *Scheutz et al.,* 2009]. For modeling purposes, the major controls are: (1) engineered gas recovery which lowers CH_4 concentrations at the base of the cover, in turn reducing the driving force for diffusive flux of CH_4 to the atmosphere [*Bogner et al*., 1997b; *Park and Shin,* 2001; *Zhang et al.,* 2008] and (2) major surface processes, which rely on the site-specific

properties of the cover materials as well as seasonally-variable CH_4 transport and methanotrophic oxidation [*Maurice and Lagerkvist,* 2003; *Zhang et al.,* 2008; *Scheutz et al.,* 2009]. The three major types of cover materials include thin daily covers over recently-placed refuse; thicker intermediate covers overlying older refuse with high rates of methanogenesis; and final covers which are placed when a site reaches final grade. Oxidation rates are strongly coupled to engineered controls (cover design; landfill gas recovery); for example, engineered gas extraction can facilitate oxidation due to reduced rates of gross CH_4 flux to the base of cover soils. Observed CH_4 transport and oxidation rates are strongly linked to infiltration events and temperature changes at various temporal scales, both in natural ecosystems [*Morrissey and Livingston*, 1992; *Hargreaves and Fowler*, 1998] and landfill cover soils [*Maurice and Lagerkvist*, 2003; *Scheutz et al.,* 2009].

The purpose of this project was to develop an improved site-specific landfill CH_4 inventory methodology for California by focusing on the fundamental processes which control emissions. The model addressed herein (CALMIM, California Landfill Methane Inventory Model) is an annual landfill CH_4 emissions inventory model developed for California landfill sites and field-validated for daily, intermediate, and final cover soils during 2007-2008. CALMIM models typical annual emissions based on 1-D diffusional flux and seasonal oxidation in site-specific cover soils, focusing specifically on inputs and outputs which can be validated at field scale. A major driver for this study was a research review for California [*Farrell et al.,* 2005] which indicated that an improved landfill CH_4 inventory methodology was a high priority due to uncertainties associated with current methods. An important consideration for California was, according to data

compiled by the California Department of Resources Recycling and Recovery, >90 % of the waste in place in permitted California landfills is currently under active gas extraction, which constitutes a major control on emissions. Moreover, CALMIM is also compliant with current IPCC National Inventory Guidelines for CH_4 emissions from solid waste disposal sites [*IPCC,* 2006] as a "Tier III" model using "validated higher quality" methods [*IPCC,* 2006]. It is important to note that California has greenhouse gas reporting requirements which are separate and distinct from U.S. national greenhouse gas inventory reporting to the UNFCCC and other evolving U.S. requirements.

CALMIM is designed for site-specific applications and is the first landfill inventory model which decouples emissions from gas generation modeling. Although the literature contains several complex, process-based models which rigorously address the seasonality of gaseous carbon and nitrogen fluxes in other managed and natural ecosystems [e.g., CENTURY [*Parton*, 1996]; CASTANEA [*Davi et al.,* 2006]; and LPJmL [*Bondeau et al*., 2007]], similar seasonal models have not been developed for landfill settings [*de Visscher and van Cleemput,* 2003; *Mollins et al.,* 2008; *Scheutz et al.,* 2009]. Therefore, consistent with recent literature emphasizing strong seasonal dependencies for CH_4 transport, oxidation, and emissions in other managed and pristine soil ecosystems [*Cao et al.,* 1995; *Wille et al.,* 2008], a major goal of this study was to develop a functional, field-validated annual CH_4 emissions model for California landfill sites. As California landfills must currently comply with a variety of existing Federal, state, and local regulations pertaining to operational practices and monitoring, a secondary consideration was to realistically limit default input data requirements to

readily available information. CALMIM also contains "advanced" features which can be implemented when additional site-specific data are available.

2. Methods

2.1 Model Structure and Components.

Table 1 provides an overview of the model structure, components and default boundary conditions. CALMIM (https://www.ars.usda.gov/services/software/download.htm?softwareid=300) is a freely-available JAVA program which integrates site-specific data (location and cover design) with climatic simulation and one-dimensional soil microclimate and gas diffusion models for daily, intermediate, and final cover areas inclusive of CH_4 oxidation over a typical annual cycle. Figure 1 gives an overview of model components and linked structure. CALMIM includes: (1) the effect of engineered gas extraction; (2) the variable physical effects of daily, intermediate, and final cover materials to retard emissions; and (3) seasonal moisture and temperature effects on both gaseous transport and methanotrophic CH_4 oxidation in cover soils. The major driving force for emissions is the CH_4 concentration gradient through user-selectable cover materials, which is, in turn, related to the presence of engineered gas extraction systems and the efficiency of CH_4 oxidation in any particular cover soil. Both transport and oxidation are rigorously linked to seasonal climatic and soil microclimate variability through modified versions of existing, globally-validated models: Global TEMPSIM, Global RAINSIM, SOLARCALC, STM^2 [*Spokas and Forcella* 2006, 2009]. Thus, CALMIM estimates annual CH_4 emissions while accounting for climate-induced variability on transport and microbial oxidation.

Although more complex models exist for predicting the flow of landfill gas as a function of diffusion and advection [*Findikakis et al.,* 1979, 1988; *Lang et al.,* 1989; *Kindlein et al.,* 2006; *Donovan et al.,* 2010; *Yu et al.,* 2010], a number of the assumptions in these models are often violated in field settings (e.g., homogeneity of waste mass; uniform characteristics; static CH_4 generation rates). [Please consult Supplemental Information for a detailed discussion of diffusive vs. advective processes in landfill cover soils.] Moreover, required model input parameters are often unknown, highly variable or cannot be directly measured in field settings (e.g. gas flux to the base of soil cover). Thus, the theoretical complexity of existing models linked to various uncertainties relative to field settings hinders our ability to arrive at a robust tool that can be field-validated for prediction of surface CH_4 emissions. Therefore, we relied on a 1-D gaseous diffusion model, since this approach focuses directly on the factors that control surface emissions (e.g. cover soil characteristics, microbial CH_4 oxidation, climate, and CH_4 concentration gradient through the cover materials). Each of the model components shown in Figure 1 will be described in separate sections below. Many components have both default settings as well as settings which can be customized by the user based on field measurements or site management practices. Such site-specific practices including various cover materials and engineered gas recovery are extremely important for landfill settings which, compared to other CH_4-emitting settings such as wetlands or rice production systems, represent a highly-managed endpoint [*Bogner et al.,* 2000].

2.1.1 Overview of model structure and site-specific inputs

Required CALMIM inputs include the site location (latitude and longitude), cover description (material type and layer thickness), and the corresponding CH_4 concentration

gradient. The site information is collected from the user through data input screens (Figure S1). Each daily, intermediate, and final cover material, up to a total of 10 different covers, is modeled separately with the results summed for an estimate of annual total site emissions. The user can choose between typical California cover designs [see Table 1] or a customized sequence using the "cover designer" where any layered soil sequence can be entered. For a particular cover, the minimum thickness for any layer is 2.5 cm with a maximum total thickness of about 2.5 m, which is related to limits for typical PC memory resources. USDA standard soil texture classes, alternative daily cover (ADC) and other non-soil materials (e.g. composts, biosolids, tire chips, geomembranes) are also available with their corresponding transport properties taken from published literature (Supplemental Table S1). If the concentration gradient is not known, the model utilizes default settings based on the cover type selected (daily, intermediate, or final) (Table 1). The default settings are based on values taken from the literature; in general, higher base CH_4 concentrations reflecting mature methanogenesis characterize the intermediate and final cover soils.

Engineered gas recovery systems consisting of either vertical wells or horizontal collectors are an important influence on emissions. CALMIM requires input on whether engineered gas recovery underlies each particular cover type and the corresponding spatial extent of coverage, expressed as % of total area with engineered gas extraction. Using the default gas concentrations, the model scales the base CH_4 concentration using the following formula:

$$CH_4 \text{ Base} = (CH_{4\_Default})\ (1 - 0.3 * \text{Coverage \%}), \qquad (1)$$

where $CH_{4\_Default}$ is the default cover concentration (Table 1), and Coverage % is the aerial extent of the gas recovery system under the particular cover type (range of 0-1 representing 0-100%). If the user enters a custom gas concentration at the base of the cover, this linear correction is not performed, since the measurement would already include the correct concentration reduction attributed to the gas recovery system [*Bogner et al.,* 1997b; *Zhang et al.,* 2008]. The estimation of a 30% reduction due to a gas recovery system covering 100% of the cover type is a conservative estimate, based on the field observations ranging from <1% to 35% v/v CH_4 at the base of final covers with a gas recovery system in place [*Bogner et al.,* 1997b; *Zhang et al.,* 2008; *Bogner et al.,* 2011]. We strongly advocate the field measurement of this gradient as the driving force for emissions, using a statistically-significant number of soil gas probes monitoring CH_4 concentration at the waste-soil interface for the various cover types; field values are entered in the custom boundary dialog of the model (Fig. S1c, Supplemental Information).

2.1.2 Climate Simulation Models

The existing models SolarCALC, GlobalTempSIM and GlobalRainSim [*Spokas and Forcella* 2006, 2009] were incorporated into CALMIM to simulate a typical annual cycle of air temperature, precipitation, and incoming solar radiation referenced to site latitude and longitude. These models were previously validated for a number of global locations [*Spokas and Forcella,* 2006, 2009; *Kahimba et al.*, 2009] and rely on 30-yr (1961 – 1990) interpolated databases of *Legates and Willmott* [1990a and 1990b], *Willmott and Matsuura* [1995], and *New et al.* [1999]. Although the CALMIM model

was developed for application in California, these bundled simulation models confer global applicability at the 0.5 X 0.5 degree [latitude-longitude] scale. Average diurnal air temperature patterns are simulated in CALMIM using methods described by *Cesaraccio et al.* [2001] yielding air temperature values interpolated down to 10 min intervals for an annual cycle.

2.1.3 Soil Microclimate Model

The soil microclimate simulation is linked to both site-specific soils (discussed in the next section) and a modified version of the existing soil temperature/moisture model, STM^2 [*Spokas and Forcella,* 2009]. The original STM^2 boundary conditions, developed for agricultural settings [*Spokas and Forcella,* 2009], were altered for CALMIM (Table 1) because landfills have a heat source (decomposing refuse) and saturated gas boundary conditions at the cover/refuse interface. CALMIM also permits the user to override these defaults through user-selectable boundary conditions (Table 1 and Fig. S2c). In general, CALMIM incorporates default soil physical properties based on the soil texture and selected alternative cover materials permitted in California (Supplemental Information Table 2). It should be noted that the soil properties were derived from literature and databases for a variety of ecosystems [e.g. *Clapp and Hornberger,* 1978; *Wösten and van Genuchten,* 1988; *Bouma,* 1989] and not specifically for landfill soils. Compared to agricultural and other non-landfill soils, landfill covers are compacted to higher bulk densities [*Spokas and Bogner,* 2011], adding conservatism to the transport modeling because the more highly-compacted landfill soils would be expected to have lower effective diffusion coefficients and lower gaseous fluxes. The accuracy of these assumptions requires additional evaluation.

2.1.4 Diffusion/Oxidation Modeling and CALMIM Output

Gas diffusion was assumed to obey Fick's law, which is widely used and observed to provide satisfactorily comparisons for gas transport in soils [*Grable and Siemer,* 1968; *Simunek and Suarez,* 1993; *Moldrup et al.*, 1998, 2000, 2003]. From Fick's law,

$$J = D_S \frac{dC}{dz} \approx D_S \frac{\Delta C}{\Delta z}, \tag{2}$$

where J is the flux of gas species, $D_s = D_s(\theta,\phi)$ is the soil gas diffusion coefficient that varies with time as a function of soil porosity (ϕ) and volumetric water content (θ), C is the gas concentration, and z is depth. *Moldrup et al.* [1998] suggested a soil-type dependent gas diffusivity model (referred to as the Buckingham-Burdine-Campbell equation) for gas diffusivity:

$$D_s = D_{a,T}\left(\phi^2\right)\left(\frac{\theta_{air}}{\phi}\right)^{2+\frac{3}{B}}, \tag{3}$$

where $D_{a,T}$ is the free-air diffusion coefficient at temperature T, ϕ is the total soil porosity ($cm^3\ cm^{-3}$), θ_{air} is the air filled porosity ($cm^3\ cm^{-3}$), and B is the Campbell B or the slope of the soil moisture retention curve in a $\log(\theta)$–$\log(-\Psi)$ coordinate system [*Campbell*, 1985]. This model of the soil diffusivity was found to provide better prediction than other models across multiple soil types [*Rolston and Moldrup*, 2002; *Moldrup et al.,* 2004]. Temperature also influences diffusion and can be accounted for by the relationship:

$$D_{a,T} = D_{a,20C}\left(\frac{T}{293K}\right)^{1.75}, \tag{4}$$

where D_{a_T} is the free air diffusion coefficient at temperature T, D_{a20C} is the free-air diffusion coefficient at 20 ^{o}C and T is the temperature (^{o}K) [*Jones*, 1992]. Since we know the soil texture, temperature and soil moisture content of each node at any given time step, the effective diffusivity can be calculated for each layer. For the flux calculation, Fick's law was solved at each time step using the Thomas algorithm [*Campbell,* 1985]. The mass balance at any node N is given by:

$$J_N - J_{N-1} - U_N = 0, \quad (5)$$

Where J_N is the gas flux at node N, J_{N-1} is the flux at node N-1, and U_N is the sink at node N (of oxygen or methane). For oxygen consumption, the assumptions by *Campbell* [1985] were used (surface consumption rate of 5 x 10^{-4} g O_2 m^{-3} sec^{-1} with an exponential decrease with depth). Therefore, oxygen diffuses in from the atmosphere and is attenuated by the average heterotrophic bacterial O_2 consumption in soils, prior to being available for CH_4 oxidation.

For CH_4 oxidation, extensive supporting laboratory studies using daily, intermediate, and final cover soils from the two major field validation sites permitted the development of empirical relationships for node- and time-specific oxidation rates [*Spokas and Bogner*, 2011]. These relationships scale the rate of CH_4 oxidation as a function of soil temperature and soil moisture potential for each node and time step. Optimal oxidation rates from the California soils ranged from 112 to 644 µg CH4 g^{-1} d^{-1}, with an optimal temperature of 27.6 ^{o}C and soil moisture potential of -33 kPa [*Spokas and Bogner*, 2011]. The impact of temperature on microbial oxidation is estimated as a Gaussian function and the impact of soil moisture as a sigmoid function [*Spokas and Bogner*, 2011]. The default optimum rates for CH_4 oxidation capacity as a function of

cover type are given in Table 1. However, these values can be altered (Figure S2c) if site-specific data are available. These empirical models are a simplification of the complex microbial dynamics of the various populations of methantrophic bacteria present in landfill cover soils [*Scheutz et al.,* 2009]. However, similar empirical models are used to explain other biological responses to soil moisture and temperature by both microbial species [e.g., *Stark and Firestone*, 1995] and plant processes [e.g., *Watt et al.*, 2010]. Due to the fact that CH_4 oxidation alters the concentration gradient and thereby the flux of CH_4 through the entire cover, the non-oxidized and oxidized scenarios are modeled independently to adequately account for the net difference in the surface emissions as a result of methanotrophic activity. This also allows quantification of the overall impact of CH_4 oxidation, as well as visualization of the temporal effects (daily or seasonal) in the standard output plots.

Standard model output generated by CALMIM includes surface CH_4 emissions with and without CH_4 oxidation, site percent oxidation estimate, graphs of the profile (surface, middle and bottom nodes) of the nodal soil temperature, soil moisture, air-filled porosity, oxygen concentration, methane concentration (with and without oxidation), and corresponding CH_4 oxidation rate for the annual cycle, as well as the annual average depth profile of CH_4 oxidation. CALMIM also automatically generates EXCEL-compatible output files which archive the results of each simulation, including the calculated soil properties as a function of depth and time during model simulation [e.g. profiles for soil temperature/moisture, air-filled porosity, O_2 concentration, CH_4 oxidation rate, and CH_4 surface flux and soil gas concentrations with and without CH_4 oxidation (Figure S2d)].

2.2 Sensitivity Analysis

In order to isolate the response behavior of individual input variables, model sensitivity analysis was conducted by incrementally-varying single input parameters (cover properties, thickness, extent of gas recovery) and examining impact on resulting emission and oxidation rates. Of course, this analysis does not validate the model, but confirms the reasonable operation of the model over a wide range of inputs, as well as the overall sensitivity of outputs to variable input parameters.

2.3 Field Validation

Field validation was conducted over two years at two California sites, including the coastal Marina Landfill (36.71^{o} N, 121.762^{o} W, Monterey County) and the Scholl Canyon Landfill (34.158^{o} N, 118.196^{o} W, Los Angeles County). The field validation and model development were independent efforts and collected data were not utilized for parameterization of the numeric model. Because both sites had full gas recovery systems and engineered cover soils as primary controls on emissions, we conducted four field campaigns at each site focusing on the historically wettest and driest months in order to capture the seasonal wet (March 2007, 2008) and dry (August 2007, 2008) extremes. Methane emissions were quantified using multiple randomized deployments of 9 stainless steel static chambers across the three major cover types (daily, intermediate, and final). Because static chambers can quantify the spatial variability of both positive fluxes and negative fluxes (uptake of atmospheric CH_4) across a given cover type, this is the method of choice for small-scale process-related studies. Moreover, because we were developing an annual inventory model, non-soil fluxes associated with cracks, fissures, and piping leakages were not considered, since California and U.S. regulations require

quarterly monitoring of surface CH_4 concentrations followed by remediation and re-monitoring as part of normal operations and maintenance (i.e., South Coast Air Quality Management District Rule 1150.1; see http://www.aqmd.gov/rules/reg/reg11/r1150-1.pdf). The properties of the cover materials and soil methods are described in detail by *Spokas and Bogner* [2011] and *Bogner et al.* [2011]. Weather stations (Onset Computing[6]) and depth arrays of soil temperature/moisture sensors were installed at each site to continuously monitor wind speed, air temperature, relative humidity, and soil temperature and moisture profiles (Onset Computing). Sampling and analysis techniques for chamber samples, soil gas probes, and source gas (composite landfill gas) are discussed in detail in *Bogner et al.* [2011]. Gas samples were analyzed at the USDA-ARS laboratories in St. Paul and Morris, MN. Soil moisture (TDR) and temperature (RTD) were also measured at each of the >800 chamber locations. The minimum detectable CH_4 flux was ± 12 mg CH_4 m^{-2} d^{-1}.

In addition, field measurements of CH_4 emissions from intermediate cover materials at three additional California Landfills (Kirby Canyon; 37.185 ^{o}N 121.671 ^{o}W, Lancaster; 34.747 ^{o}N 118.116 ^{o}W; and Tri-Cities; 37.51 ^{o}N 121.99 ^{o}W) [*Green et al.,* 2009] were compared to CALMIM results. All of these sites are large, active municipal solid waste landfills [>1200 metric tons d^{-1}] with operational landfill gas collection systems underlying these cover soils. The Lancaster site is located in an arid, high desert region (Mojave Desert), while the Tri-Cities and Kirby Canyon sites are characterized by a Mediterranean climate. Field measurements included both static chambers and an

[6] - Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

above-ground technique using a TDL (tunable diode laser) instrument for vertical and horizontal radial plume mapping [see *Green et al.*, 2009].

For all five field validation sites, stable carbon isotopes for CH_4 for selected chamber and probe samples were analyzed at Florida State University. Fractional CH_4 oxidation (as % oxidation) was calculated using published methods [*Liptay et al.,* 1998; *Chanton and Liptay,* 2000; *Chanton et al.,* 2008] based on a comparison of the $\delta^{13}C$ for anoxic zone CH_4 compared to the emitted CH_4 (chambers or probes).

2.4 Statistical Model Validation

Although Pearson correlation coefficients (R^2) were calculated as a routine measure of correspondence for climatic and soil microclimate outputs, significant R^2 values do not automatically correlate to model accuracy [*Willmott,* 1982]. Therefore, for air and soil temperature comparisons an "index of agreement" or modeling index (d) was calculated with the following expression:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{\sum_{i=1}^{n} \left(\left| x_i - \bar{x}_i \right| + \left| y_i - \bar{x}_i \right| \right)^2} \right], \qquad (6)$$

where x_i are the field measured values with a mean of $\bar{x}_i$ and y_i are the modeled values and corresponding $\bar{y}_i$ [*Willmott* 1981; *Mayer and Butler,* 1993]. The value of d will range between 0 and 1, with a value of 1 indicating perfect model agreement [*Willmott,* 1981].

Two other statistical measures [root mean square error (RMSE) and mean absolute error (MAE)] were also calculated, since the units are the same for the parameter as the observed quantity and therefore allow a more meaningful comparison. These

statistical measures have been used in other modeling comparisons [e.g. *Wegehenkel* 2000; *Winslow et al.* 2001; *Spokas and Forcella,* 2006] and are recommended measures in assessing model performance [*Willmott,* 1982].

Surface CH_4 flux and oxidation results were analyzed by comparing the mean and associated standard deviation of the measurement compared to the modeled annual surface CH_4 emission and associated estimated CH_4 oxidation.

3.0 Results and Discussion

3.1 Sensitivity Analysis

3.1.1 Effect of variable soil texture

A 30 cm soil cover with a base CH_4 concentration of 10% (v/v) was assumed to have different soil textures and was analyzed under the same climatic conditions (Marina Landfill, Monterey County). Figure 2a indicates the variability in the CH_4 emission rate with and without oxidation along with the total estimated annual CH_4 oxidized. Diffusive flux is reduced by finer soil texture (Fig. 2a). For this scenario, the variability in the prediction ranged from 46 to 163 g CH_4 m^{-2} d^{-1} without oxidation and 18 to 122 g CH_4 m^{-2} d^{-1} with oxidation, as a function of soil texture. Typically, coarser soil textures resulted in higher predicted surface emissions both with and without oxidation. On the other hand, the estimated annual amount of CH_4 oxidized as a function of soil texture ranged from 21 to 41 g CH_4 m^{-2} d^{-1}. Coarser textured soils resulted in higher predicted oxidation capacities, while finer-textured soils have a lower total CH_4 oxidation capacity, which is in agreement with the literature [*Scheutz et al.,* 2009].

The percent CH_4 oxidation (Fig. 2b) is a function of the non-oxidized diffusive flux and is the parameter commonly quantified by current isotopic methods for positive

CH_4 fluxes [*Liptay et al.,* 1998; *Chanton and Liptay,* 2000; *Chanton et al.,* 2008]. Unfortunately, these methods cannot be applied to negative fluxes (uptake of atmospheric CH_4) and, because of the observed variability in field results, may be difficult to apply where positive CH_4 fluxes are low. Importantly, percent oxidation is only a relative measure of the CH_4 that is oxidized in a particular landfill cover soil and is not a direct quantitative assessment of the CH_4 oxidation rate. Because percent CH_4 oxidation is a function of the non-oxidized diffusive flux, it is therefore highly variable across soil textures and climates. This oxidation percentage varied from 25-60% across soil textures in the soil texture analysis (Fig. 2b) within the same climatic region, with coarser-textured soils having higher predicted oxidation capacities. However, finer-textured soils typically have higher percent oxidation due to the reduced magnitude of CH_4 flux as a function of the soil texture (Fig. 2a). Because of these relationships, the depth- and climate-dependent oxidation rate (g CH_4 m^{-2} d^{-1}) would be the preferred measure of oxidation capacity in a particular cover soil cover for a particular climate rather than the percent oxidation. Moreover, both published field data [*Bogner et al,* 2007; *Borjesson and Svensson,* 1997; *Scheutz et al.,* 2009; *Zheng et al.,* 2008] and CALMIM model output indicate that the percent CH_4 oxidation at a particular site can range from 0 to 100%, with high temporal variability. In CALMIM, this variability is directly attributable to the coupling of soil cover properties and climatic driving forces to estimate soil microclimate as a function of depth. This microclimate data are then utilized to estimate the rate of microbial CH_4 oxidation based on the empirical relationship with temperature and soil moisture [*Spokas and Bogner*, 2011]. However, even though the *in situ* oxidation rate (g CH_4 m^{-2} d^{-1}) would be the preferred measure for

oxidation within a particular soil cover in a particular climate, it is not currently possible to quantify this oxidation rate in the field; instead, one must rely on numerical modeling coupled to laboratory studies [*Bogner et al.*, 2000].

3.1.2 Effect of cover soil thickness and CH_4 concentration gradient

The thickness of a variety of cover materials (Fig. 3a) and the concentration gradient (Fig. 3b) across a uniform 100 cm clay cover were independently varied. There is a non-linear response to the changing thickness of the cover soil (Fig. 3a). On the other hand, alterations in the concentration gradient result in a linear relationship with surface flux (Fig. 3b), which is consistent with the assumption of diffusive flux (Eq. 2). As discussed above, the CH_4 oxidation percentage is determined relative to the net flux of CH_4 into the base of the cover material. This can be seen in Figure 3b, where the 100 cm clay cover was capable of oxidizing virtually all of the gross diffusive CH_4 flux to the base of the cover material. As discussed above and in the Supporting Information, the model does not account for advection in its current form.

3.1.3 Effect of gas recovery system

The sensitivity of the model to the presence of an engineered gas recovery system was examined for a 30-cm clay cover. This dependency was scaled by altering the base concentration according to the relationship given in Eq. 1(Fig. 4a) and the assumption for diffusive transport results in a direct linear relationship between surface flux and the concentration gradient (Fig. 4b). However, the estimated CH_4 oxidation potential in the cover is equivalent for each scenario, because this is dependent on the soil texture (e.g. O_2 diffusion profile), soil moisture, and temperature (which were held equal for all scenarios) (Fig. 4b). Therefore, the percent oxidation is not related to the amount of CH_4

oxidized (same in all scenarios), but is a function of the non-oxidized flux (Fig. 4c). Importantly, this same pattern has been observed in other measurement campaigns [*Chanton et al, 2011a, 2011b*]. The presence of a recovery system (with 100% coverage) for this particular scenario reduced emissions by over 50% (128 to 62 g CH_4 m^{-2} d^{-1}), even though the base concentration was only reduced by 30%, due to the increased impact of oxidation on the reduced (net) CH_4 flux to the atmosphere at the top of the cover soil. These modeling results agree with other studies indicating that the optimal mechanism to reduce surface CH_4 emissions is to reduce the CH_4 loading into the base of the cover soil [*Park and Shin, 2001; Zhang et al., 2008; Chanton et al., 2011a, 2011b*].

3.1.4 Effect of climate

Table 2 presents the data from the comparisons of three different landfill cover scenarios:

1. Daily cover (30 cm daily cover of sand),
2. Intermediate cover (30 cm sandy loam), and a
3. Final cover (0.8 m final cover: [30 cm sandy clay loam (bottom), 25 cm clay, and 25 cm loam (surface)]).

These comparisons assumed the default CH_4 boundary conditions for the cover type (Table 1) and were analyzed at various global locations. As can be seen in Table 2, there is considerable variability in the prediction of surface CH_4 emissions as a function of the global climate and cover type. Typically, higher emissions were predicted in colder climates, where soil microclimate conditions for CH_4 oxidation are not optimal year round (Figure S2). For the daily cover, the variability ranged from 4.3 to 5.8 g CH_4 m^{-2} d^{-1} across the various climates. However, larger differences were observed for the

intermediate and final cover types across these climates. In particular, one can see the range in the percent oxidation from 3.5 to 12% for the intermediate covers and 32 to 100% for the final cover as a function of climate (Table 2). These higher estimates for the percent oxidation have been supported by recent field measurements [e.g., *Chanton et al.*, 2009], but depend on the cover soil type and particular climate. As seen in these simulations, the attenuating role of CH_4 oxidation increases with greater cover thicknesses and warmer climates. There was strong seasonal variability observed for the global sites (Figure S2), with equatorial sites possessing reduced annual variability compared to the northern colder locations.

3.2 Field Validations

3.2.1 Marina Landfill

Figure 5 compares model results and field data for the northern California coastal site (Marina) using model parameters in Table 3. Average air temperature predictions (Fig. 5a) matched the overall trend (R^2 = 0.694; d-index = 0.831), with a slight positive bias (RMSE= 2.45 ^oC; MAE = +2.10 ^oC). The solar radiation predictions (Fig. 5b) were correlated (R^2= 0.572; d-index= 0.869) and had small relative errors (<10%) in the magnitude of the daily incoming radiation estimate (RMSE = 60.4 W m^{-2}; MAE= +46.1 W m^{-2}). Precipitation predictions were somewhat overestimated due to the ongoing drought in California during 2007-2008 (Fig. 5c). However, the Mediterranean pattern, where a majority of the annual precipitation falls in the cooler part of the year (November-March), was accurately simulated, despite relative differences in predicted quantities. Not surprisingly, results for the climate simulations were comparable to other

published validations for these models [*Spokas and Forcella,* 2006, 2009; *Kahimba et al.*, 2009].

The predicted and measured soil temperature at 10 cm in the final cover and 15 cm depth in the intermediate cover area are shown in Figures 5d and 5e, respectively. These shallow depths were chosen based on the observations that maximum rates of soil CH_4 oxidation are typically found in the upper portion of the soil profile (e.g., 5-25 cm) where optimum microclimate conditions exist for methanotrophic activity as a function of O_2 availability, soil temperature, moisture, and CH_4 supply [e.g. *Scheutz et al.,* 2009]. For the final cover, the model demonstrated good prediction of the overall cover soil temperature trend (R^2 = 0.919; d-index = 0.814) and a RMSE of 2.4 ^oC and a MAE of 2.1 ^oC. These errors are virtually identical to the air temperature prediction errors and similar in magnitude to errors observed in other modeling studies [*Granberg et al.,* 1999; *Cannavo et al.,* 2006; *Bittelli et al.,* 2008]. This is vital, due to the importance of soil temperature on microbial reactions [*Riveros-Iregui et al.,* 2007; *Or et al.,* 2007]. It should be noted that this correspondence to field data was achieved using modeled meteorological data and not site-specific weather data which could, of course, improve model comparisons. Due to a localized decrease in the lower boundary temperature (soil-refuse interface) which was not reproduced in the modeling (steady state condition), the measured intermediate cover soil temperature did not match the modeled temperature as well during the winter (Figure 5e). Overall, the intermediate cover comparisons at Marina were relatively poor (R^2 = 0.462; d-index = 0.595; RMSE = 6.7 ^oC and a MAE of 4.9 ^oC). Figure 5f illustrates the modeled temperature profile for the daily cover at 5 cm. Due to operational constraints, it was not possible to monitor the daily cover on a

continuous basis. Point measurements from the field monitoring (average and standard deviation; Fig. 5f) were compared to model results. Overall, the model did follow the same trend as the individual measurements, and generally the predicted daily temperature was within the standard deviation of the field measurements.

Volumetric soil moisture predictions for the final (10 cm) and intermediate (15 cm) are shown in Figures 5g and 5h, respectively. Only the final cover at Marina was instrumented with soil moisture sensors. However, soil moisture was not further statistically compared, since the model used simulated annual weather data rather than site-specific data. Nevertheless, predicted soil moisture profiles for the final cover matched the seasonal trends observed in the field data (Fig. 5g). Also, the dry season range of volumetric moisture contents measured in the field overlapped the modeled output (Fig. 5h), suggesting a good match for measured-to-modeled soil physical parameters (Table S1) at this site.

Model outputs for predicted surface CH_4 emissions at Marina during an annual cycle with and without oxidation are shown for the final (Fig. 6a), intermediate (Fig. 6b) and the daily cover areas (Fig. 6c), with the corresponding field measurement averages and standard deviations. As seen in Figure 6, the model results were typically within the same order of magnitude as the field measurements but slightly higher, indicating that the model results were conservative for annual inventory purposes. Daily cover area comprises a small fraction of the typical landfill footprint (<4 ha). The final cover had very low measured fluxes (<0.1 g CH_4 m^{-2} d^{-1}). The corresponding modeled percent oxidation is also shown for the final, intermediate, and daily cover types in Figure 6d. The estimated range of percent CH_4 oxidation from the isotopic measurements was 1 to

84% with an average of 30 to 40% for all cover types depending on whether the estimation was made from chamber flux measurements or soil gas probes, which is similar to range reported by *Chanton et al.* [2009]. In general, the model predicted 100% CH_4 oxidation over the full annual cycle for the final cover soil, 50% for the intermediate cover soil, and less than 1% oxidation occurring in the daily cover. These oxidation percentages are solely estimates from the ratio of the modeled fluxes with and without oxidation. Therefore, the error associated with each prediction is difficult to ascertain.

In large part, the numeric differences between percent oxidation between cover types (Fig. 6d) are related to the significantly lower oxidation potential for the daily cover compared to the intermediate and final covers, because the daily cover had not previously been exposed to elevated CH_4 concentrations [*Spokas and Bogner*, 2011 and references cited therein]. These differences are accounted for in the model by scaling the rate of CH_4 oxidation in the model as a function of cover type selected (Table 1).

3.2.2 Scholl Canyon Landfill

Figure 7 (using model input parameters in Table 2) compares model results and field data for the Scholl Canyon site (Los Angeles County). The air temperature predictions (Fig. 7a) matched the overall trend (R^2 = 0.722; d-index = 0.521), with a slightly higher positive bias (RMSE = 3.9; MAE = +3.0 ^oC) than at Marina. Solar radiation predictions (Fig. 7b) were well-correlated to field data (R^2=0.779; d-index=0.608) with small relative errors (<10%) relative to the magnitude of the daily average prediction (RMSE = 57.9 W m^{-2}; MAE= +42.3 W m^{-2}). Mediterranean

precipitation patterns (Fig. 7c) were simulated but with an overestimation due to the extreme drought conditions for 2007-2008 in southern California.

The predicted and measured soil temperatures at 20 cm in the final cover and at 15 cm in the intermediate cover are shown in Figures 7d and 7e, respectively. As discussed above, CH_4 oxidation activity would be optimized at these shallow depths. CALMIM predicted the final soil cover temperature trend (R^2 = 0.920; d-index = 0.846) with a RMSE of 5.4 ^oC and a MAE of 4.4 ^oC. The intermediate cover was modeled adequately with a R^2 = 0.944; d-index = 0.892; RMSE = 4.7 ^oC and a MAE of 3.8 ^oC over the field monitoring period. Figure 7f compares modeled to actual soil temperatures at 5 cm for the daily cover; the superimposed bars indicate the point measurements (average and standard deviation). Intermediate and final cover soils at Scholl Canyon were highly compacted (estimated 2 g cm^{-3} for intermediate and final covers; [*Spokas and Bogner*, 2011]). Therefore, we suggest that the differences between modeled and measured emissions at the Scholl Canyon site are an artifact of the assumption of the lower bulk density values in the CALMIM modeling (Table S1).

Volumetric soil moisture predictions for the final (10 cm) and intermediate (15 cm) are shown in Figures 7g and 7h, respectively. As seen in the data, soil moisture responds directly to precipitation events. Moreover, the predicted soil moisture profiles for the final and intermediate covers closely match seasonal trends seen in the field data (Figures 7g, 7h). As mentioned above for the soil temperature comparisons, field deviations from the assumed soil physical properties for the highly-compacted Scholl soils could lead to observed errors in the soil moisture predictions for the dry soil conditions. This difference is more dramatic for the Scholl Canyon site compared to

Marina because the Marina cover soils had lower soil bulk densities closer to the assumed model parameters (Table S1). In addition, the extreme drought conditions also could explain the overestimation observed in the modeled soil moisture results (Fig. 7g and 7h).

Modeled surface CH_4 emissions with and without oxidation were compared to field measurements for the final (Fig. 8a), intermediate (Fig. 8b) and the daily cover (Fig. 8c) with modeled % oxidation (Fig. 8d) for all three covers. From the isotopic field measurements, the estimated range of CH_4 oxidation was 10-100% with an average of 48-52% depending on whether the estimation was made from chamber flux measurements or soil gas probes. The model predicted 100% oxidation for the final cover but <1% oxidation for the daily cover, with rapid responses to infiltration events (Fig. 8c), thus capturing the response of oxidation to moisture and indicating that very low soil moisture resulted in reduced oxidation rates. The overall response of emissions and oxidation to soil moisture events is very significant for Scholl Canyon due to the lower CH_4 fluxes with CH_4 oxidation an important contributing mechanism to mitigating emissions. Furthermore, as seen in Figure 8d, the percent oxidation of the daily cover can exceed the intermediate cover, since this percentage is both a function of the gas diffusion rates, soil microclimate conditions, and the soil texture differences (Figure 2b).

3.2.3 Other California Landfill sites

Comparisons at other California sites were limited to the intermediate cover areas at three sites (Lancaster, Kirby Canyon, Tri-Cities) and are summarized in Table 2 using model input parameters given in Table S2. In general, intermediate cover areas are the most important cover type at active landfill sites with respect to emissions because these generally comprise the largest percentage of the total surface area during the active filling

phase. Intermediate covers are thinner than final soil covers, are placed when a cell is completed, and buried when new cells overlie older phases. Intermediate cover areas can remain exposed for extended periods of time (>3 years) but are characterized by well-established methanogenesis in the underlying waste which can result in higher surface emissions. Overall, there was good agreement between the flux measurements and the modeling results, with CALMIM outputs for the three sites exhibiting relatively low surface emission estimates. In general, the vertical radial plume mapping (VRPM) [*Thoma et al.*, 2008, 2010; *Green et al.,* 2009] results were consistently higher than the chamber and corresponding CALMIM results. These differences are attributable to uncertainties regarding the area contributing to flux using VRPM methods along with other complicating issues (e.g. model assumptions vs. actual climatic stability, terrain, and interferring CH_4 sources from adjacent cells) [*Babilotte et al.,* 2010]. Furthermore, the VRPM method (as do all above-ground methods) captures secondary emissions from cracks, fissures, and piping system leakages. As discussed above, by regulatory mandate, these are detected and remediated on a quarterly basis as part of normal operations and maintenance and thus are not modeled for annual inventory purposes by CALMIM.

4.0 Conclusions

CALMIM is an IPCC Tier III methodology for landfill CH_4 emissions relying on "validated higher quality" methods. Importantly, this project has developed a field-validated modeling methodology based directly on the physical and biochemical processes that control emissions during typical annual climatic and soil microclimate variability for site-specific daily, intermediate, and final cover soils. As published literature has demonstrated, the "net" landfill CH_4 emissions to the atmosphere are

dependent on the presence of engineered gas recovery, the site-specific cover materials, their seasonal moisture and temperature profiles, and the variability of seasonal methanotrophic CH_4 oxidation in various cover materials. A major focus of CALMIM as an annual inventory model is on the effect of larger-scale climatic processes and their influence on soil microclimate [*Entin et al.,* 2000; *Muttiah and Wurbs,* 2002] as an important control on landfill CH_4 emissions in California. The accuracy of the global climate models embedded in CALMIM is adequate to establish typical or average annual conditions [*Spokas and Forcella,* 2009]. In general, as discussed above, CALMIM predicts field CH_4 emissions within the same order of magnitude and provides a framework for an improved methodology for predicting annual landfill CH_4 emissions. Comparisons of CALMIM modeling output to field measurements of emissions and oxidation at additional landfill sites outside of California has been initiated, including both U.S. and international sites.

The current model represents an initial step with respect to the decoupling of landfill surface emission predictions from gas generation modeling. Some anticipated future improvements include facilitating the routine use of site-specific climate and soil microclimate data, potential inclusion of advective gas transport, as well as developing a default soils database specifically for gaseous transport in landfill cover soils with high compaction. However, for inventory purposes, the use of the current soils database within CALMIM, based on agricultural soils, adds conservatism to the modeling output, since estimated transport rates would typically be higher for agricultural soils with lower compaction. Importantly, the CALMIM results also illustrate the limitations of a historical dependence on the percent CH_4 oxidation as a measure of the total potential

oxidation capacity of various landfill soil cover systems [e.g., *Czepiel et al.* 1996]. Rather, a more comprehensive accounting for the actual CH_4 oxidation rate is preferred, which is dependent on the magnitude of the non-oxidized flux and is a function of soil texture, climate, CH_4 and O_2 concentration gradients, and diffusive flux rates.

References:

Babilotte, A., T. Lagier, E. Fiani, and V. Taramini (2010), Fugitive methane emissions from landfills: Field comparison of five methods on a French landfill, *J. Environ. Engrg.* 136, 777-784.

Bittelli, M., F. Ventura, G.S. Campbell, R.L. Snyder, F. Gallegati, P.R.Pisa (2008), Coupling of heat, water vapor, and liquid water fluxes to compute evaporation in bare soils, *J. Hydro.*, 362, 191-205.

Bogner, J., M. Vogt, C. Moore and D. Gartman (1987). Gas pressure and concentration gradients at the top of a landfill. In: *Proceedings 10th International Landfill Gas Symposium*, Solid Waste Association of North America (SWANA), Silver Spring, Maryland.

Bogner, J., M. Meadows, and P. Czepiel (1997a), Fluxes of methane between landfills and the atmosphere: natural and engineered controls, *Soil Use and Manage.*, 13, 268-277.

Bogner, J., K. Spokas, and E. Burton (1997b), Kinetics of methane oxidation in landfill cover materials: major controls, a whole-landfill oxidation experiment, and modeling of net methane emissions, *Environ. Sci. Tech.*, 31,2504-2614.

Bogner, J.E., R. Sass, and B. Walter (2000), Model comparisons of methane oxidation across a management gradient: Wetlands, rice production systems, and landfills, *Global Biogeochem. Cycles,* 14, 1021-1033.

Bogner, J.E. and E. Matthews (2003), Global methane emissions from landfills: New methodology and annual estimates 1980-1996, *Global Biogeochem. Cycles*, 17, 34-1 to 34-18.

Bogner, J., M.A. Ahmed, C. Diaz, Q. Gao, A. Faaij,S. Hashimoto, K. Mareckova, R. Pipatti,and T. Zhang (2007), Waste Management, in *Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer, Cambridge University Press, Cambridge, United Kingdom and New York, NY USA. (http://www.ipcc.ch. Accessed May 11, 2010)

Bogner, J., and K. Spokas. 2010. Landfills, In D. Reay et al. (ed.) Methane and Climate Change. Earthscan Pub. Ltd., London, UK, p. 176–200.

Bogner, J., K. Spokas, and J. Chanton (2011), Seasonal variability in CH_4, CO_2, and N_2O emissions from daily, intermediate, and final cover materials at two California landfills. *J. Env. Qual*., in press.

Borjesson, G., and B.H. Svensson (1997), Seasonal and diurnal methane emissions from a landfill and their regulation by methane oxidation, *Waste Manage. Res.*15, 33-54.

Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D.Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith (2007), Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biol.* 13, 679-706.

Bouma, J. (1989), Using soil survey data for quantitative land evaluation, *Adv. Soil Sci.*, 9, 177–213.

Bousquet, P., P. Ciais, J. B. Miller, E. J. Dlugokencky, D. A. Hauglustaine, C. Prigent, G. R. Van der Werf, P. Peylin, E.-G. Brunke, C. Carouge, R. L. Langenfelds, J. Lathière, F. Papa, M. Ramonet, M. Schmidt, L. P. Steele, S. C. Tyler, and J. White (2009), Contribution of anthropogenic and natural sources to atmospheric methane variability, *Nature* 443, 439-443.

Cannavo, P., F. Lafolie, B. Nicolardot, and P. Renault (2006), Modeling seasonal variations in carbon dioxide and nitrous oxide in the vadose zone. *Vadose Zone J.,* 5, 990 - 1004.

Campbell, GS (1985), *Soil physics with Basic: transport models for soil-plant systems.* Elsevier, New York.

Cao, M, J.B. Dent, and O.W. Heal (1995) Modeling methane emission from rice paddies. *Global Biogeochem. Cycles* 9, 183-195.

Chanton, J., and K. Liptay (2000), Seasonal variation in methane oxidation in a landfill cover soil as determined by an i*n situ* stable isotope technique, *Global Biogeochem. Cycles*, 14, 51-60.

Chanton, J.P., D.K. Powelson, T. Abichou, and G. Hater (2008), Improved field methods to quantify methane oxidation in landfill cover materials using stable carbon isotopes, *Environ. Sci. Tech*., 42, 665-670.

Chanton, J. P., D.K. Powelson,and R.B. Green (2009), Methane oxidation in landfill cover soils, is a 10% default value reasonable?, *J. Environ. Qual.*, 38, 654-663.

Chanton, J.P., T. Abichou, C. Langford, K. Spokas, G. Hater, C.D. Goldsmith, and M. Barlaz (2011a), Observations on the Methane Oxidation Capacity of Landfill Soils, *Waste Manage.***,** 31, 914–925.

Chanton, J., T. Abichou, C. Langford, G. Hater, R. Green, D. Goldsmith and N. Swan (2011b). Landfill Methane Oxidation Across Climate Types in the U.S., *Environ. Sci. Tech.***,** 45, 313-319.

Cesaraccio, C., D. Spano, P. Duce, and R. L. Snyder (2001), An improved model for degree-days form daily temperature data, *Int. J. Biomet.,* 45, 161–169.

Clapp, R.B. and G.M. Hornberger (1978), Empirical equations for some soil hydraulic properties, *Water Resources Res.*, 14, 601-604.

Czepiel, P. M., B. Mosher, P. M. Crill, and R. C. Harriss (1996), Quantifying the effect of oxidation on landfill methane emissions, *J. Geophys. Res.*, 101(D11), 16721–16729.

Davi, H., E. Dufrene, C. Francois, G. Le Maire, D. Loustau, A. Bosc, S. Rambal, A. Granier, and E. Moors (2006), Sensitivity of water and carbon fluxes to climate changes from 1960 to 2100 in European forest ecosystems, *Ag. For. Meteor.*, 141, 35-56.

de Visscher, A., and O. Van Cleemput (2003), Simulation model for gas diffusion and methane oxidation in landfill cover soils, *Waste Manage.*, 23, 581-591.

Donovan, S.M., T. Bateson, J.R. Gronow, and N. Voulvoulis (2010), Modelling the behaviour of mechanical biological treatment outputs in landfills using the GasSim model, *Sci. Total Environ.*, 408, 1979-1984.

Entin, J.K., A. Robock, K.Y. Vinnikov, S.E. Hollinger, S. Liu, and A. Namkhia (2000), Temporal and spatial scales of observed soil moisture variations in the extratropics, *J. Geo. Res.,* 105, D9: 11865-11877.

Farrell, A., A. C. Kerr, A. R. Brandt, M. S. Torn, and G. Franco (2005), *Research Roadmap for Greenhouse Gas Inventory Methods*, Final report to the California Energy Commission: Public Interest Energy Research, (CEC-500-2005-097), Sacramento, CA.

Findikakis, A. N., C. Papelis, C. P. Halvadakis, and J. O. Leckie (1988), Modeling gas production in managed sanitary landfills,*Waste Manage. Res.*, 6, 115-123.

Findikakis, A. N. and J. O. Leckie (1979), Numerical simulation of gas flow in sanitary landfills, *J. Environ. Eng.,* 105, 927-945.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, D.C. Lean, G. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland (2007), Changes in atmospheric constituents and in radiative forcing, in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.(http://www.ipcc.ch. Accessed May 11, 2010.)

Grable, A.R., and E.G. Siemer (1968), Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots, *Soil Sci. Soc. Am. Proc.*, 32, 180-186.

Granberg, G., H. Grip, M. Ottoson Löfvenius, I,. Sundh, B.H. Swensson, and M. Nilsson, (1996), A simple model for simulation of water content, soil frost, and soil temperatures in boreal mixed mires, *Water Resources Res.,* 35, 3771-3782.

Green, R., G. Hater, C.D. Goldsmith, J. Chanton, N. Swan, and T. Abichou (2009), Estimates of methane emissions from three California landfills using two measurement approaches, First International Greenhouse Gas Measurement Symposium, Air & Waste Management Association. San Francisco, CA. March 22-25, 2009. (Extended Abstract #89) In *Proceedings First International Greenhouse Gas Measurement Symposium*, March 22-25, 2009, San Francisco, CA, Air & Waste Management Association, Pittsburgh, PA, USA.

Hargreaves, K. J., and D. Fowler (1998), Quantifying the effects of water table and soil temperature on the emission of methane from peat wetland at the field scale, *Atmos. Environ.,* 32,3275–3282.

IPCC (1996), *Greenhouse gas inventory reference manual,* Revised 1996 IPCC guidelines for national greenhouse gas inventories, Reference manual Vol. 3, edited by J.T. Houghton, L.G. Meira Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs and B.A. Callender, IPCC/OECD/IEA. UK Meteorological Office, Bracknell, pp. 6.15-6.23.

IPCC (2006), *IPCC Guidelines for National Greenhouse Gas Inventories,* IPCC/IGES, Hayama, Japan. (http://www.ipcc-nggip.iges.or.jp/public/2006gl/ppd.htm)

Jones, H.G. (1992), *Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology*, Cambridge University Press, New York, USA, 51 pp.

Jones, H., and D.B. Nedwell (1990), Soil atmosphere concentration profiles and methane emission rates in the restoration cover above landfill sites: equipment and preliminary results, *Waste Manage. Res.*, 8, 21-31.

Kahimba, F.C.,P.R. Bullock, R. Sri Ranjan, and H.W. Cutforth (2009), Evaluation of the SolarCalc model for simulating hourly and daily incoming solar radiation in the Northern Great Plains of Canada, *Can. Biosys. Eng./Le génie des biosystèmes au Canada*, 51, 1.11-1.21.

Kindlein, J. D. Dinkler, and H. Ahrens (2006), Numerical modelling of multiphase flow and transport processes in landfills, *Waste Manage. Res.*, 24, 376 - 387.

Kightley, D., D.B. Nedwell, and M. Cooper (19950, Capacity for methane oxidation in landfill cover soils measured in laboratory scale microcosms, *Appl. Environ. Microbiol.,* 61, 592–601.

Klusman, R.W. and C.J. Dick (2000), Seasonal variability in CH_4 emissions from a landfill in a cool, semiarid climate, *J. Air Waste Mange. Assoc.,* 50, 1632-1636.

Lang, R. J., W. M. Stallard, L. C. Stiegler, T. A. Herrera, D. P. Chang, and G. Tchobanoglous (1989), *Movement of gases in municipal solid waste landfills*, final report prepared for the California Waste Management Board (February, 1989).

Legates, D. R. and C. J. Willmott (1990a), Mean seasonal and spatial variability global surface air temperature, *Theoret. Appl. Climat.*, 41, 11-21.

Legates, D. R. and C. J. Willmott (1990b), Mean seasonal and spatial variability in gauge-corrected global precipitation, *Int. J. Clim.*, 10, 111-127.

Liptay, K., J. Chanton, P. Czepiel, and B. Mosher (1998), Use of stable isotopes to determine methane oxidation in landfill cover soils, *J. Geophys. Res.,* 103, 8243-8250.

Maurice, C. and A. Lagerkvist (2003), LFG emission measurements in cold climatic conditions: seasonal variations and methane emissions mitigation, *Cold Regions Sci. Tech.*, 36, 37-46.

Mayer, D.G. and D.G. Butler (1993), Statistical validation, *Ecol. Model.*, 68, 21-32.

Mertins, L., C. Vinolas, A. Bargallo, G. Sommer, and J. Renau (1999), *Development and application of waste factors - An overview*. Technical Report No. 37, European Environment Agency, Copenhagen, Denmark.

Moldrup, P., T. G. Poulsen, P. Schjonning, T. Olesen, and T. Yamaguchi (1998), Gas permeability in undisturbed soils: Measurements and predictive models, *Soil Sci.,* 163, 180–188.

Moldrup, P., T. Olesen, P. Schjonning, T. Yamaguchi, and D. E. Rolston (2000), Predicting the gas diffusion coefficient in undisturbed soils from soil water characteristics, *Soil Sci. Soc. Am. J.*, 64, 94–100.

Moldrup, P., T. Olesen, T. Komatsu, S. Yoshikawa, P. Schjonning, and D. E. Rolston. (2003), Modeling diffusion and reaction in soils: X. A unifying model for solute and gas diffusivity in unsaturated soils, *Soil Sci.,* 168, 321–337.

Moldrup, P., T. Olesen, S. Yoshikawa, T. Komatsu, and D.E. Rolston (2004), Three-porosity model for predicting the gas diffusion coefficient in undisturbed soil, *Soil Sci. Soc. Am. J.* , 68, 750–759.

Molins S., K. U. Mayer, C. Scheutz, and P. Kjeldsen (2008), Transport and reaction processes affecting the attenuation of landfill gas in cover soil, *J. Env. Qual.*, 37, 459-468.

Morrissey, L. A. and G. P. Livingston (1992), Methane emissions from Alaska arctic tundra: an assessment of local spatial variability, *J. Geophys. Res.,* 97, 16661–16670.

Muttiah, R.S. and R. A. Wurbs (2002), Scale-dependent soil and climate variability effects on watershed water balance of the SWAT model, *J. Hydrol.*, 256, 264-285.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T. Y. Jung, T. Kram, E. L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H. H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Z. Dadi (2006), *Special Report on Emissions Scenarios. IPCC Special Report on Scenarios*, Cambridge University Press, Cambridge.

New, M., M. Hulme, and P. D. Jones (1999), Representing twentieth century space-time climate variability. Part 1: Development of a 1961-90 mean monthly terrestrial climatology, *J. Climate,* 12, 829-856.

Or, D., B. F. Smets, J. M. Wraith, A. Dechesne, and S. P. Friedman (2007), Physical constraints affecting bacterial habitats and activity in unsaturated porous media: A review, *Adv. Water Resour.*, 30, 1505 – 1527.

Park, J.W., and H. C. Shin (2001), Surface emission of landfill gas from solid waste landfill, *Atmos. Environ.*, 35, 3445-3451.

Parton, W. J. (1996). The CENTURY model. In: D. S. Powlson, P. Smith, and J. U. Smith, (Eds.), *Evaluation of soil organic matter models using existing long-term datasets*, Springer-Verlag, Berlin, Germany, pp. 283-293.

Peer, R. L., S. A. Thorneloe, and D. L. Epperson (1993), A comparison of methods of estimating global methane emission from landfills, *Chemosphere,* 26, 387–400.

Pruess, K. (1987), *TOUGH User's Guide*, NUREG/CR-4645, SAND86-7104, LBL-20700, U.S. Nuclear Regulatory Commission.

Richards, K. (1989), Landfill gas: Working with gala, *Biodeterioration Abstracts* 3, 525-539.

Riveros-Iregui, D. A., R. E. Emanuel, D. J. Muth, B. L. McGlynn, H. E. Epstein, D. L. Welsch, V. J. Pacific, and J. M. Wraith (2007), Diurnal hysteresis between soil CO2 and soil temperature is controlled by soil water content, *Geophys. Res. Lett.*, 34, L17404, doi:10.1029/2007GL030938.

Rogner, H-H.; D. Zhou, R. Bradley, P. Crabbé, O. Edenhofer, B. Hare, L. Kuijpers, M. Yamaguchi,(2007), Introduction. In *Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY USA.

Rolston, D. E., and P. Moldrup (2002), Gas diffusivity. In J.H. Dane and G.C. Topp (ed.), *Methods of soil analysis. Part 4,* SSSA Book Ser. 5. SSSA, Madison, WI. 1113–1139.

Scharff, H. and J. Jacobs (2006), Applying guidance for methane emission estimation for landfills, *Waste Manage.,* 26, 417-429.

Scheutz, C.; P. Kjeldsen, J. Bogner, A. deVisscher, J. Gebert, H. Hilger, M. Huber-Humer, and K. Spokas (2009), Microbial methane oxidation processes and

technologies for mitigation of landfill gas emissions. *Waste Manage. Res.*, 27, 409-455.

Simunek, J., and D. L. Suarez (1993), Modeling carbon dioxide transport and production in soil. 1. Model development, *Water Resour. Res.*, 29, 487–497.

Spokas K., C. Graff, M. Morcet, and C. Aran (2003), Implications of the spatial variability of landfill emission rates on geospatial analyses, *Waste Manage.,* 23, 599-607.

Spokas K., J. Bogner J. Chanton, M. Morcetm, C. Aran, C. Graff, Y. Moreau-le-Golvan, N. Bureau, and I. Hebe (2006), Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?, *Waste Manage.,* 26, 516-525.

Spokas K.A. and F. Forcella (2006), Estimating hourly incoming solar radiation from limited meteorological data, *Weed Sci.*, 54,182-189.

Spokas K.A. and F. Forcella (2009), Software tools for weed seed germination modeling. *Weed Sci.*, 57, 216–227.

Spokas, K. and J. Bogner (2011), Limits and dynamics of methane oxidation in landfill cover soils, *Waste Manage.* 31, 823-832.

Stark, J. and M. Firestone (1995), Mechanisms for soil moisture effects on activity of nitrifying bacteria, *Appl. Environ. Microbiol.* 61, 218-221.

Stern, J. C., J. Chanton, T. Abichou, D. Powelson, L.Yuan, S. Escoriza, J. Bogner (2007), Use of a biologically active cover to reduce landfill methane emissions and enhance methane oxidation, *Waste Manage.,* 27, 1248-1258.

Thoma, E. D, S. A. Thorneloe, R. R. Segall, R. B. Green, G. R. Hater, R. A. Hashmonay, M. T. Modrak, M. J. Chase, and C. D. Goldsmith (2008), Development of EPA OTM-10 for landfill applications, Interim report 2, In: *Proceedings of the Global Waste Manage. Symposium*, Copper Mountain, CO, September 7-10, 2008.

Thoma, E.D., R. B. Green, G. R. Hater, C. D. Goldsmith, N. D. Swan, M. J. Chase, and R. A. Hashmonay (2010), Development of EPA OTM 10 for Landfill Applications, *J. Envir. Engrg.* 136, 769-773, DOI:10.1061/(ASCE)EE.1943-7870.0000157.

Thompson, S., J. Sawyer, R. Bonam, J.E. Valdivia (2009), Building a better methane generation model: Validating models with methane recovery rates from 35 Canadian landfills, *Waste Manage.*, 29, 2085-2091.

United States Environmental Protection Agency (2005), *Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide,* U.S. EPA: Washington, D.C.

US EPA AP-42 (2008), *United States Environmental Protection Agency AP-42 document, Municipal solid waste landfills*, Fifth Edition, Volume I, Chapter 2: Solid Waste Disposal, October 2008 (draft).

U.S. Environmental Protection Agency (2011), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990- 2009* Draft http://www.epa.gov/climatechange/emissions/usinventoryreport.html. (Accessed March 24, 2011.)

Vachaud, G., P. de Silans, P. Balabanis, and M. Vauclin (1985), Temporal stability of spatially measured soil water probability density function, *Soil Sci. Soc. Am. J.*, 49, 822-828.

van Zanten, B. and M. J. J. Scheepers (1995), Modeling of Landfill Gas Potentials. In *Proceedings from the SWANA 18'" Annual Landfill Gas Symposium*, New Orleans, LA.

Watt, M. S., V. Xu, and M. Bloomberg (2010), Development of a hydrothermal time seed germination model which uses the Weibull distribution to describe base water potential, *Ecol. Model.*, 221, 1267-1272.

Weeks, E.P., D. E. Earp, and G. M., Thompson (1982), Use of atmospheric fluorocarbons F-11 and F-12 to determine the diffusion parameters of the unsaturated zone in the Southern High Plains of Texas, *Water Resour.Res.*, 18, 1365-1378.

Wegehenkel, M. (2000), Test of a modeling system for simulating water balances and plant growth using various different complex approaches. *Ecol. Model.* 129:39–64.

Wille, C., L. Kutzbach, T. Sachs, D. Wagner, E. M. Pfeiffer (2008), Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling, *Global Change Biol,* 14, 1395-1408.

Willmott, C. J. (1981), On the validation of models, *Phys. Geography*, 2, 184-194.

Willmott, C.J. (1982), Some comments on the evaluation of model performance, *Bull. Am. Meteor. Soc.*, 64, 1309-1313.

Willmott, C. J. and K. Matsuura (1995), Smart interpolation of annually averaged air temperature in the United States, *J. Appl. Meteorol.*, 34, 2577-2586.

Winslow, J. C., E. R. Hunt, and S. C. Piper (2001), A globally applicable model of daily solar irradiance estimated from air temperature and precipitin data, *Ecol. Model.,* 143, 227-243.

Wösten, J. H. M. and M. Th. van Genuchten (1988), Using texture and other soil properties to predict the unsaturated hydraulic functions, *Soil Sci. Soc. Am. J.,* 52, 1762–1770.

Yu, L., F. Batlle, and A. Lloret (2010), A coupled model for prediction of settlement and gas flow in MSW landfills, *Int. J. Numeric. Anal. Methods in Geomechanics*, doi: 10.1002/nag.856 (in press)

Zhang, H., P. He, and L. Shao (2008), Methane emissions from MSW landfill with sandy soil covers under leachate recirculation and subsurface irrigation, *Atmos. Environ.*, 42, 5579-5588.

Table 1. Overview of CALMIM input parameters, bundled models and outputs.

					Description	**Value/Units/Reference**
Model Inputs	Site				Latitude	Decimal degrees (+N , -S)
					Longitude	Decimal degrees (-W, +E)
					Waste Footprint	Acres
	Cover Characteristics				Coverage	0-100% of waste footprint
					Organic Matter	Low-high (0-5%)
					Vegetation Presence	0-100% cover (slider bar) Modifies incoming solar radiation [Si = (1-Veg%)*Si]
					Gas Recovery System	0-100% coverage (slider bar) Reduces the lower methane concentration in default cover scenarios
		Cover Type Selection				
		Daily		Temperature	Upper	Air temperature simulation
					Lower	25 ^{o}C
				CH_4	Upper	2 ppmv
					Lower	0.3 % (v/v)
				Oxygen	Upper	20 % (v/v)
					Lower	5 % (v/v)
				CH_4 oxidation rate		1 µg CH_4 $g_{soil}^{-1}d^{-1}$
		Intermediate		Temperature	Upper	Air temperature simulation
					Lower	35 ^{o}C
				CH_4	Upper	2 ppmv
					Lower	45 % (v/v)
				Oxygen	Upper	20 % (v/v)
					Lower	1 % (v/v)
				CH_4 oxidation rate		200 µg CH_4 $g_{soil}^{-1}d^{-1}$
		Final		Temperature	Upper	Air temperature simulation
					Lower	40 ^{o}C
				CH_4	Upper	2 ppmv
					Lower	55 % (v/v)
				Oxygen	Upper	20 % (v/v)
					Lower	0 % (v/v)
				CH_4 oxidation rate		400 µg CH_4 $g_{soil}^{-1}d^{-1}$
		Custom		User selectable boundary conditions		
		Layer Characteristics		Material		Various materials (Table 2)
				Thickness		Variable: 2.5 cm to 2.5 m (1 to 100")

Table 1. Continued

				Description	Value/Units/Reference
Bundled Models	GlobalTempSIM			Air temperature simulation	Spokas and Forcella, 2009
	GlobalRainSIM			Precipitation simulation	Spokas and Forcella, 2009
	SolarCalc			Solar radiation simulation	Spokas and Forcella, 2006
	STM^2			Soil temperature and moisture model	Spokas and Forcella, 2009
	Gas Diffusion			Oxygen and methane diffusion	Campbell, 1985
Model Outputs	*Model outputs are written directly to Excel compatible files for each cover type*				
	Daily Surface CH_4 emissions			With oxidation	g CH_4 $m^{-2}d^{-1}$
				Without oxidation	g CH_4 $m^{-2}d^{-1}$
	Soil Nodes (2.5 cm layer in cover)			Soil Temperature	^oC
				Soil Moisture	Volumetric (cm^3 cm^{-3})
				Air-filled porosity	cm^3 cm^{-3}
				Oxygen Concentration	% O_2
		CH_4 Concentration		With oxidation	% CH_4
				Without oxidation	% CH_4
				CH_4 oxidation rate	g CH_4 $m^{-2}d^{-1}$
				CH_4 oxidation percentage	%
				Bulk density	g cm^{-3}
				Fraction of time oxidizing	0 to 100% (0-1)
	Simulated Weather Data			Maximum air temperature	^{o}C
				Minimum air temperature	^{o}C
				Precipitation	mm

Table 2. Model results for various global locations for the three simulated default cover designs

				Daily		Intermediate		Final		% CH_4 Oxidation		
	Lat/Lon	Average Annual Temp (^oC)	Average Annual Precipitation (mm)	Without Oxidation	With Oxidation	Without Oxidation	With Oxidation	Without Oxidation	With Oxidation	Daily	Int.	Final
				($g\ CH_4\ m^{-2}\ d^{-1}$)						(% Oxidation)		
London, UK	51.5 N 0 E	9.6	607.3	5.0	4.8	512.5	452.8	202.1	18.1	4.5	11.7	90.8
Rio De Janeiro, Brazil	22.92 S 43.10 W	21.5	123.3	4.6	4.1	470.9	386.0	161.3	-	9.4	18.1	100
Vancouver, Canada	49.18 N 123.17 W	10.3	986.6	4.7	4.7	507.5	446.2	187.3	10.1	4.7	12.1	94.0
Stockholm, Sweden	59.35 N 18.07 E	5.0	406.2	5.2	5.0	527.3	479.3	215.7	59.3	3.4	9.3	73.4
Cairo, Egypt	30.13N 31.40 E	21.1	24.3	4.7	4.3	490.1	409.0	204.9	1.7	7.5	16.6	99.2
Lima, Peru	12.0 S 77.09 W	21.5	123.3	4.7	4.3	490.4	404.6	213.7	0.01	8.0	17.5	99.9
Sydney, Australia	33.95 S 151.10 E	17.6	869.8	4.7	4.4	493.4	415.1	201.1	0.1	7.3	15.9	99.7
Mexico City, Mexico	19.43 N 99.08 W	13.7	737.7	4.8	4.6	506.5	434.9	210.8	7.1	5.9	14.2	97.0
Beijing, China	39.93 N 116.20 E	9.9	457.0	5.0	4.8	518.4	459.7	223.0	55.6	5.2	11.7	77.1
Juneau, Alaska US	58.3 N 134.4 W	6.4	1766.2	4.9	4.7	507.1	456.8	155.8	27.1	3.7	10.0	83.6
Moscow, Russia	55.80 N 37.60 E	3.65	425.8	5.2	5.1	532.0	415.9	219.1	72.9	3.4	8.9	68.7
Barrow, Alaska	71.28 N 156.78 W	-12.3	70.05	5.8	5.8	585.4	565.9	254.8	174.7	1.2	3.5	32.2

Table 3. CALMIM model Comparisons for Intermediate Cover Areas at Other California Landfill Sites

Site Name	Location	Field Measurements [*Green et al.,* 2009] Flux Chamber ($g\ CH_4\ m^{-2}\ d^{-1}$)	Field Measurements [*Green et al.,* 2009] VRPM ($g\ CH_4\ m^{-2}\ d^{-1}$)	Model Annual Prediction (with oxidation) ($g\ CH_4\ m^{-2}\ d^{-1}$)
Lancaster	34.747 °N 118.116 °W	-0.21 to 0.47 Mean: +0.02 Median: 0	1 to 5	0.47
Kirby Canyon	37.185 °N 121.671 °W	-0.04 to 0.05 Mean: -3.36 Median: 0	8 to 11	0.14
Tri-cities	37.510 °N 121.99 °W	-0.02 to 9.2 Mean:+6.82 Median:+0.03	23 to 42	3.9

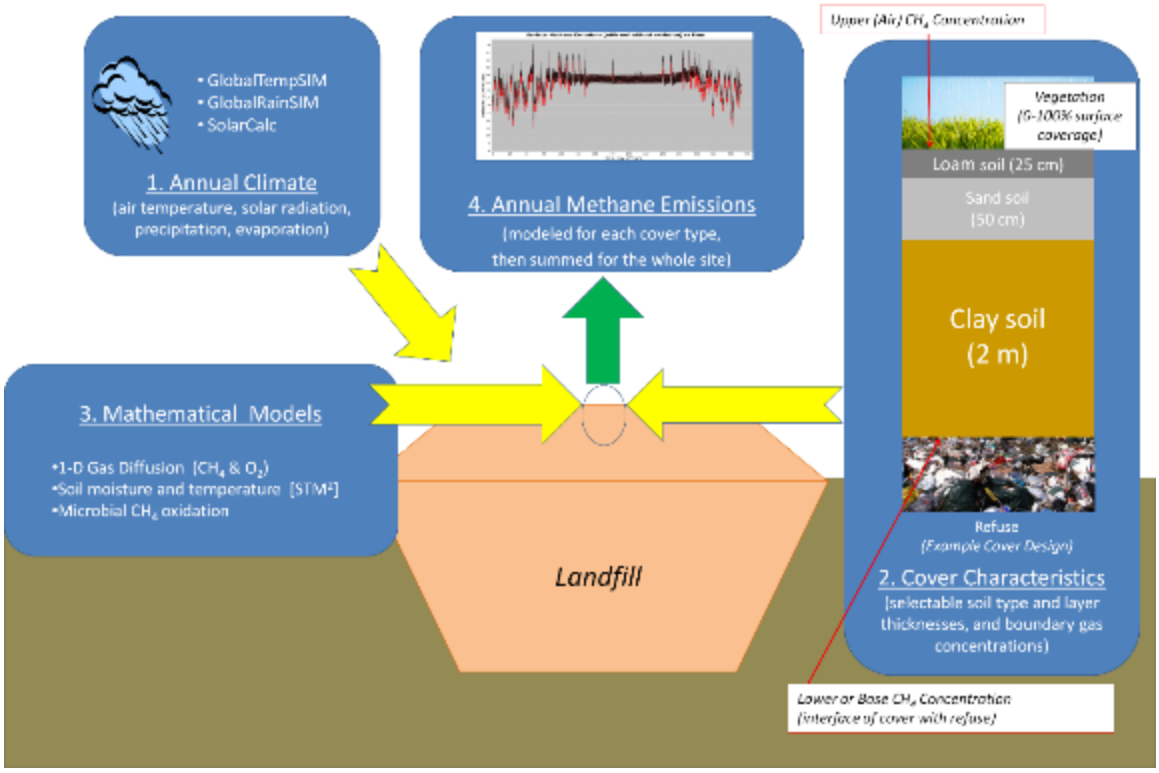

• GlobalTempSIM
• GlobalRainSIM
• SolarCalc
1. Annual Climate
(air temperature, solar radiation, precipitation, evaporation)
4. Annual Methane Emissions
(modeled for each cover type, then summed for the whole site)
Upper (Air) CH4 Concentration
Vegetation
(0-100% surface coverage)
Loam soil (25 cm)
Sand soil
(50 cm)
Clay soil
(2 m)
Refuse
(Example Cover Design)
2. Cover Characteristics
(selectable soil type and layer thicknesses, and boundary gas concentrations)
3. Mathematical Models
•1-D Gas Diffusion (CH4 & O2)
•Soil moisture and temperature (STM²)
•Microbial CH4 oxidation
Landfill
Lower or Base CH4 Concentration
(interface of cover with refuse)

Figure 1.

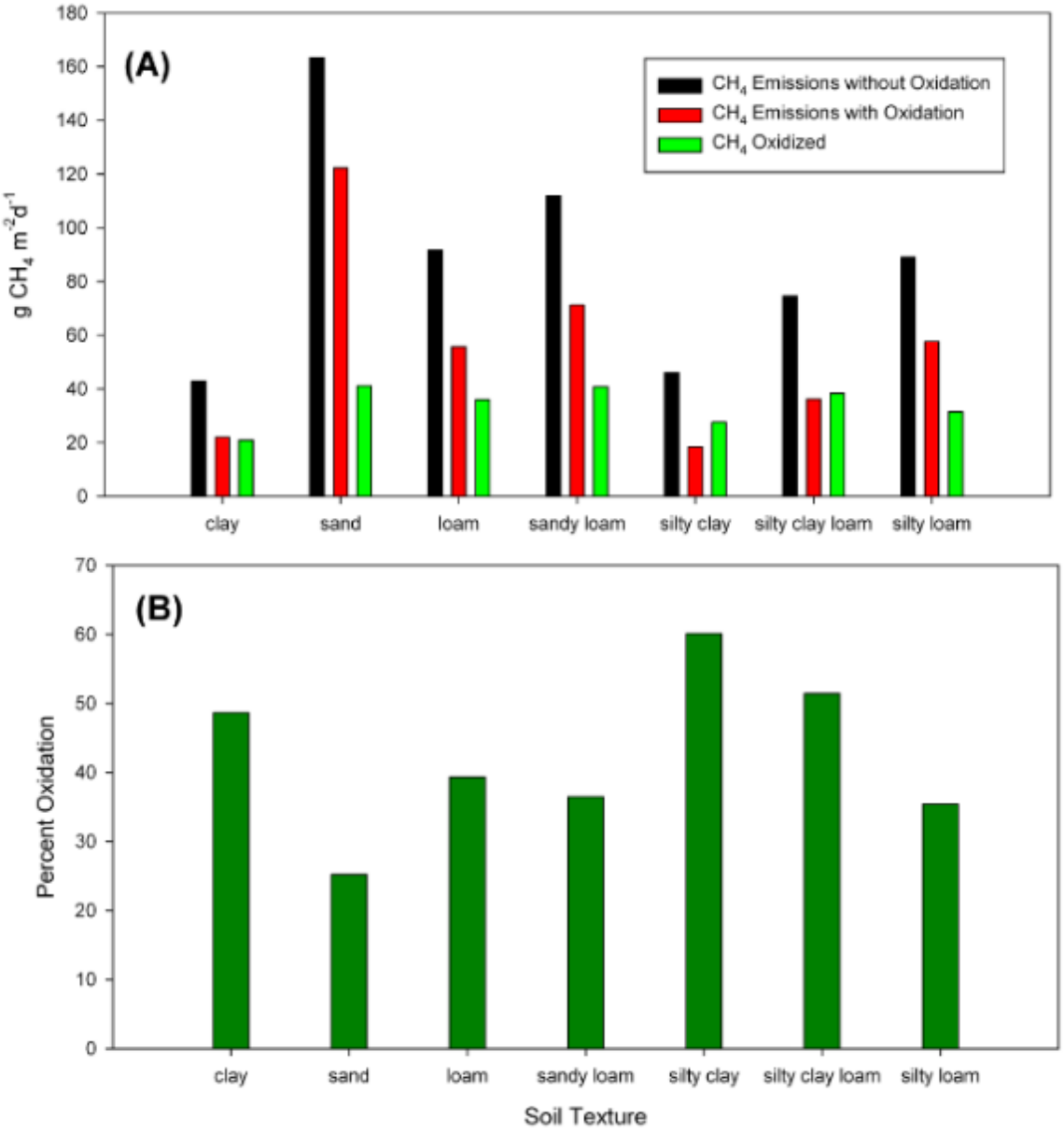

(A)
CH_4 Emissions without Oxidation
CH_4 Emissions with Oxidation
CH_4 Oxidized
g CH_4 $m^{-2}d^{-1}$
0
20
40
60
80
100
120
140
160
180
clay
sand
loam
sandy loam
silty clay
silty clay loam
silty loam
(B)
Percent Oxidation
0
10
20
30
40
50
60
70
clay
sand
loam
sandy loam
silty clay
silty clay loam
silty loam
Soil Texture

Figure 2.

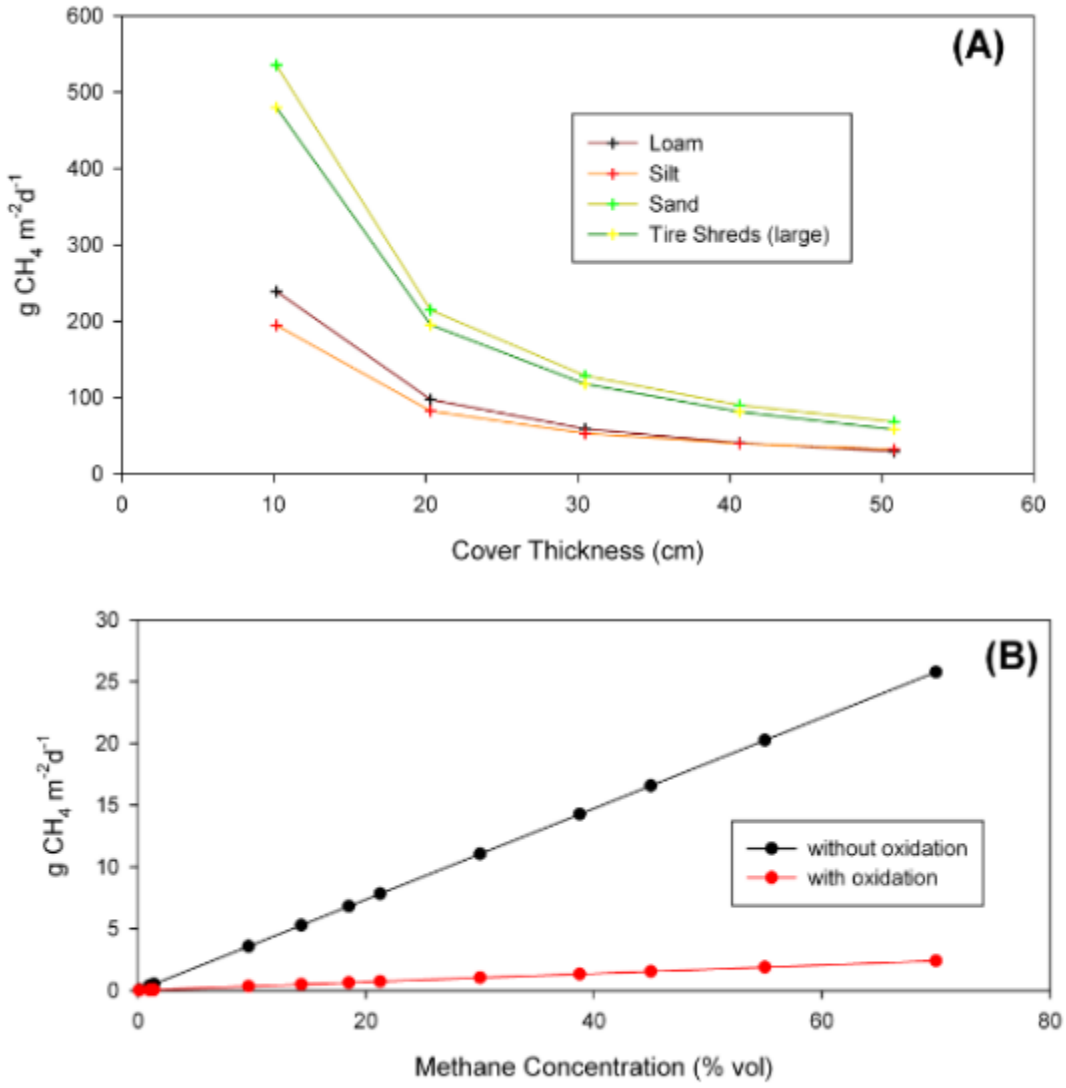

(A)
Loam
Silt
Sand
Tire Shreds (large)
g CH_4 $m^{-2}d^{-1}$
Cover Thickness (cm)
(B)
without oxidation
with oxidation
g CH_4 $m^{-2}d^{-1}$
Methane Concentration (% vol)

Figure 3

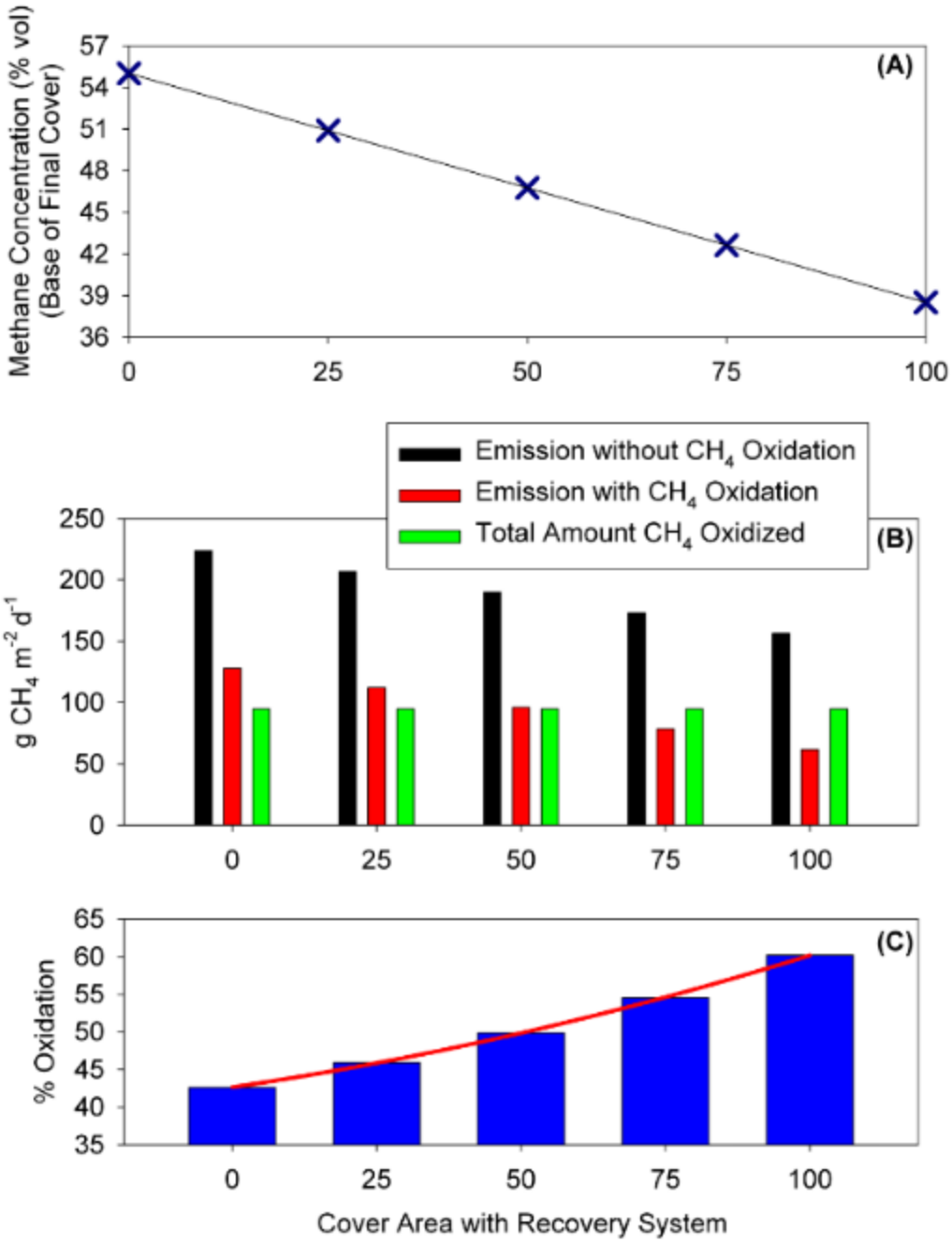

Methane Concentration (% vol)
(Base of Final Cover)
57
54
51
48
45
42
39
36
0
25
50
75
100
(A)
Emission without CH_4 Oxidation
Emission with CH_4 Oxidation
Total Amount CH_4 Oxidized
(B)
g CH_4 m^{-2} d^{-1}
250
200
150
100
50
0
0
25
50
75
100
(C)
% Oxidation
65
60
55
50
45
40
35
0
25
50
75
100
Cover Area with Recovery System

Figure 4

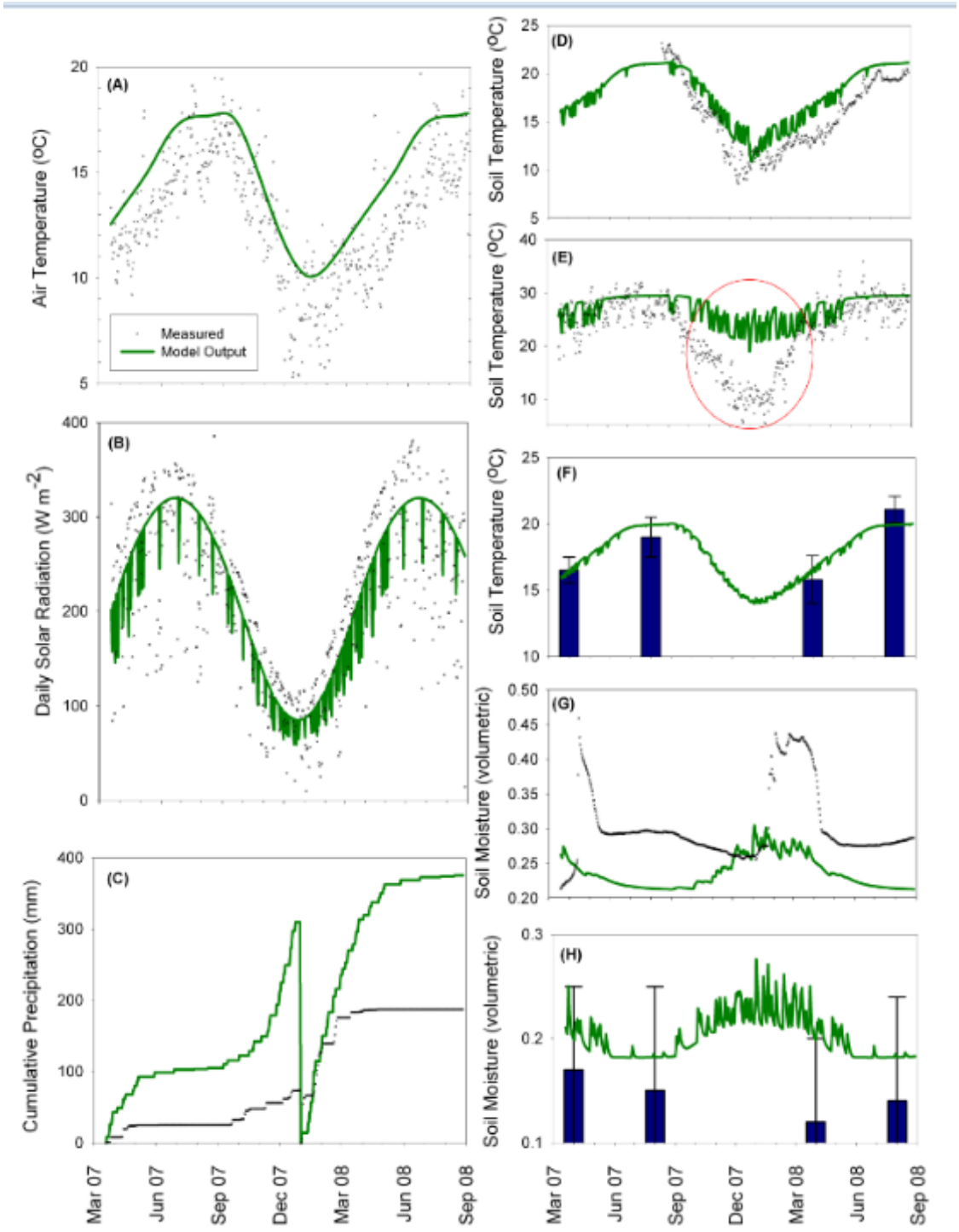

(A)
Air Temperature (°C)
Measured
Model Output
(B)
Daily Solar Radiation (W m-2)
(C)
Cumulative Precipitation (mm)
(D)
Soil Temperature (°C)
(E)
Soil Temperature (°C)
(F)
Soil Temperature (°C)
(G)
Soil Moisture (volumetric)
(H)
Soil Moisture (volumetric)
Mar 07
Jun 07
Sep 07
Dec 07
Mar 08
Jun 08
Sep 08

Figure 5

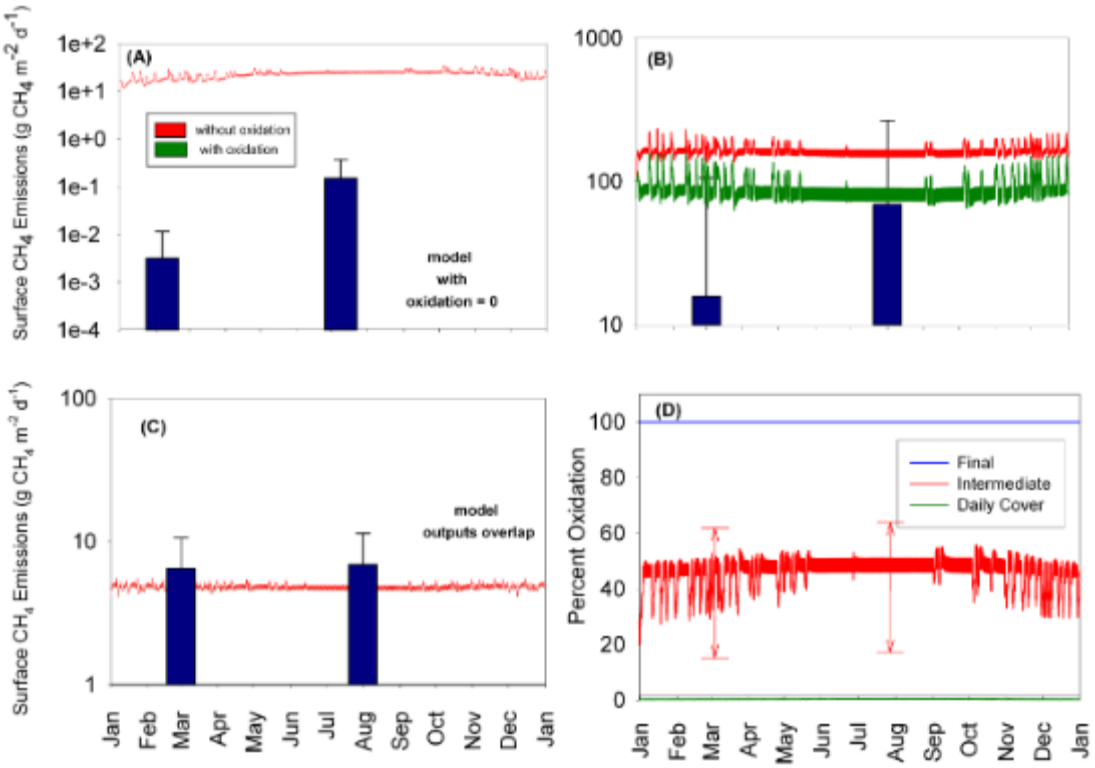

(A)
without oxidation
with oxidation
model
with
oxidation = 0
(B)
(C)
model
outputs overlap
(D)
Final
Intermediate
Daily Cover
Percent Oxidation
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

Figure 6

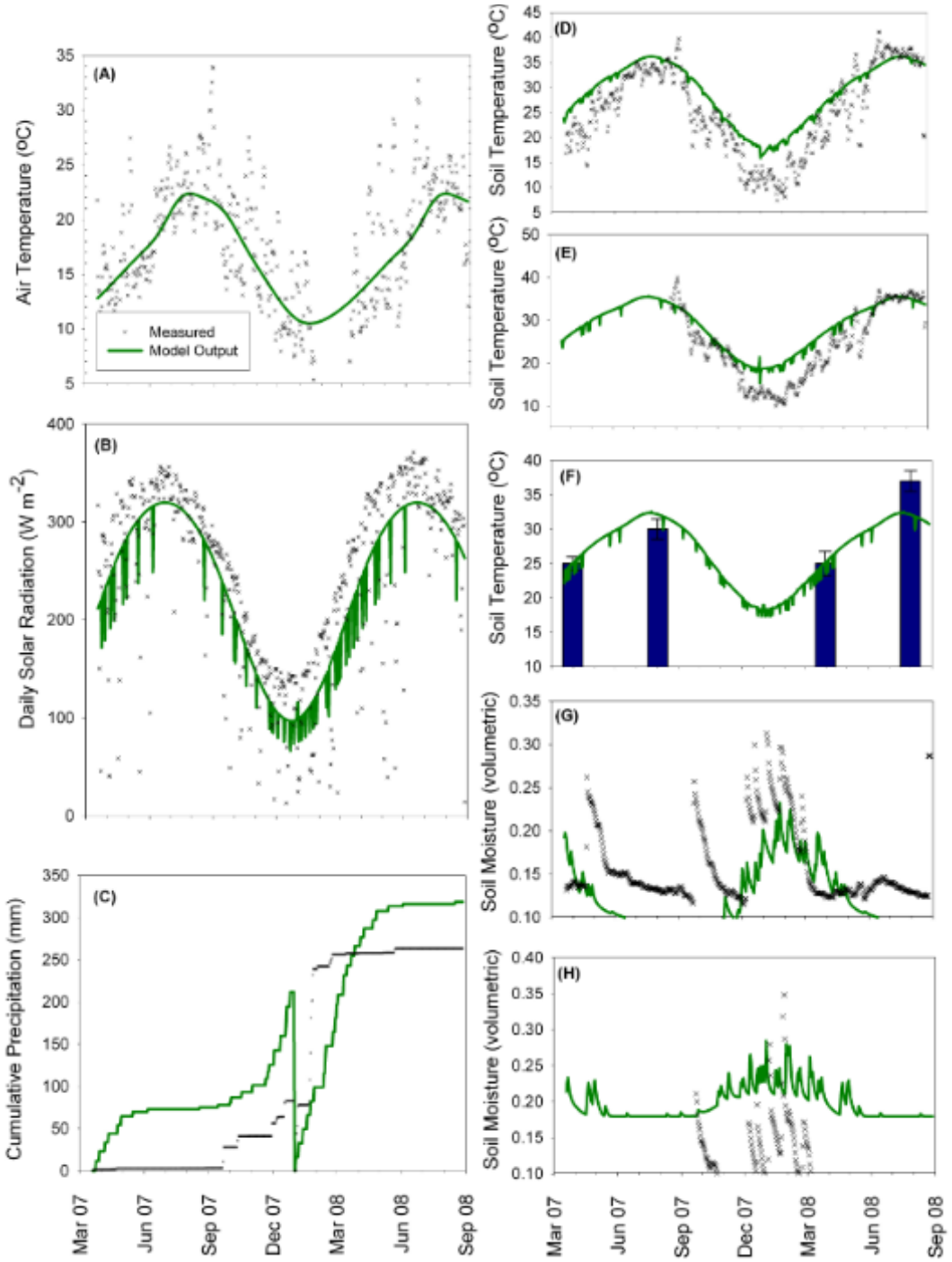

(A)
Air Temperature (°C)
Measured
Model Output
(B)
Daily Solar Radiation (W m-2)
(C)
Cumulative Precipitation (mm)
(D)
Soil Temperature (°C)
(E)
Soil Temperature (°C)
(F)
Soil Temperature (°C)
(G)
Soil Moisture (volumetric)
(H)
Soil Moisture (volumetric)
Mar 07
Jun 07
Sep 07
Dec 07
Mar 08
Jun 08
Sep 08

Figure 7.

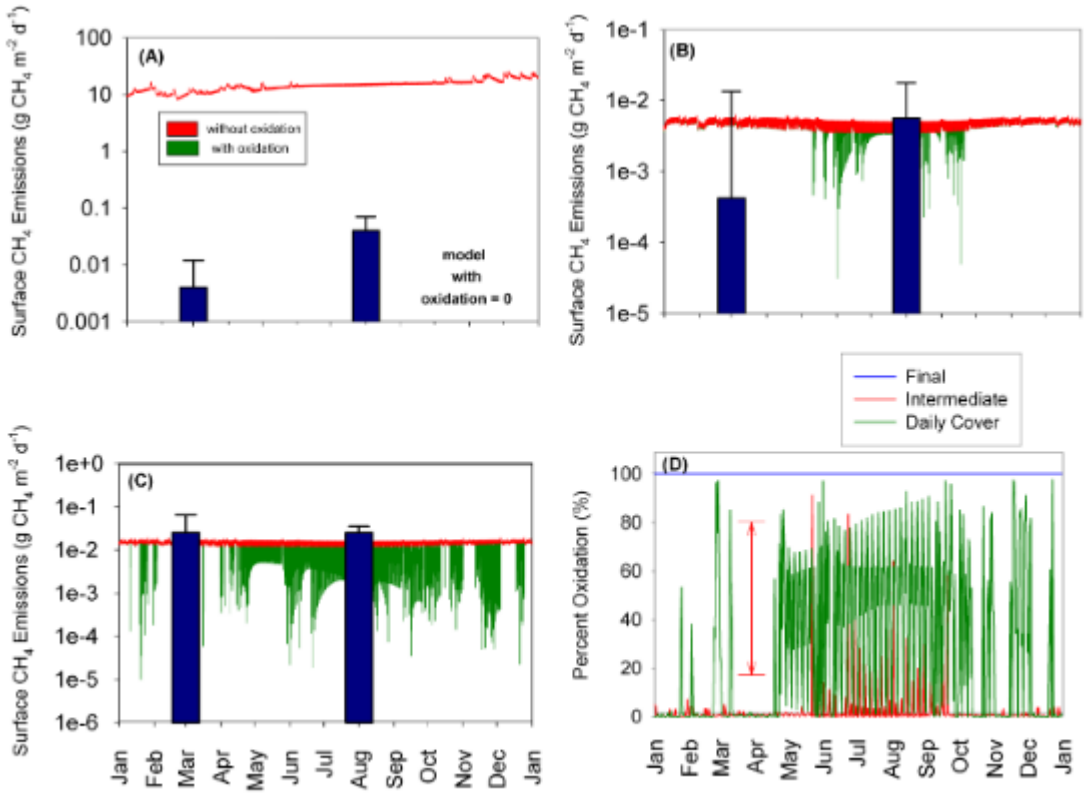

(A)
without oxidation
with oxidation
model with oxidation = 0
Surface CH4 Emissions (g CH4 m-2 d-1)
100
10
1
0.1
0.01
0.001
(B)
1e-1
1e-2
1e-3
1e-4
1e-5
Final
Intermediate
Daily Cover
(C)
1e+0
1e-1
1e-2
1e-3
1e-4
1e-5
1e-6
(D)
Percent Oxidation (%)
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

Fig. 8


(A)
(B)
(C)
(D)
Surface Methane Emissions (with and without oxidation) vs Time

Figure S1

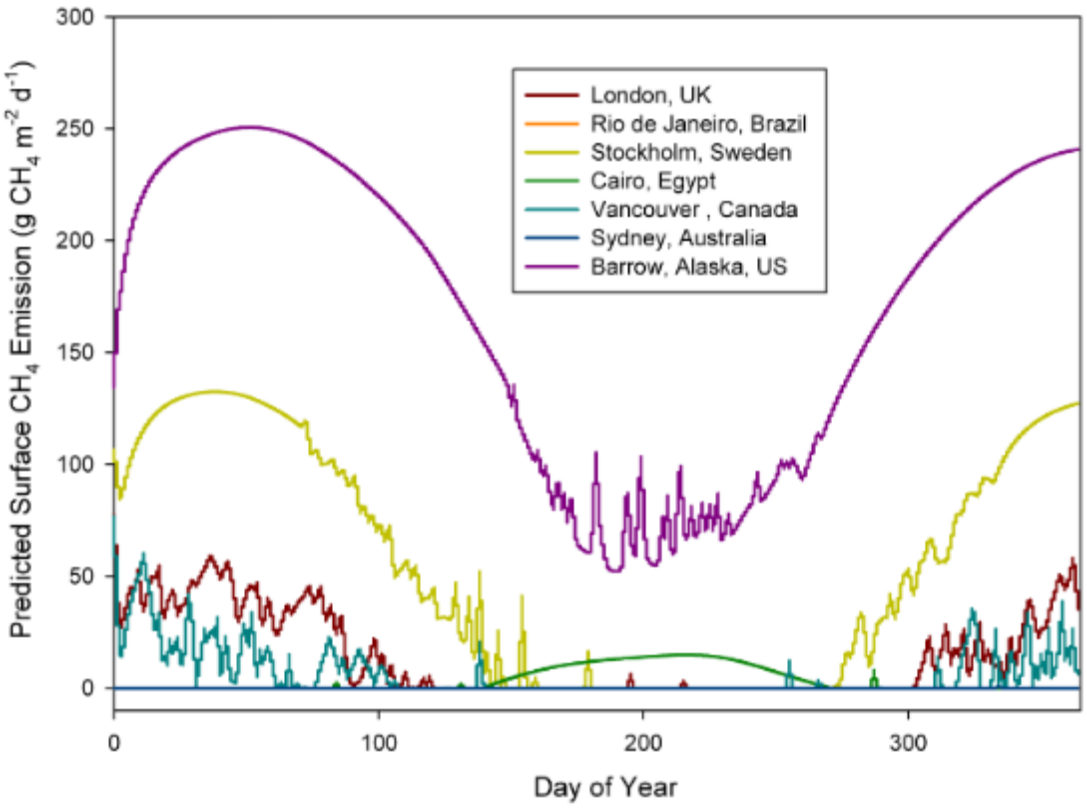

Predicted Surface CH_4 Emission (g CH_4 m^{-2} d^{-1})
Day of Year
0
50
100
150
200
250
300
0
100
200
300
London, UK
Rio de Janeiro, Brazil
Stockholm, Sweden
Cairo, Egypt
Vancouver , Canada
Sydney, Australia
Barrow, Alaska, US

Figure S2.

Appendix C. List of project deliverables generated at the time of final report submission

Journal Articles 2011-2013

Spokas, K., Bogner J., and Chanton, J., A Process-Based Inventory Model for Landfill CH_4 Emissions Inclusive of Soil Microclimate and Seasonal Methane Oxidation, J. Geophysical Research-Biogeosciences, 116: paper G04017, 19 p. (2011).

Bogner, J., Spokas, K., and Chanton, J., Seasonal Greenhouse Gas Emissions (methane, carbon dioxide, nitrous oxide) from Engineered Landfills: Daily, Intermediate, and Final California Landfill Cover Soils, J. Environ. Quality 40:1010-1020 (2011).

Bellucci F., Bogner J., and Sturchio N.C., Greenhouse Gas Emissions at the Urban Scale, Elements, Special Issue on Urban Geochemistry, 8:445-450 (2012).

Spokas, K., and Bogner, J., Limits and dynamics of methane oxidation in landfill cover soils, Waste Management 31:823-832 (2011).

Report

Bogner, J., Contributing Author, United Nations Environment Program (UNEP), November, 2011, Bridging the Emissions Gap: A U.N. Synthesis Report, published by UNEP [ISBN:978-92-807-3229-0, DEW/1470/NA].

Conference Papers and Presentations

Bogner, J., Evolutionary & Revolutionary Thinking about Landfill Processes, Keynote Presentation (part of "Lifetime" award), Sardinia '13 International Solid Waste and Landfilling Symposium, October, 2013, St. Marguerita di Pula, Sardinia (Italy). (2013)

Bogner, J., Spokas, K., and Corcoran, M., Site-specific Landfill CH_4 Emissions: Shortcomings of Current GHG Inventory Guidelines and a Field-Validated, Process-Based Approach Inclusive of Local Climate, Proceedings Sardinia '13 International Solid Waste and Landfilling Symposium, October, 2013, St. Marguerita di Pula, Sardinia (Italy). (2013)

Asadi, M., Yuen, S., Chen, D., Bogner, J., and Lightbody, P., Methane Emissions from a Municipal Waste Landfill in South Australia without Gas Recovery: Comparison Between Field Measurements and CALMIM Modeled Results, Proceedings Sardinia '13 International Solid Waste and Landfilling Symposium, October, 2013, St. Marguerita di Pula, Sardinia (Italy). (2013)

Bogner, J., Spokas, K., and Corcoran, J., 2012, Site-Specific Landfill CH_4 Emissions: Shortcomings of National GHG Inventory Guidelines and a New Process-Based Approach Linked to Climate and Soil Microclimate, Oral Presentation, American Geophysical Union (AGU), San Francisco, December, 2012.

Bogner, J., Spokas, K., Chanton, J., and Corcoran, M., CALMIM: A New Field-validated Model for Site-Specific Landfill CH_4 Emissions, Proceedings SWANA 35nd Landfill gas Symposium, March 2012, Published by Solid Waste Association of North America (SWANA), Silver Spring, Md. (2012).

Corcoran, M., Bogner, J., and Spokas, J., CALMIM: A Process-based Annual Inventory Model for Site-Specific Landfill CH_4 Emissions, Presentation by M. Corcoran, U.S. EPA Landfill Methane Outreach Program 15th Annual Conference, January 2012, Baltimore, Maryland (2012).

Bogner, J., Spokas, K., Chanton, J., Field Measurement of Greenhouse Gas Emissions (CH_4, CO_2, N_2O) from Daily, Intermediate, and Final California Cover Soils, Proceedings Sardinia '11 International Solid and Hazardous Waste Symposium, October, 2011, CISA, Univ. of Cagliari, Sardinia (2011).

Appendix D. Supporting information that is not appropriate to include in main report (e.g. additional tables, figures, raw data, etc.)

Table D.1. Individual Site Reports Comparing Field Measurements to Modeled Results Using CALMIM Version 5.4

1. St. Polten

Site Name: St. Polten

Site Location: Austria

Latitude: 48.196777 **Longitude:** 15.592389

Total Size: Entire landfill 14ha (34.6 acres). Total for test cells 0.31ha (0.77 acre)

Site Description: St. Polten is an operating landfill in lower Austria. Five (5) test cells were put in place in 1999 to determine whether CH_4 oxidation in biocovers made of compost would reduce methane emissions. All test cells contain 10-12m of waste placed during 1975 – 1999, overlain by 3m of fresh organic waste placed in 1999 just prior to the field testing [to ensure CH_4 production]. Each test cell is 25 x 25m, or 625m^2. Test cell TC5 had no cover, but in order to run CALMIM a very thin cover of 7.5 cm was added.

Covers

	Test Cell TC1	Test Cell TC2	Test Cell TC3	Test Cell TC4	Test Cell TC5
Hectares (Acres) *	0.06 (0.15)	0.06 (0.15)	0.06 (0.15)	0.06 (0.15)	0.06 (0.15)
Cover Type	Final	Final	Final	Final	Final
Coverage % *	20%	20%	20%	20%	20%
Organic Matter %	high	high	high	high	high
Gas Recovery %	100%	100%	100%	100%	100%
Vegetation %	98%	95%	95%	90%	60%

* For use in CALMIM model

Layers

		Test Cell TC1	Test Cell TC2	Test Cell TC3	Test Cell TC4	Test Cell TC5
1	**Material ****	ADC Sludge [SS compost]	ADC Composted Organic Material [MSW Compost]	ADC Sludge [SS compost]	ADC Sludge [SS compost]	DCA Composted Organic Material [None. Used DCA COM so CALMIM could run.]
	Thickness	90cm	90cm	40cm	30cm	7.5cm
2	**Material**	Rocks – Pebbles [Gravel]	Rocks – Pebbles [Gravel]		Loam	
	Thickness	30cm	30cm		30cm	

** The first material listed was used in the CALMIM model. The material in brackets [] is the description from literature. See additional notes below.

Custom Boundaries

Upper Temp:					
Lower Temp:					
Methane Upper:					
Methane Lower:	60	60	70	60	
Oxygen Upper					
Oxygen Lower:					
Methane Rate					

Additional Notes:
For the layered materials shown above, the first material is the material selected in CALMIM, the second [in brackets] is the description from the study. Study materials are described as follows:
SS Compost: 50% sewage sludge, 50% wood chips, composted for 2 years. Not sieved, so had some large wood chips.
MSW Compost: about 16 months old, sieved to < 25mm.
Gravel: silicate, grain size > 63mm, deficient in lime (< 30% $CaCO_3$)
Actual weather data was provided for the year 2000, including average daily temperature and daily precipitation. No daily temperature minimum and maximum was available, so custom weather was not used in CALMIM.
Two CALMIM files were created. One uses the default conditions and contains all five test cells in one file, and a second file, copied from the first to retain identical generated weather data, using custom bottom methane boundaries for cells TC1 through TC4. Because TC5 has no cover there is no bottom methane value so the custom CALMIM run used default values for TC5, the same as in the first CALMIM file. Custom CH_4 boundaries are based on the measured gas profiles from the field study.

Field Results:
Field testing was performed using an open tunnel [large chamber] method from February, 2001 through September, 2001.
FID-scans and gas profiles were performed starting in spring 1999 and completed in autumn 2001 (a period of 2.5 years).
Emission measurements were performed in two to three campaigns per month between February and September of 2001. The tunnel was placed on sites with pre-scanned surface methane concentrations according to FID-mapping or on visible "hot spots" (lack of vegetation, etc.)

Field Results ($g/m^2/day$) (Huber-Humer and Lechner, 2001; Huber-Humer, 2004; Huber-Humer et al., 2009)

	TC1	TC2	TC3	TC4	TC5
Area weighed mean of field results from Feb, 2001 through Sept., 2001	0.1	0.6	12.6	10.4	39.5

Mean Modeled Annual Emissions with Oxidation ($g/m^2/day$)

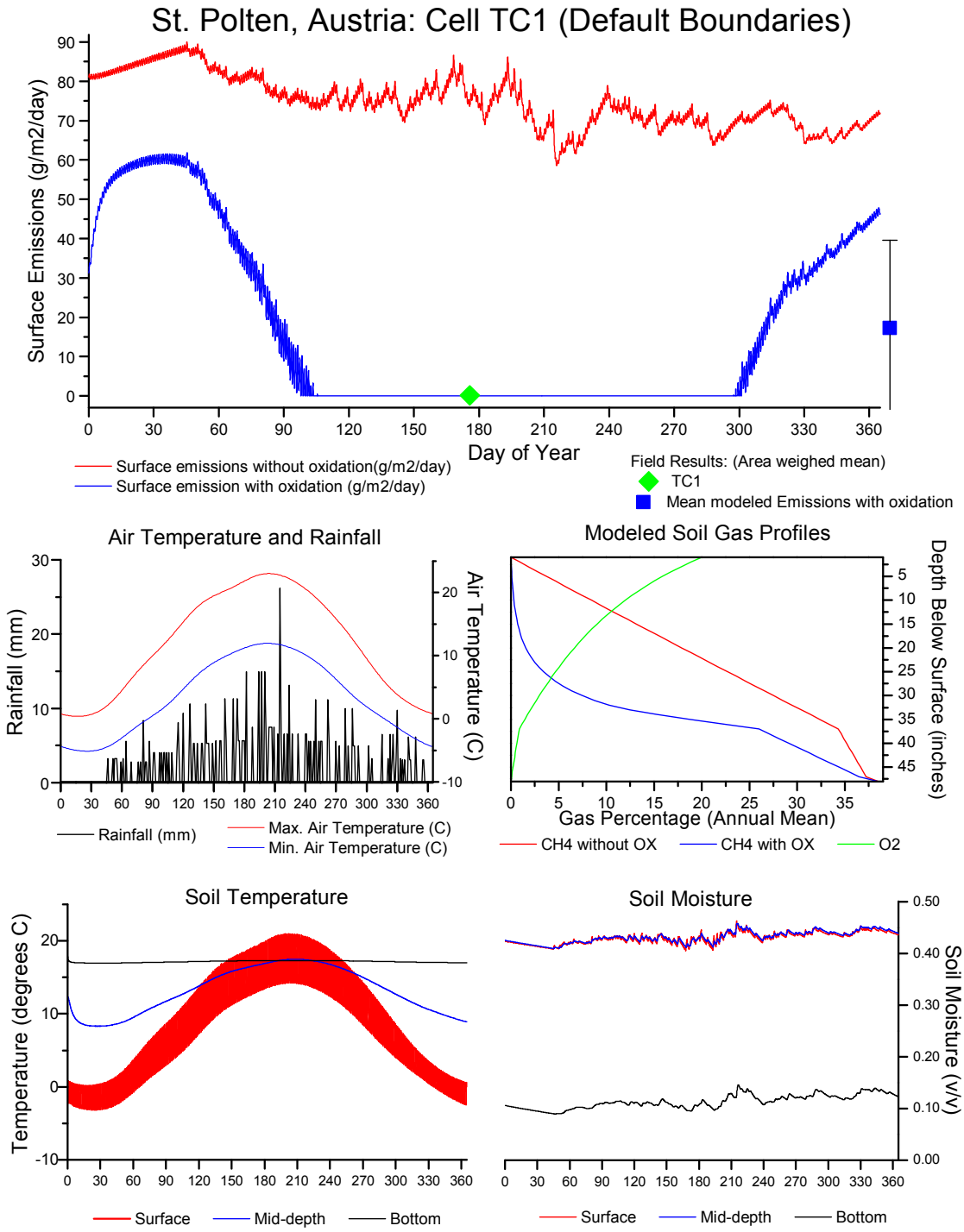
CALMIM 5.4 Default boundaries	17.30	3.28	164.95	40.48	2053.54
CALMIM 5.4 With Custom CH_4 Bottom Boundaries	39.49	16.09	391.19	106.39	N/A

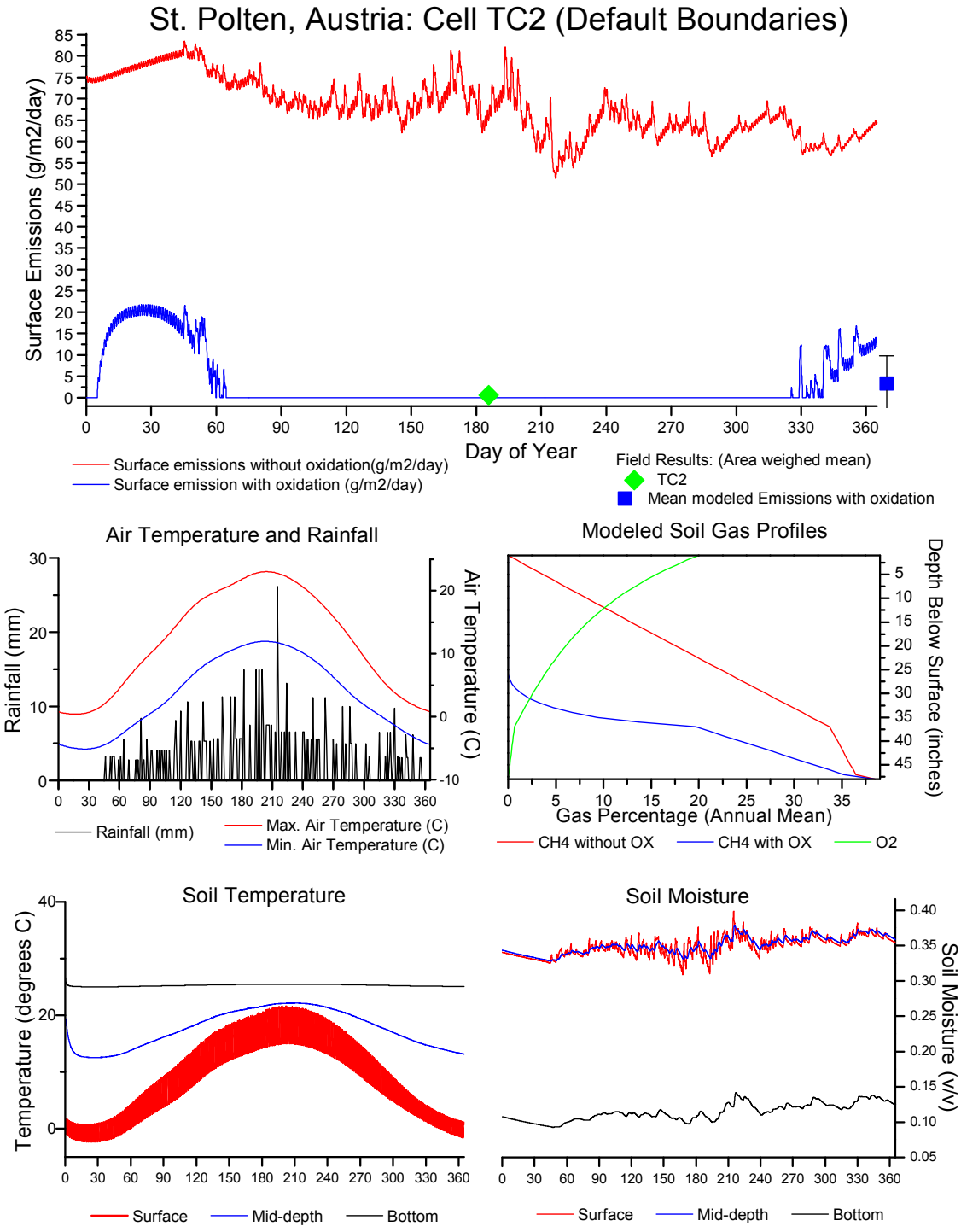
References:

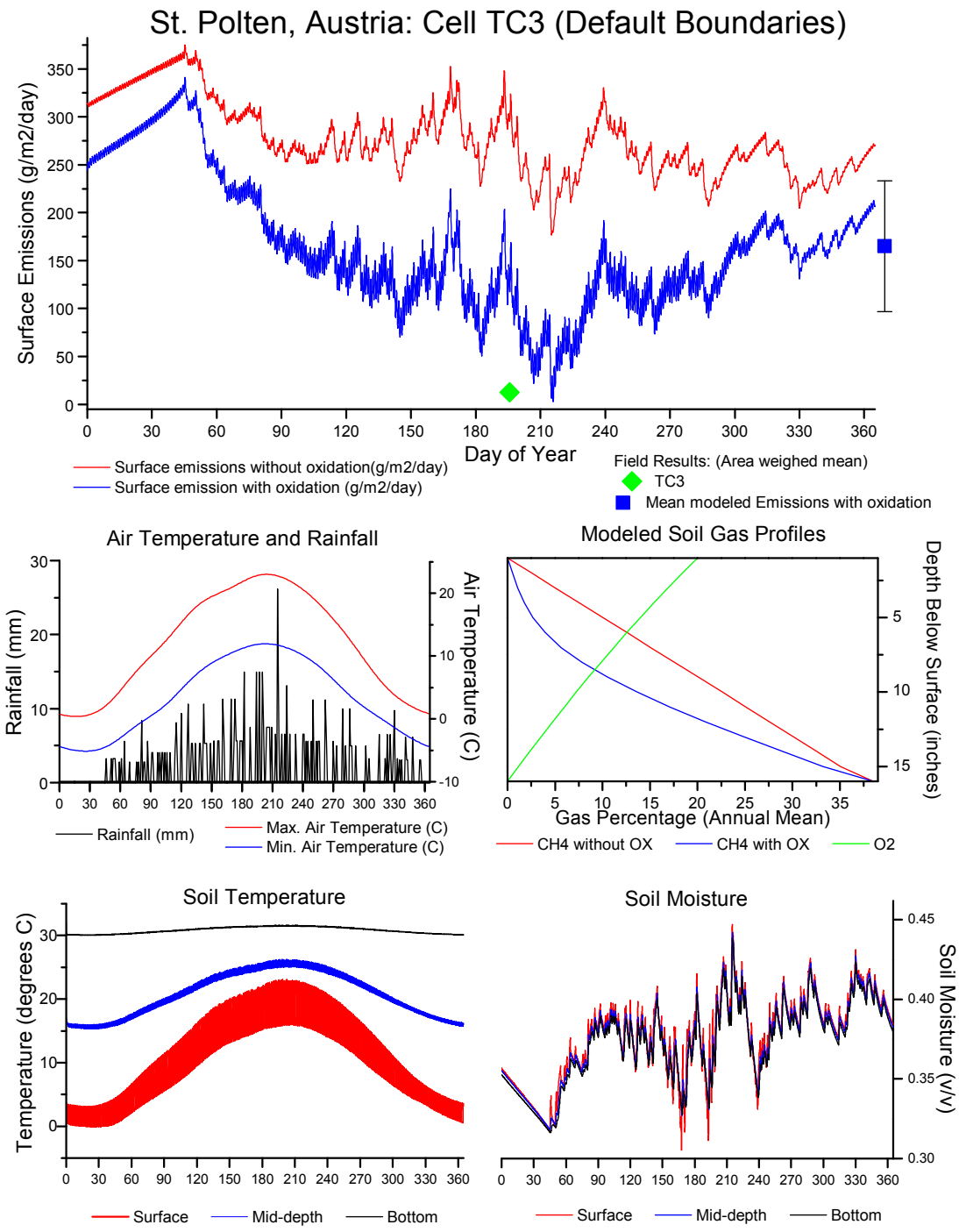
Huber-Humer, M., 2004. Abatement of landfill methane emissions by microbial oxidation in biocovers made of compost. Doctoral Thesis, University of Natural Resources and Applied Life Sciences Vienna, Institute of Waste Management, Vienna, Austria.

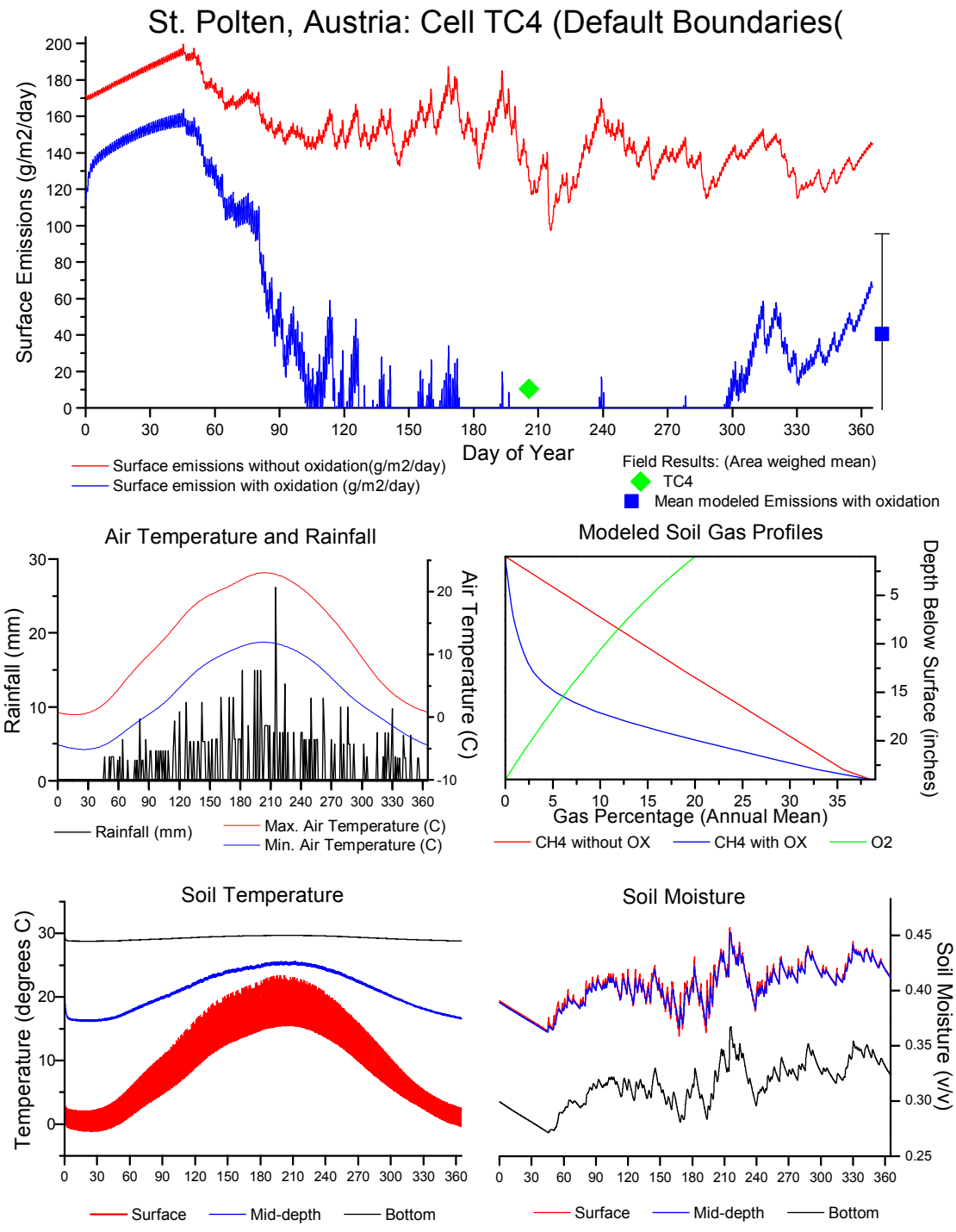
Huber-Humer, M., Lechner, P., 2001. Design of a landfill cover layer to enhance methane oxidation - results of a two year field investigation, Proceedings of "SARDINIA 2001 – Eighth International Waste Management and Landfill Symposium", Leachate and Landfill Gas, vol. II. Environmental Sanitary Engineering Centre (CISA), Cagliari, Italy, pp. 541-550.

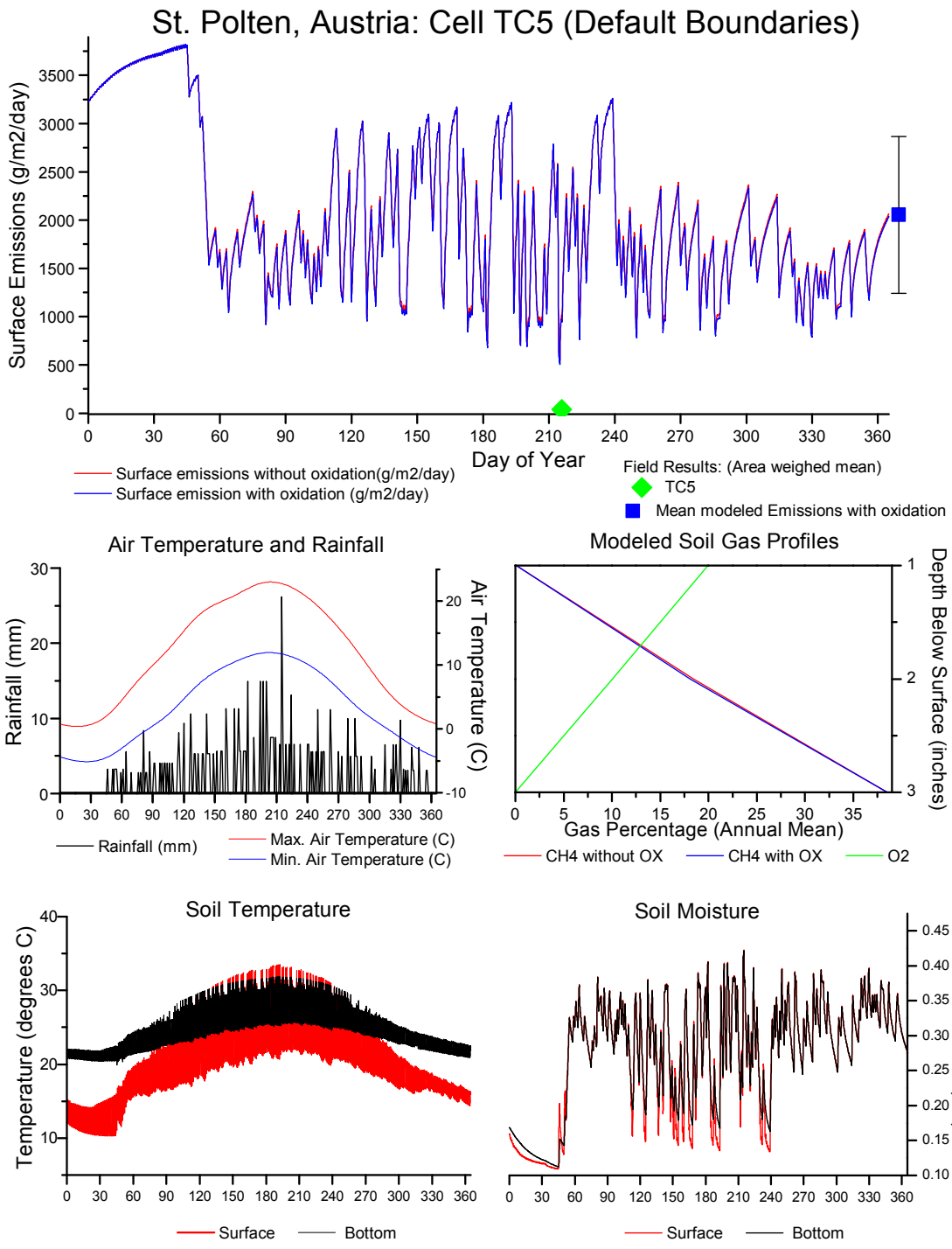
Huber-Humer, M., Roder, S., Lechner, P., 2009. Approaches to assess biocover performance on landfills. Waste Management, 29(7), 2092-2104.

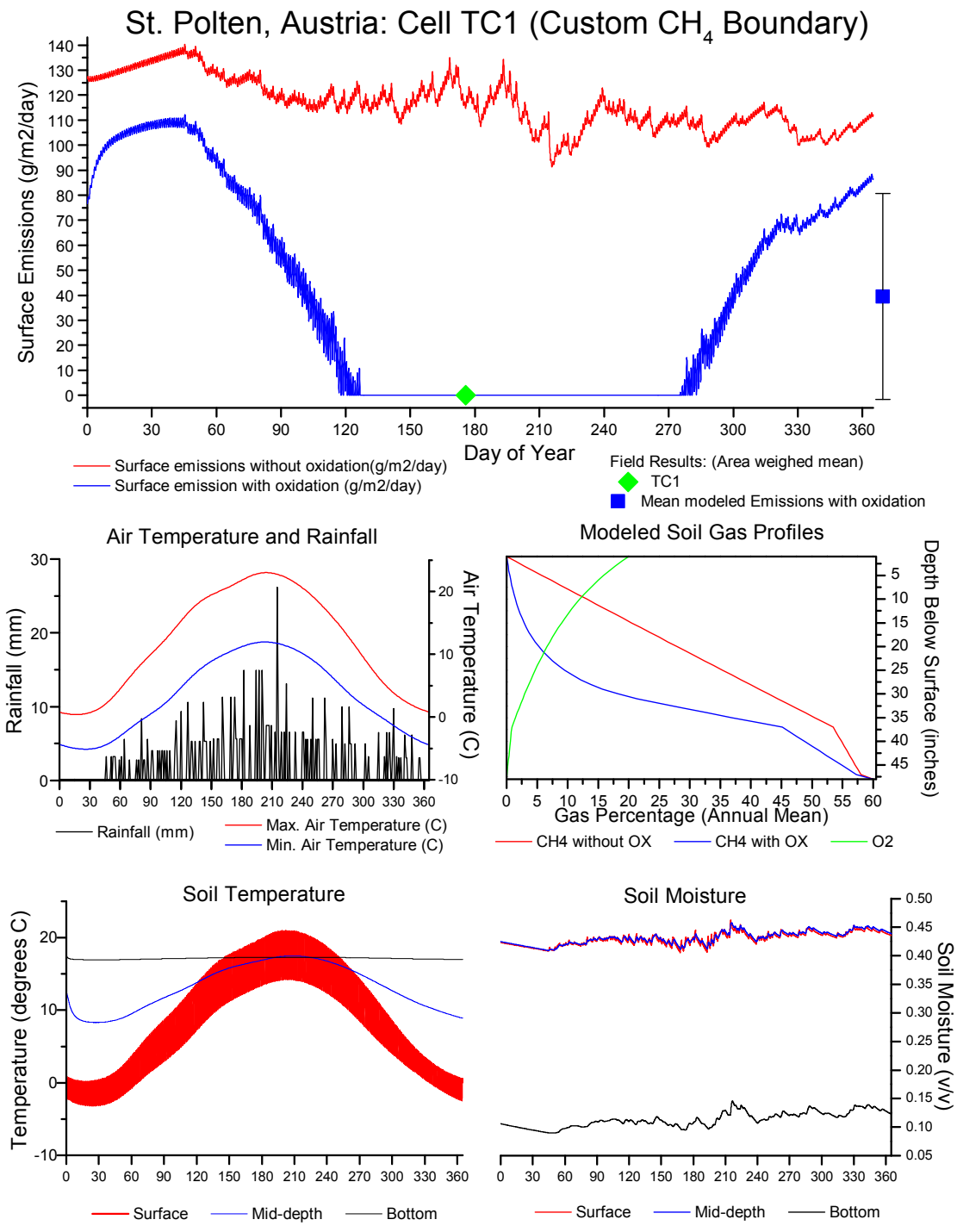

St. Polten, Austria: Cell TC1 (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC1
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

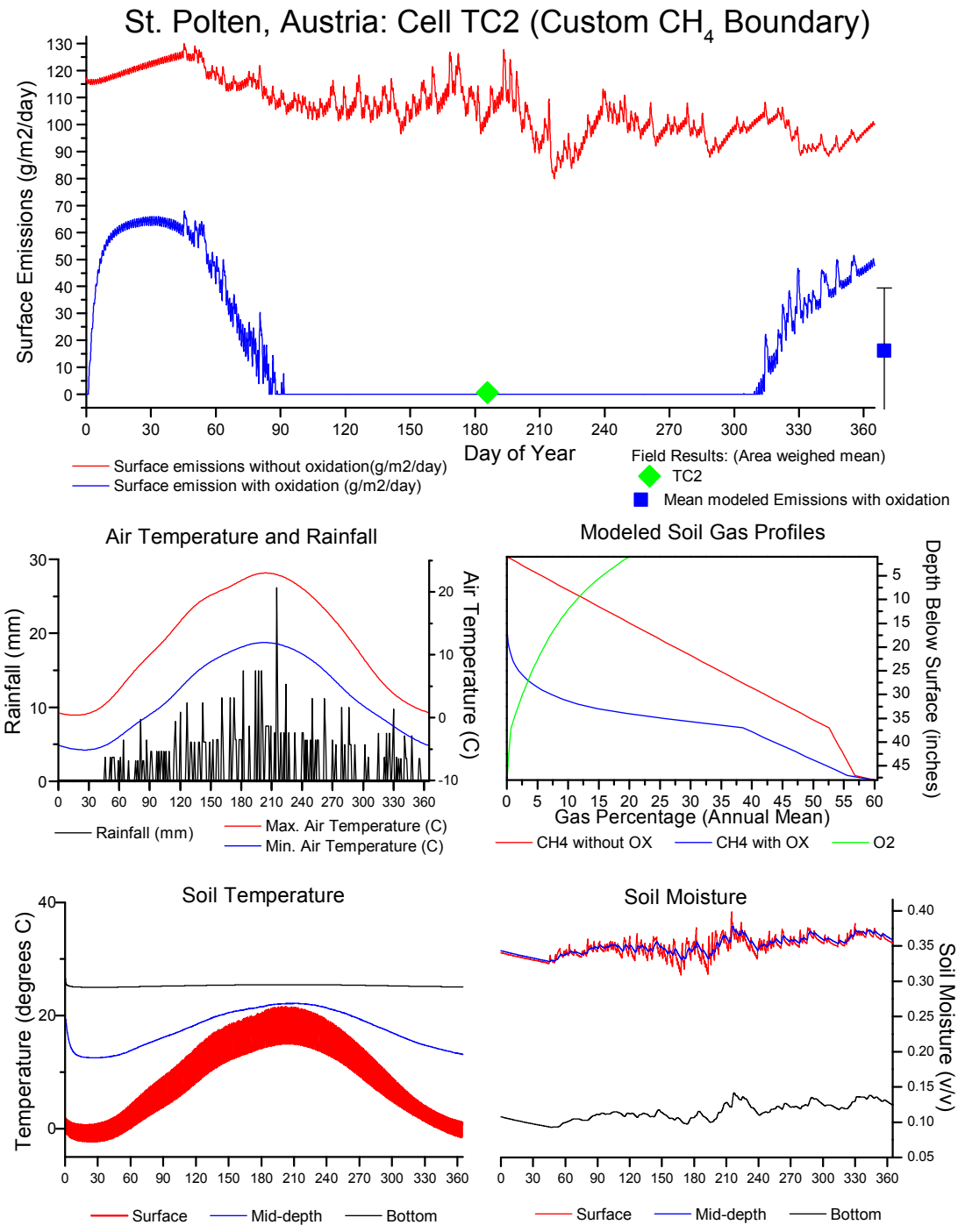

St. Polten, Austria: Cell TC2 (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC2
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

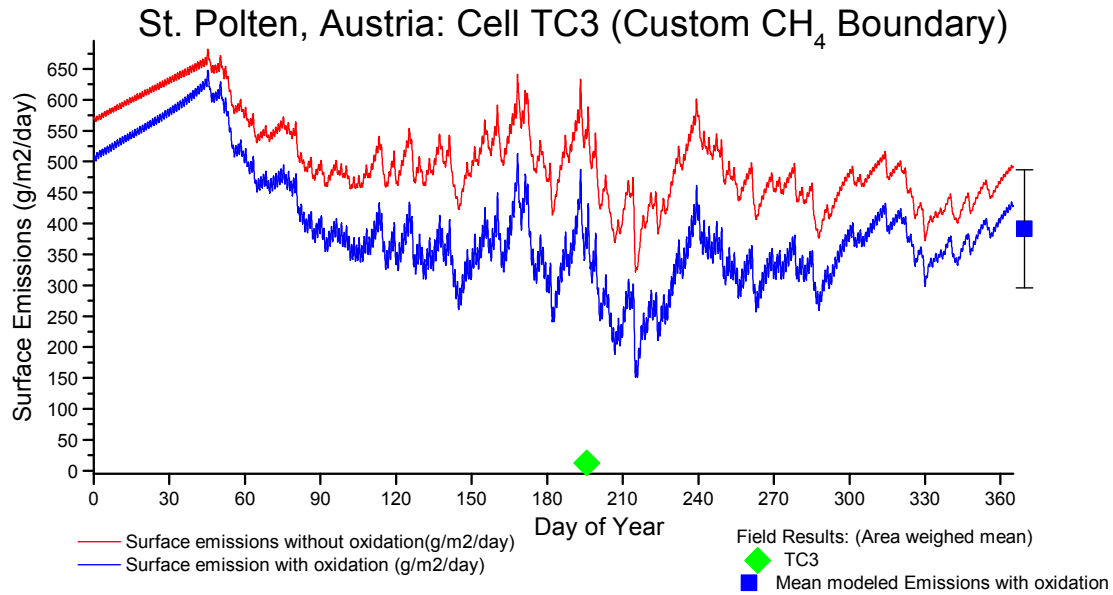

St. Polten, Austria: Cell TC3 (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC3
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

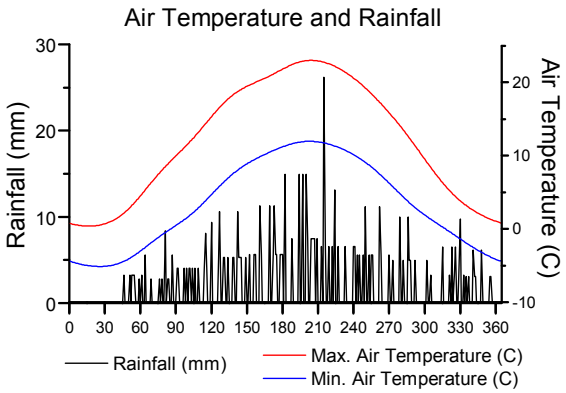

St. Polten, Austria: Cell TC4 (Default Boundaries(
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC4
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

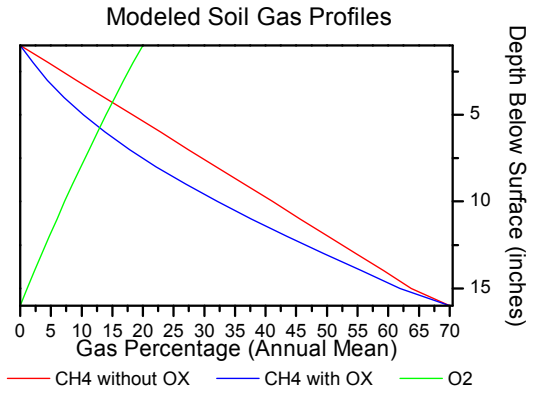

St. Polten, Austria: Cell TC5 (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC5
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Bottom

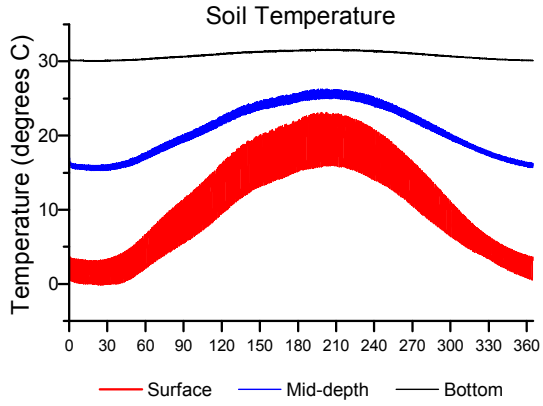

St. Polten, Austria: Cell TC1 (Custom CH4 Boundary)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC1
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

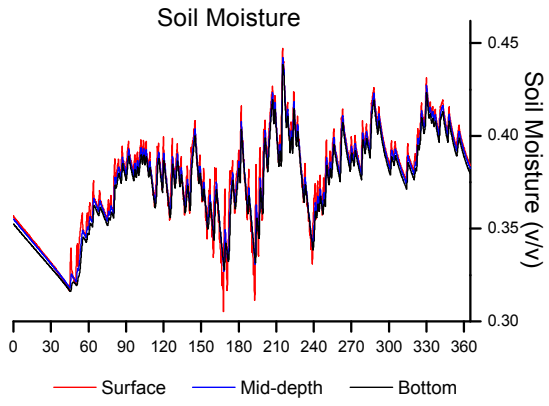

St. Polten, Austria: Cell TC2 (Custom CH4 Boundary)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC2
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

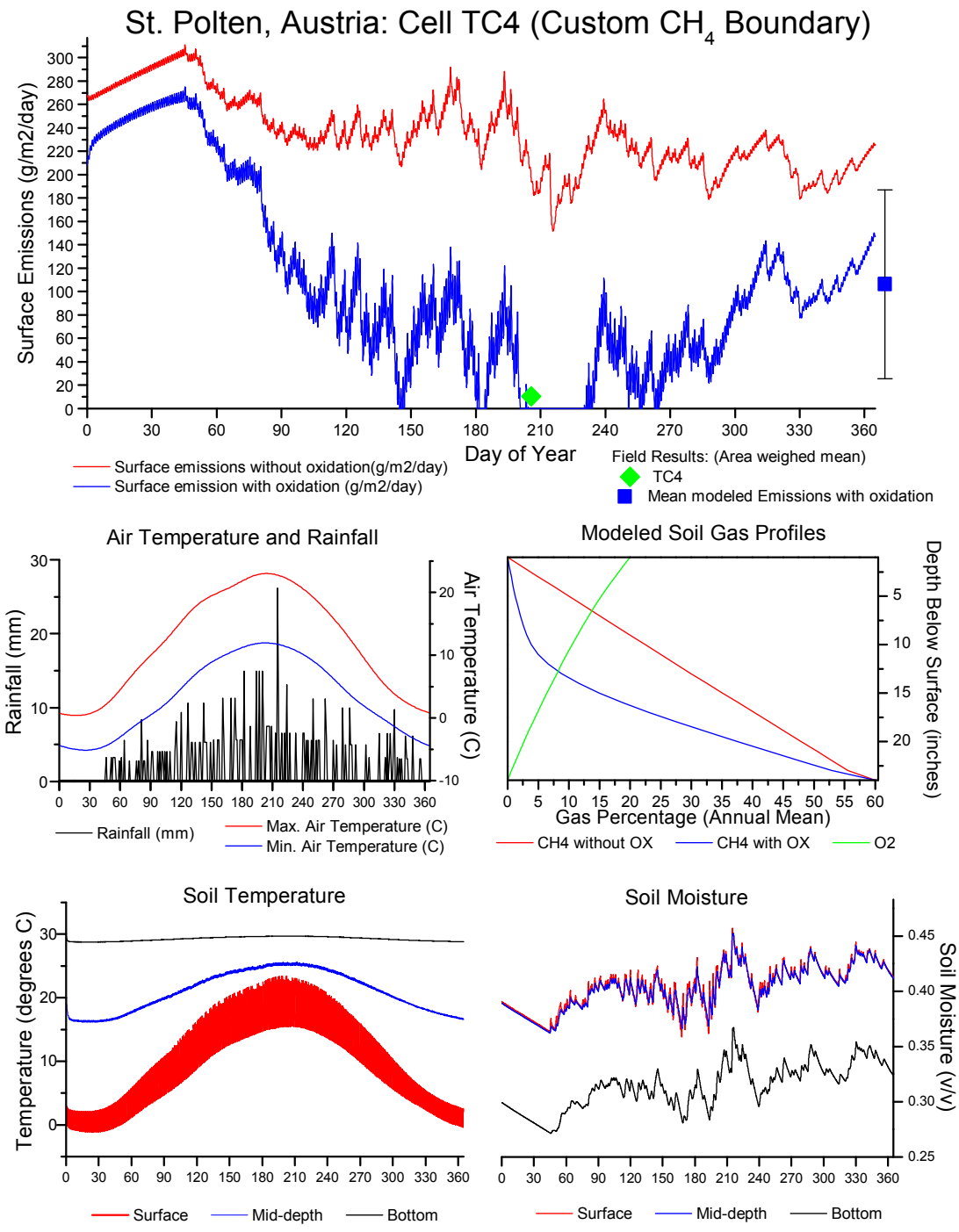

St. Polten, Austria: Cell TC3 (Custom CH4 Boundary)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC3
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


St. Polten, Austria: Cell TC4 (Custom CH4 Boundary)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (Area weighed mean)
TC4
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

2. Site Name: Grand'Landes

Site Location: France

Latitude: +46.821403 **Longitude:** -1.65

Total Size: 26 hectares (64.25 acres) total, approximately 1 hectares (2.47 acres) each for the study cells

Site Description:

This site has been an active landfill since 1989. The study area consisted of two cells. One (25A) had a conventional cover with gas recovery. The second (25B) had an innovative gas collection system consisting of horizontal pipes in a coarse gravel layer underlying a geomembrane and additional cover above the geomembrane.

Covers	**25A Default**	**25B Default**	**25A Custom (High)**	**25A Custom (low)**
Hectares (Acres)	1 (2.47)	1 (2.47)	1 (2.47)	1 (2.47)
Cover Type	Final	Final	Final	Final
Coverage % *	25%	25%	25%	25%
Organic Matter %	Default	Default	Default	Default
Gas Recovery %	100%	100%	100%	100%
Vegetation %	100%	100%	100%	100%

* Coverage % is for use by CALMIM

Layers		**25A Default**	**25B Default**	**25A Custom (High)**	**25A Custom (low)**
1	**Material**	Loam	Loam	Loam	Loam
	Thickness	30 cm	30 cm	30 cm	30 cm
2	**Material**	Clay	Clay	Clay	Clay
	Thickness	70 cm	70 cm	70 cm	70 cm
3	**Material**		Geotextile		
	Thickness		N/A		
4	**Material**		Geomembrane (HDPE)		
	Thickness		N/A		
5	**Material**		Geotextile		
	Thickness		N/A		
6	**Material**		Gravel		
	Thickness		30 cm		

Custom Boundaries

Methane Upper:	Default (2E-04%)	Default (2E-04%)
Methane Lower:	72.76%	37.69%
Oxygen Upper:	Default (20%)	Default (20%)
Oxygen Lower:	0.99%	7.65%

Field Results (g/m^2/day) (Bogner et al., 2003; Chanton and Bogner, 2003; Scheutz et al., 2003b)							
	Value					**N=**	**Comments**
Cell 25A:F5	0.0001					1	
Cell 25A:F7	-0.0044					1	
Cell 25A:F8	0.0002					1	
Cell 25A:F9	118.9					1	
Cell 25A:F10	100.9					1	
Cell 25A:F11	5.85					1	
Cell 25B:	-0.0085					1	

Modeled Results (g/m^2/day) (CALMIM 5.4, Emissions with oxidation)

	Mean	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**	**Comments**
Cell 25A (Default)	0	0	0	0	0	8760	
Cell 25A (Custom – High)	0	0	0	0	0	8760	
Cell 25A (Custom – Low)	0	0	0	0	0	8760	
Cell 25B (Default)	0.0010	0.0012	0	0	0.0053	8760	

Additional Notes:

Gas profiles were measured at three points in 25A, one of which appeared to be atmospheric levels of CH_4 and O_2. The other two were used as the "Custom (high)" and "Custom (low)" CALMIM setting for CH_4 and O_2. Gas profiles were also measured at three points in 25B, and had very low methane concentrations (profiles measured above the geomembrane). The measured bottom methane concentrations are lower than the CALMIM minimum value, so only the default boundary conditions were used in CALMIM for 25B.

Field results are for individual sample locations. No errors were given with the results. All CALMIM covers were run in the same file so they all use identical generated weather. Note the geomembrane in Site 25B is virtually impervious to gas, as is clear from the CALMIM gas profiles for that cell.

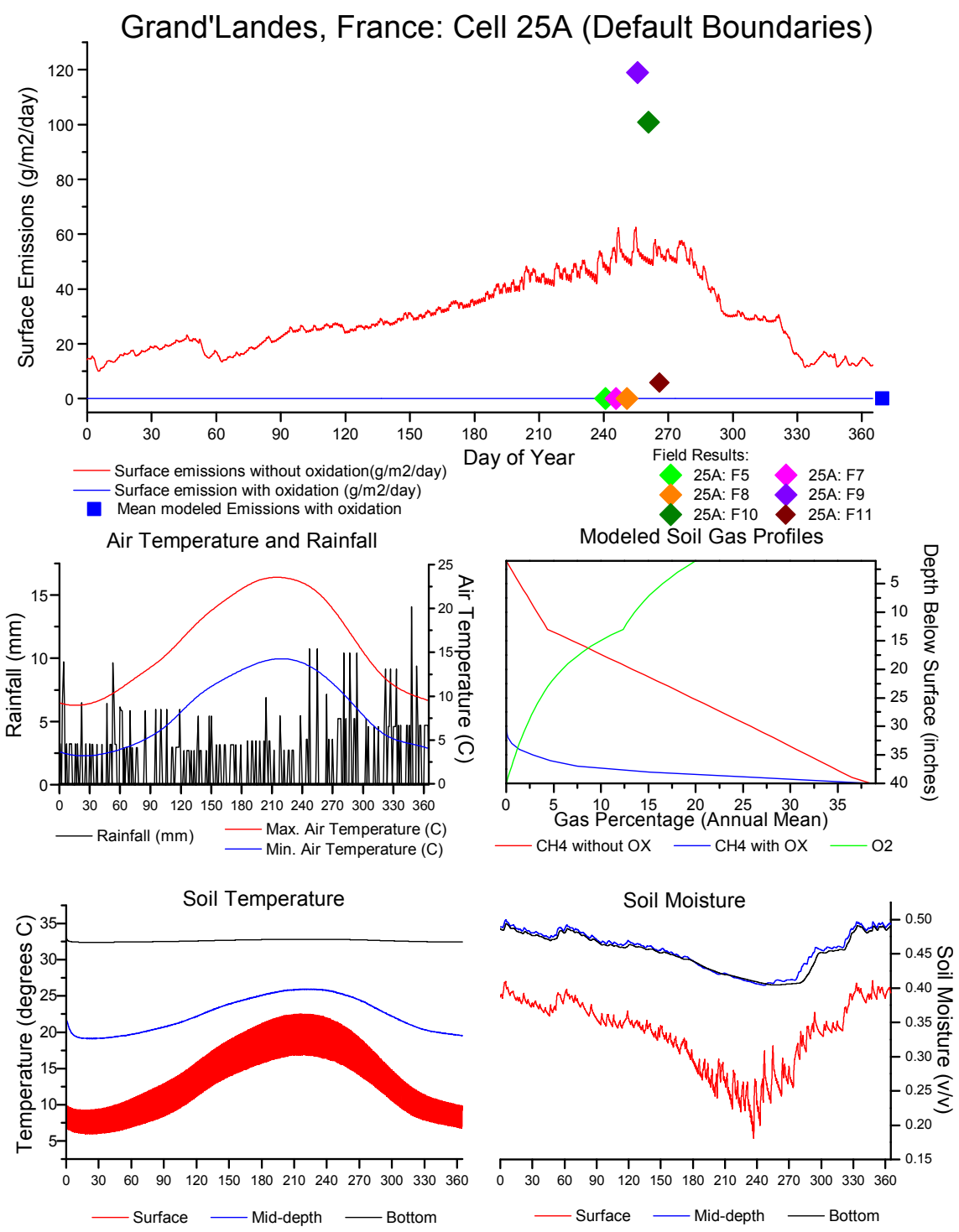
References:

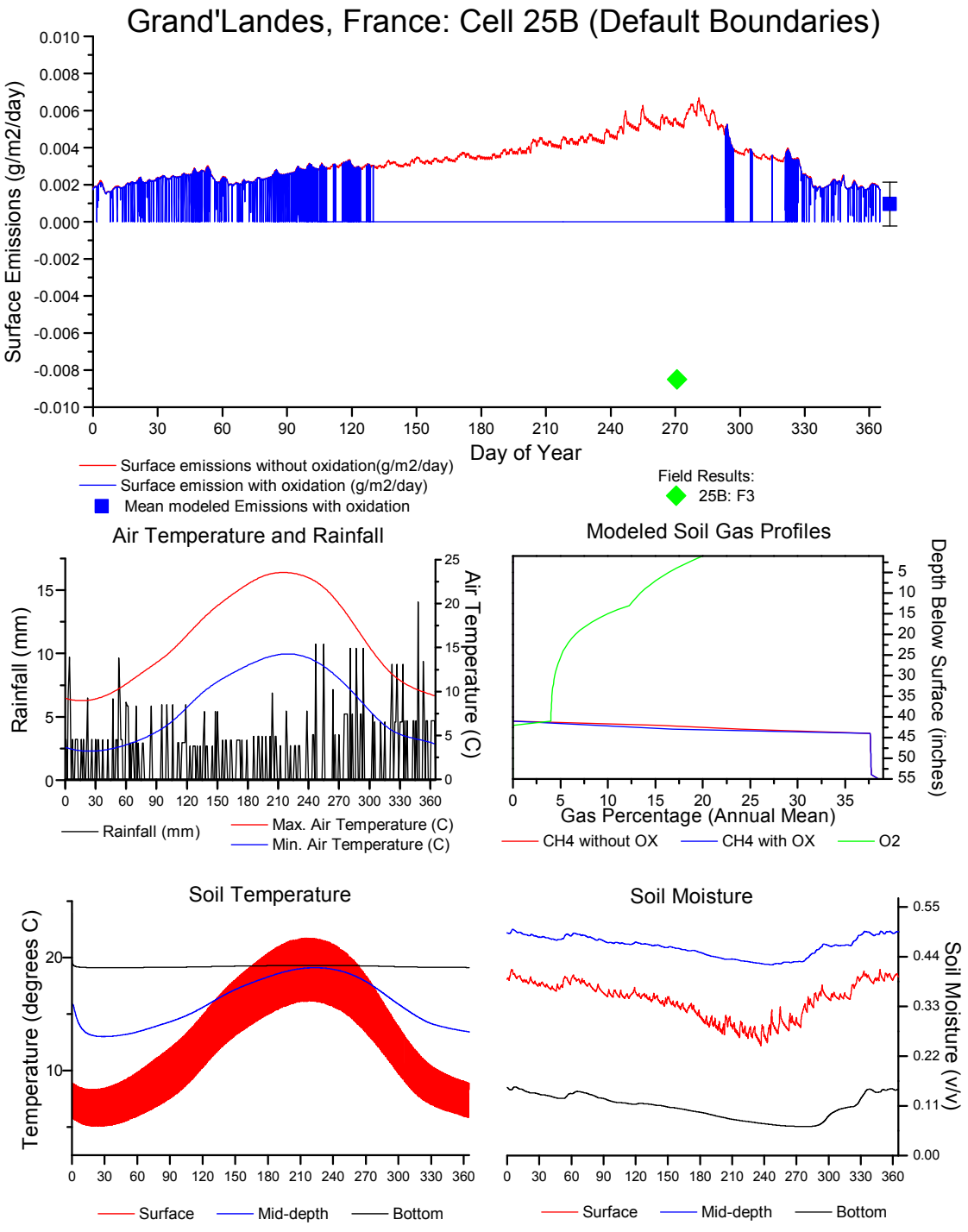
Bogner, J., Scheutz, C., Chanton, J., Blake, D., Morcet, M., Aran, C., Kjeldsen, P., 2003. Field Measurement of Speciated HAP (Hazardous Air Pollutant) Emissions from Landfill Cover Soils. In: T.H. Christensen, R. Cossu, R. Stegmann (Eds.), Sardinia 2003: International waste management and landfill symposium, Abstracts and Proceedings. Environmental Sanitary Engineering Centre (CISA), Cagliari, Italy.

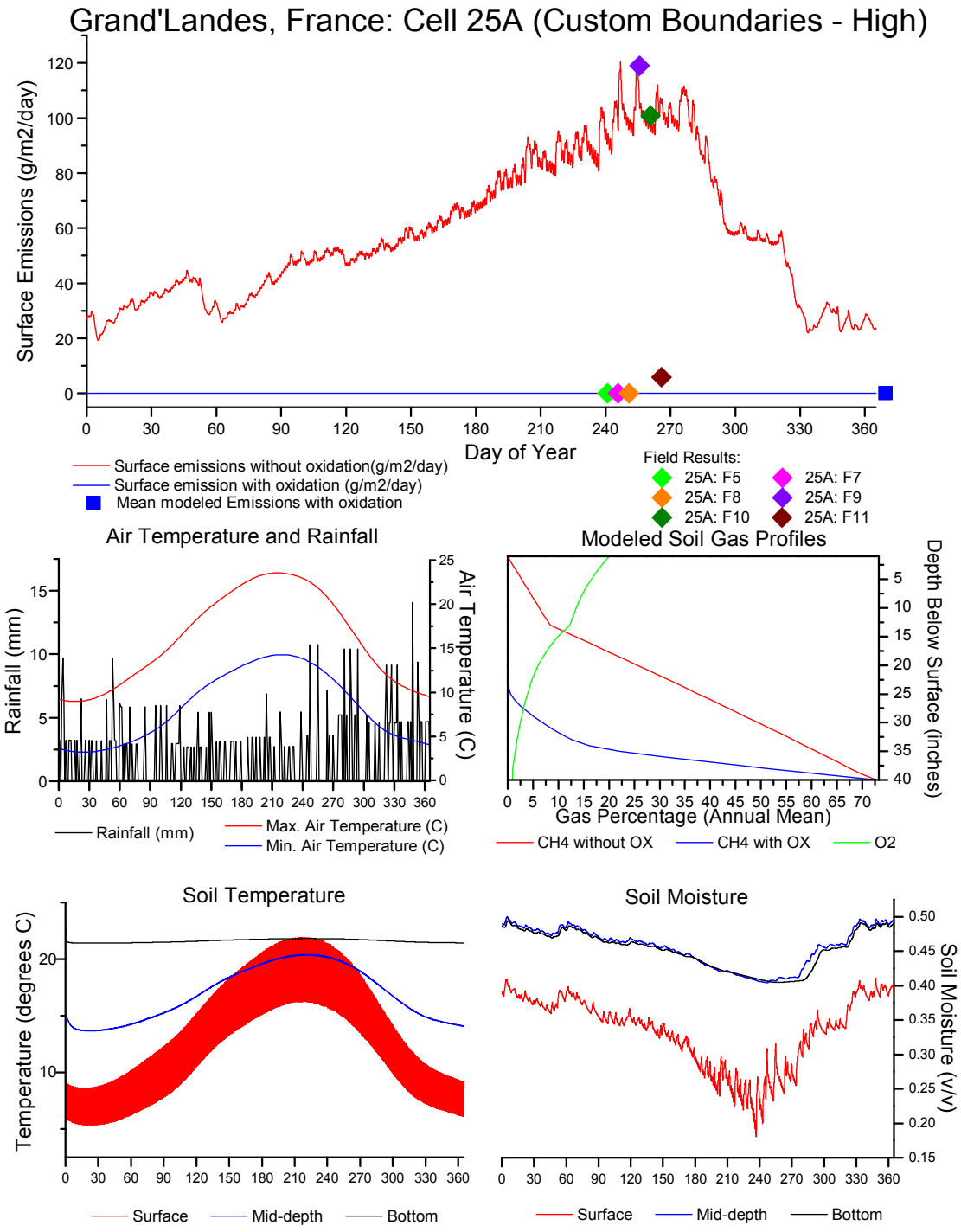
Chanton, J., Bogner, J., 2003. Methane oxidation in cover soils at the experimental Grand'Landes Landfill, Summer Conditions, 2002, Research Center for Environment and Energy Waste (CReeD), France.

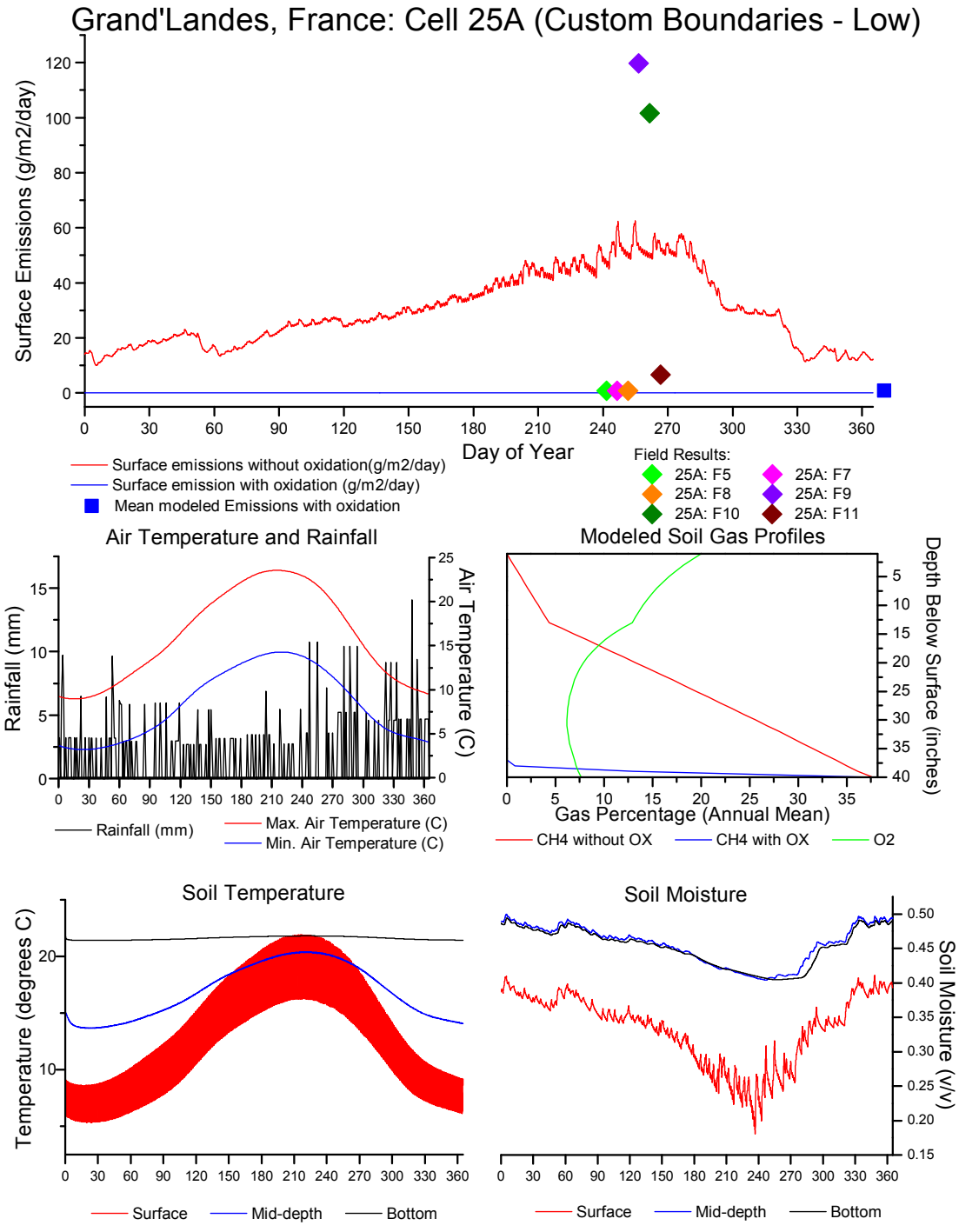
Scheutz, C., Kjeldsen, P., Bogner, J., Blake, D., Chanton, J., 2003. Atmospheric emissions and attenuation of non-methane organic compounds in cover soils at Grand'Landes Landfill, Final Report to CReeD.

Scheutz, C., Bogner, J., Chanton, J.P., Blake, D., Morcet, M., Aran, C., and Kjeldsen, P., 2008, Atmospheric Emissions and Attenuation of Non-Methane Organic Compounds in Cover Soils at a French Landfill, Waste Management 28:1892-1908.


Grand'Landes, France: Cell 25A (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results:
25A: F5
25A: F7
25A: F8
25A: F9
25A: F10
25A: F11
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Grand'Landes, France: Cell 25B (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results:
25B: F3
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Grand'Landes, France: Cell 25A (Custom Boundaries - High)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results:
25A: F5
25A: F7
25A: F8
25A: F9
25A: F10
25A: F11
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Grand'Landes, France: Cell 25A (Custom Boundaries - Low)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results:
25A: F5
25A: F7
25A: F8
25A: F9
25A: F10
25A: F11
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

3. Lapouyade

Site Location: Lapouyade, France

Latitude: +45.0854

Longitude: -0.2879

Total Size: 8.9 ha (22.08 acres) total for the cells in the study

Site Description: Lapouyade is a small town in France approximately 30 km northeast of Bordeaux. Several studies have been performed on the landfill. Results reported here are from winter (December, 2000) and summer (September, 2001) and are from two parallel studies, one using static chambers and one using dynamic chambers.

Covers

	Lapouyade Phase 1 Default	Lapouyade Phase 1 Custom	Lapouyade Phase 2 A8 Default	Lapouyade Phase 2 A8 Custom	Lapouyade Phase 2 A10 Default
Hectares (Acres) *	3.5 (8.79)	3.5 (8.79)	0.67 (1.6)	0.67 (1.6)	0.5 (1.2)
Cover Type	Final	Final	Intermediate	Intermediate	Intermediate
Coverage % *	40%	40%	7%	7%	6%
Organic Matter %	Default	Default	Default	Default	Default
Gas Recovery %	100%	100%	100%	100%	0%
Vegetation %	100%	100%	100%	100%	100%

* For use in CALMIM model

Layers

1	**Material**	Loam	Loam	Sand	Sand	Clay
	Thickness	30cm	30cm	35cm	35cm	30cm
2	**Material**	Silty Clay	Silty Clay			
	Thickness	60cm	60cm			
3	**Material**	Sand	Sand			
	Thickness	40cm	40cm			

Custom Boundaries

Methane Upper:			
Methane Lower:		9.057%	62.129%
Oxygen Upper			
Oxygen Lower:		1.5%	0.2%

Additional Notes:

Soil gas profiles were measured for both Phase 1 and Phase 2 cell A8, so CALMIM was run using default boundaries and also using the measured gas profiles as custom boundaries (Bogner et al., 2003).

Phase II cell A10 is described in Spokas et al. (2006). There was no soil gas profile data available [no custom boundary model run].

Field Results:

Three studies contained field results for Lapouyade for Dec, 2000 and Sept., 2001. Results were converted to g/m2/day for comparison to CALMIM results. Only the results from Bogner et al. (2003) included standard deviations.

Field Results (in g/m^2/day)						
	(Spokas et al., 2006)		(Diot et al., 2001)		(Bogner et al., 2003)	
	Winter (Dec. 2000) Static Chamber	Summer (Sept. 2001) Static Chamber	Winter (Dec. 2000) Dynamic chamber	Winter (Dec. 2000) Tracer gas	Summer (Sept. 2001) Dynamic chamber	
	Mean	Mean	Mean	Mean	Mean	Std. Dev.
Phase 1	1.575	8.398			1.97	0.88
Phase 2 A8	2.256	43.158			37.8	14
Phase 2 A10		1084.65	85.86	51.11		

Modeled CALMIM Results (Average emissions with oxidation, g/m^2/day)						
Cover	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Phase 1 (Default Boundaries)	0	0	0	0	0	8760
Phase 1 (Custom Boundaries)	0	0	0	0	0	8760
Phase 2 A8 (Default Boundaries)	189.6	29.8	191.0	105.8	264.0	8760
Phase 2 A8 (Custom Boundaries)	547.4	43.6	703.7	562.4	911.5	8760
Phase 2 A10 (Default Boundaries)	59.5	82.6	24.0	0	388.8	8760

References:

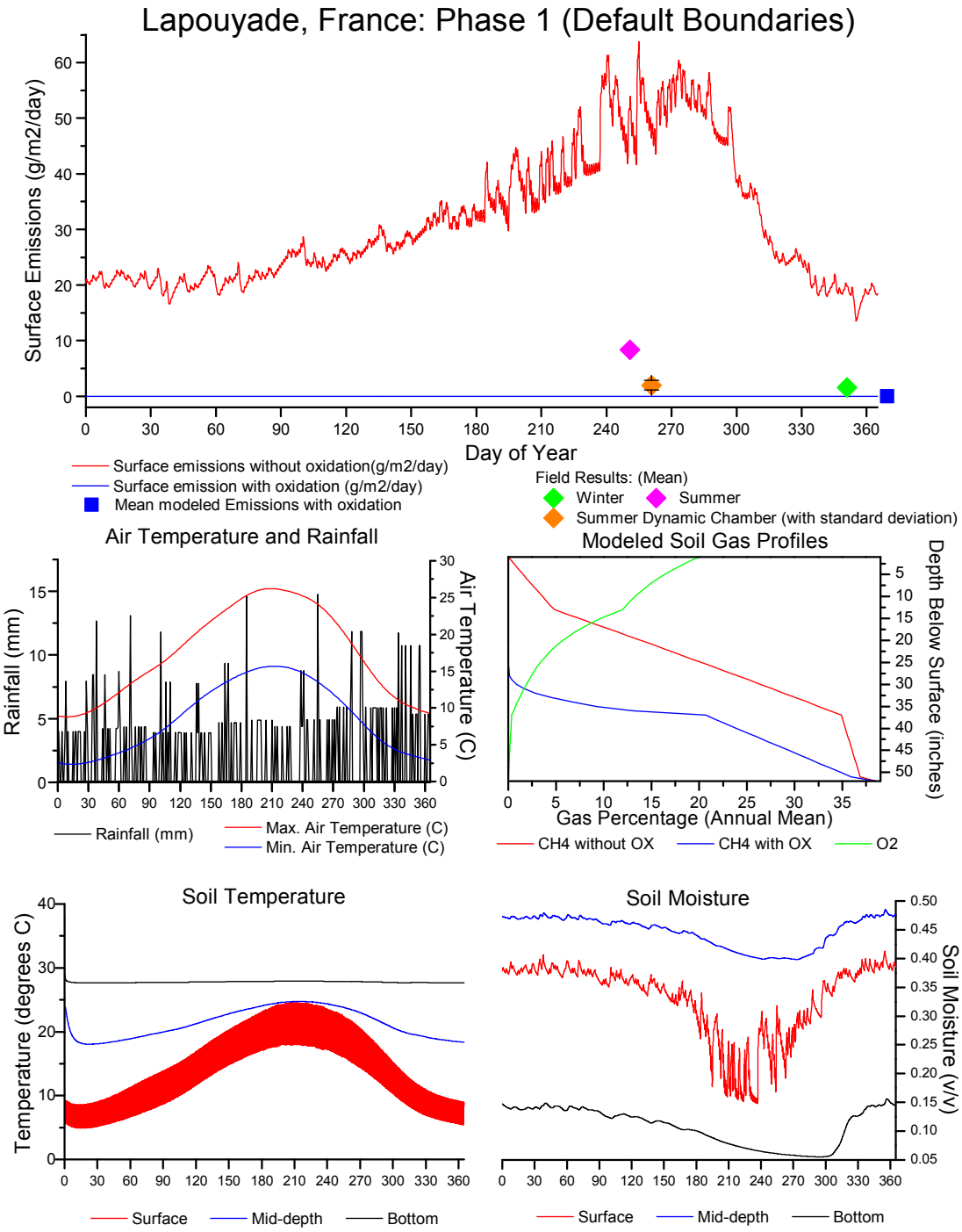
Bogner, J., Scheutz, C., Chanton, J., Blake, D., Morcet, M., Aran, C., & Kjeldsen, P. (2003). Field Measurement of Speciated HAP (Hazardous Air Pollutant) Emissions from Landfill Cover Soils. In T. H. Christensen, R. Cossu & R. Stegmann (Eds.), ***Sardinia 2003: International waste management and landfill symposium, Abstracts and Proceedings*****. Cagliari, Italy: Environmental Sanitary Engineering Centre (CISA).**

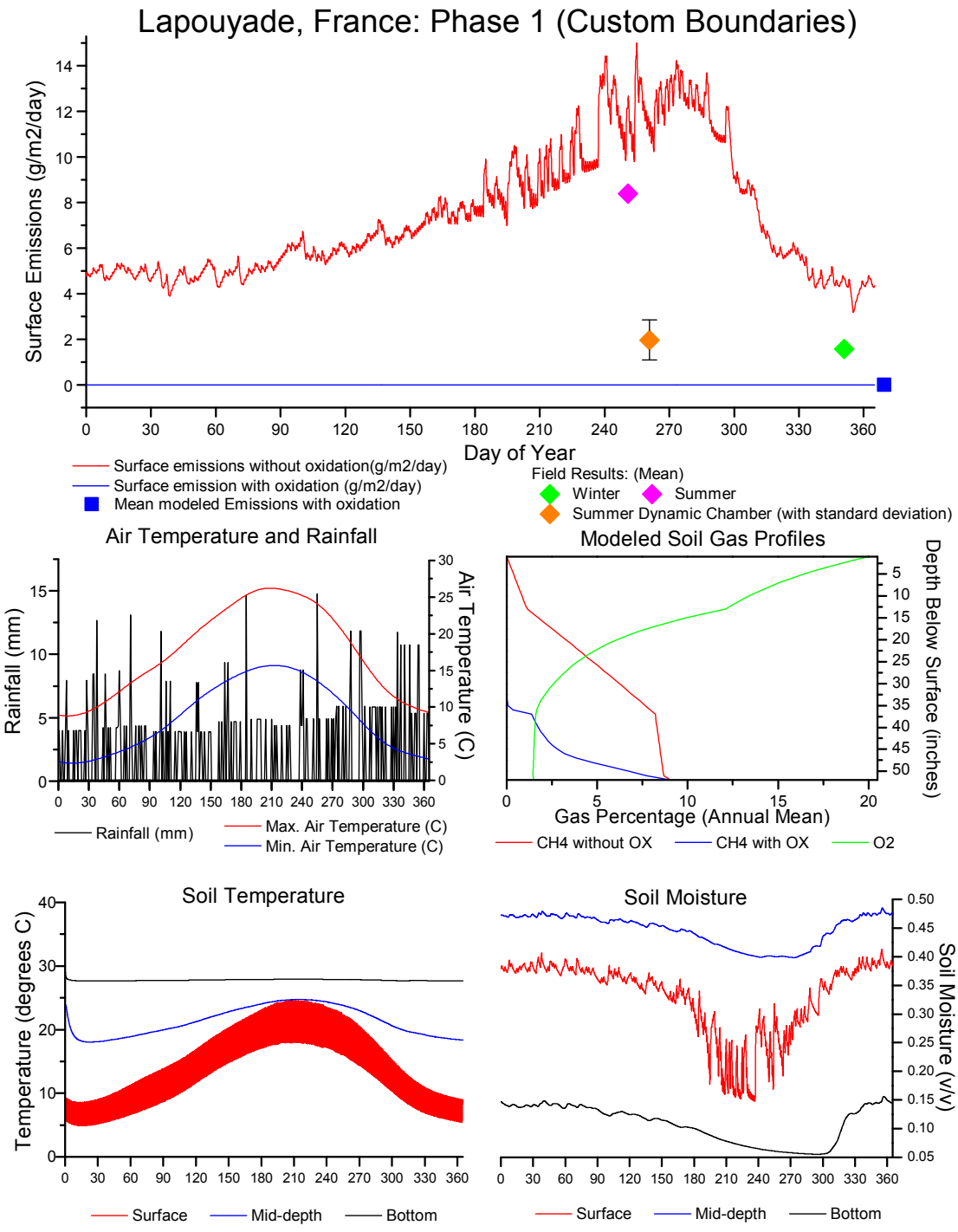
Diot, M., Golvan, Y. M. L., Hebe, I., Bogner, J. E., Chanton, J., Spokas, K., . . . Guerbois, M. (2001). ***LFG Mass Balance: A Key to Optimize LFG Recovery*****. Paper presented at the SARDINIA 2001 – Eighth International Waste Management and Landfill Symposium, Cagliari, Italy.**

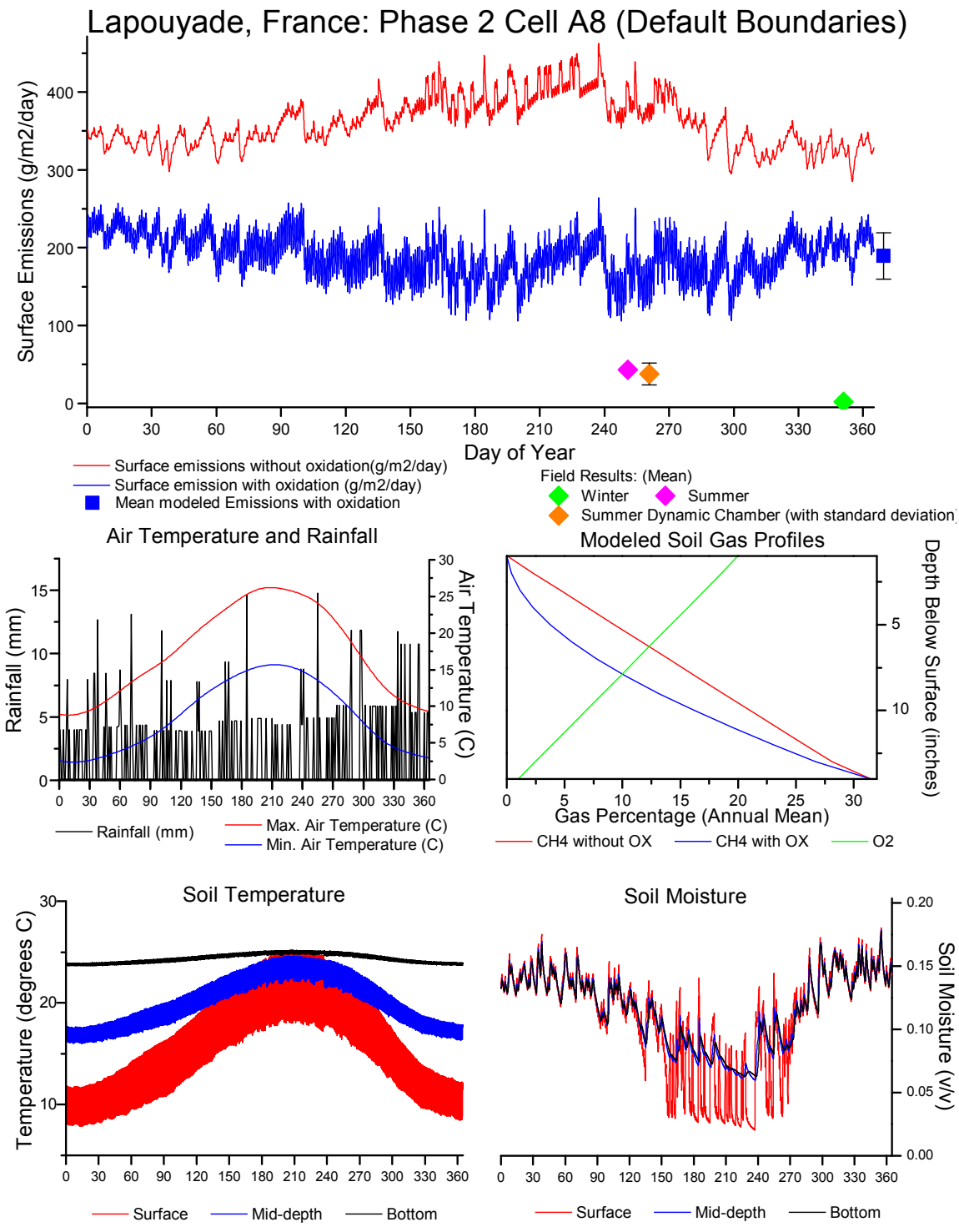
Scheutz, C., Bogner, J., Chanton, J., Blake, D., Morcet, M., & Kjeldsen, P. (2003). Comparative oxidation and net emissions of methane and selected non-methane organic compounds in landfill cover soils. ***Environmental Science and Technology, 37*****, 5150-5158.**

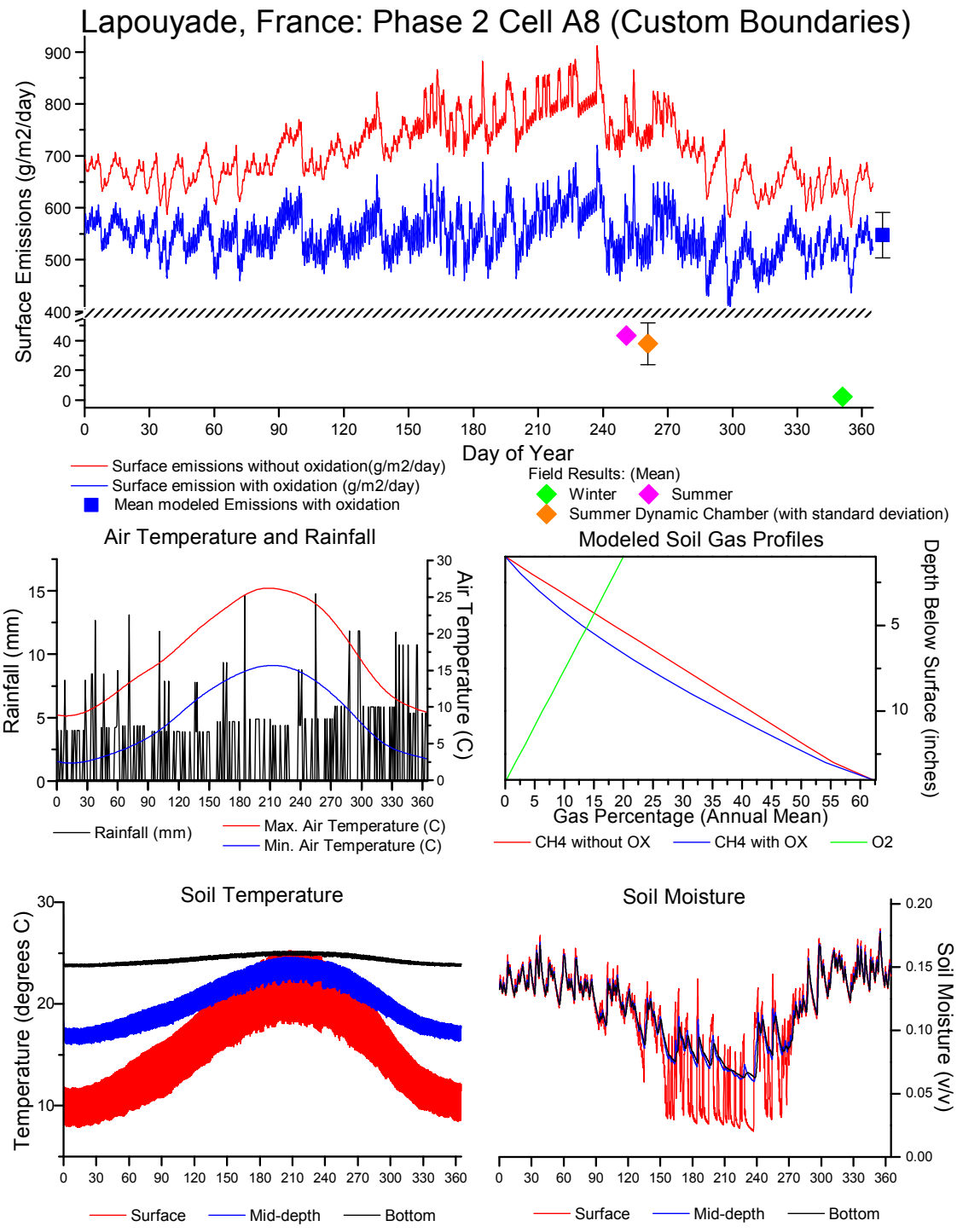
Scheutz, C., Kjeldsen, P., & Bogner, J. (2002). Attenuation of non-methane organic compounds (NMOCS) in cover soil at a French landfill: Research Center for Environment and Energy Waste (CReeD).

Spokas, K., Bogner, J., Chanton, J. P., Morcet, M., Aran, C., Graff, C., . . . Hebe, I. (2006). Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems? ***Waste Management, 26*****, 516-525.**


Lapouyade, France: Phase 1 (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results: (Mean)
Winter
Summer
Summer Dynamic Chamber (with standard deviation)
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Lapouyade, France: Phase 1 (Custom Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results: (Mean)
Winter
Summer
Summer Dynamic Chamber (with standard deviation)
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Lapouyade, France: Phase 2 Cell A8 (Default Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results: (Mean)
Winter
Summer
Summer Dynamic Chamber (with standard deviation)
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Lapouyade, France: Phase 2 Cell A8 (Custom Boundaries)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results: (Mean)
Winter
Summer
Summer Dynamic Chamber (with standard deviation)
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

4-8. South African sites

(5 near Johannesburg, 1 near Durban, South Africa)

Latitude: Various, see details **Longitude:** Various, see details

Total Size: Various, see details

Site Description:

This field study was part of the PhD thesis of Jeremy Morris, completed in 2001. He studied five existing landfills in the Johannesburg area and one on the sub-tropical eastern coastline of South Africa, along with some field test cells created in Johannesburg. The sites selected for the study were all classified as large landfills containing general waste. All of the Johannesburg sites had a negative water balance (classified GLB^- according to the South African system), meaning they are not expected to produce leachate. The Durban site (Landfill F) had a positive water balance site (GLB^+). GLB^- sites represent the greatest portion of landfill sites in South Africa. High detection limits for the GC-TCD used to measure methane concentrations resulted in negligible methane emissions from the test cells and for two of the landfills (Landfill E, Vaalpark quarry, and Landfill F, Bisasar Road landfill). Emissions were measured using a static chamber method. CALMIM models were run for 4 of the sites for comparison.

Covers	Landfill A	Landfill B (new only)	Landfill C	Landfill D	Landfill E (not modeled)	Landfill F (not modeled)
Acres	19 (7.7ha)	16.5 (6.7ha)	36 (14.6ha)	30.6 (12.4 ha)	11.6 (4.7ha)	50 (20.3ha)
Latitude	26.2 S	26.3 S	26.2 S	26.2 S	26.8 S	29.8 S
Longitude	28.5 E	27.8 E	27.6 E	28.0 E	27.8 E	30.0 E
Cover Type	Intermediate	Intermediate	Final	Final	n/a	n/a
Coverage % *	100%	100%	100%	100%	n/a	n/a
Organic Matter %	Mid-range	Mid-range	Mid-range	Mid-range	Mid-range	Mid-range
Gas Recovery %	0%	0%	0%	0%	0%	0%
Vegetation %	0%	50%	50%	100%	100%	20%

* Coverage % is for use by CALMIM. Because each site has to be run with unique latitude and longitude, each site is 100% of the acreage for CALMIM.

Layers							
1	**Material**	Sandy clay loam	Clay loam	Sandy loam	Loam	Sandy clay	Clayey sand
	Thickness (cm)	10	35 (reported 10-60)	15 (reported 10-20)	35 (reported 15-60)	unknown	50-70

Custom Boundaries

(No gas profile data available.)

Additional Notes:

The six sites in this study are:

Landfill A: 35km east of Johannesburg. This site was permitted as GLB^-, however due to the high paper

content of the waste it is wetter than typical of GLB^{-} sites. A 7.7 ha portion of the landfill (inactive for two years) was studied. Only a small section of the inactive area, approximately 15%, had been capped with a compact clayey layer. Measurements were performed twice, but only on the top, not the sides, of the inactive area: March, 1999 (summer), and August, 1999 (winter). This site has a passive gas venting system only in the small capped area of the inactive area. The area was not active during summer measurements and was shut down 24 hours before winter measurements. The remainder of the inactive area had no gas recovery or venting system.

Landfill B: Southwest of Johannesburg, serves Soweto. The landfill has two main sections: an old section covering 6.1ha which was closed five years before this study and a new section with an inactive area of 6.7ha. There wss no gas recovery or venting system for either area. Measurements were taken in March, 1999 (summer) in both areas on the top only, not the sides. Because the old section had very few sample points and only one measurable methane emission value, CALMIM modeling was done only for the new portion.

Landfill C: 20km west of Johannesburg. This landfill closed 3 years prior to the study and has a final cover with grass vegetation covering almost 100% of the site. There was no gas recovery or venting system. Measurements were taken on the flat top, not the sides, in March, 1999 (summer).

Landfill D: Located in suburban Johannesburg, this landfill closed in 1978 (21 years prior to the study). The total area is 25.1ha, however much of that area is inaccessible, e.g. paved over as part of a school, or otherwise covered. Some vertical pipes were observed near the school; these are assumed to be passive vents. The accessible area consisted of 12.4ha, is fully grassed with some trees, and also contains several squatters' camps. There was gas recovery or active (flared) venting system. Measurements were performed on the accessible area in March, 1999 (summer). CALMIM modeling was completed only for the accessible portion (12.4ha).

Landfill E (Vaalpark Quarry near Sasolburg): This site is located on the south side of the Vaal river near Sasolburg. The history of waste disposal at this site is largely unknown, although it is believed to have been an informal dumping site during the 1970s, and was closed at least 20 years prior to this study. The area is 4.7ha, with well established vegetation including trees. Borehole tests indicate that the site was extensively used for disposal of inert materials such as construction debris. There is no description of a gas recovery or venting system in the thesis. Measurements were performed in Feb. 2000 (summer). No methane emissions were found at this site, possibly due to the high minimum detection limit of the GC/TCD device used as well as the possible lack of putresible materials. CALMIM modeling was not done for this site because of the lack of measureable emissions.

Landfill F (Bisasar Road landfill in Durban): In Durban, on the sub-tropical eastern coastline of South Africa, approximately 600km from Johannesburg. Opened in 1980 and still active, the studied portion is an inactive area (20.3ha) closed 6 months prior to the study and covered with 50-70cm of well compacted clayey sand. Some vented gas is being flared but no full-scale gas recovery system was in place. [This site later became part of a Clean Development Mechanism (CDM) landfill gas project.] Emission measurements were taken only on the top, not the sides of the landfill in August, 1999 (winter). No methane emissions were detected at this site possibly due to the high minimum detection limit of the GC/TCD device used. CALMIM modeling was not done for this site because of the lack of measureable emissions.

CALMIM Model Inputs:

Latitude and Longitude: The geographic coordinates of the sites were not given in the thesis, and the names of the landfills were only given for two of the sites, Landfills E and F. For CALMIM purposes the latitude and longitude for Landfills A through D were determined using Google Earth and the rough description of the site (e.g. "20km west of Johannesburg"). Due to each site having a unique latitude and

longitude, the sites may have slightly different modeled weather profiles (solar radiation, temperature, and precipitation). For this reason the sites could not be combined into one CALMIM run and were run individually.

Minimum Detection Limit: The only device available for methane detection during this study was a Gas Chromatography –Thermal Conductivity Detector (GC/TCD). This device had a minimum detection limit of 4-5 grams CH_4/m^2/day, compared to a detection limit of 5-10 mg CH_4/m^2/day for a typical Gas Chromatography – Flame Ionization Detector (GC/FID), more commonly used today. Two landfills, (Landfill E, Vaalpark quarry, and Landfill F, Bisasar Road landfill), had no measureable methane emissions using the GC/TCD. Results for these landfills are listed as <5 g CH4/m2/day because of the high detection limit of the GC/TCD. Because of the high minimum detection limits for Landfills E and F as well as the lack of measureable emissions, these sites were not modeled in CALMIM.

Organic Content: For all the sites, there was no organic content of the cover material given, so modeling in CALMIM used the mid-range, which is 2.5%.

Gas Recovery System: None of these sites had an engineered landfill gas recovery system. Landfill A had some passive vents which were occasionally flared but not during emissions sampling for this project. Landfill F also had some flared vents. The other sites had no gas flaring.

Soil Type: Particle size measurements were given for Landfills A through D, all of which included gravel. Soil characterization in the CALMIM modeling used the measured particle sizes excluding the gravel portion (<2 mm). Soil types were given for Landfills E and F but no grain size analysis data.

Methane at base of cover: No soil gas profiles were done, so methane at the base of the cover is not known and defaults were used for CALMIM modeling (e.g. CH_4 concentration at the base of the cover default is 55% for final covers and 45% for intermediate).

Weather: Because each landfill had a different latitude and longitude, each was run in a separate CALMIM model file, and each will have unique generated weather.

E-PLUS Model:

First order decay modeling was performed using E-PLUS Version 1.0 software from the US EPA (1997) for Landfills A and B using input data described in two earlier papers. Landfills C and D were not modeled due to insufficient input data, and Landfills E and F were not modeled due to negligible emissions from the field testing. E-PLUS results are given as kg/day. To compare to CALMIM modeled results, these were converted to g/m2/day as [(E-Plus kg/day) / (landfill area ha)] * (1 ha/10,000 m^2) * (1,000g / kg).

Input Parameter	Landfill A (Study section only)	Landfill B (New section only)
Year Landfill Opened	1995	1989
Year MSW deposits started in old section	1995	1994
Year section closed	1997	1998
Current Year	1995	1998
MSW density	720kg m^{-3} (45 lbs ft^{-1})	970 kg m^{-3} (60.5 lbs ft^{-1})
Designed landfill depth	12m	15m
Designed area of landfill	7.3 ha (18 acres)	6.7 ha (16.5 acres)
Current MSW in place	0	1,069,543 tonnes (1,052,700 tons)
Average annual MSW acceptance rate	360,000 tonnes (354,240 tons)	316,800 tonnes (311,731 tons)
LFG composition as extracted	Default: (50% CH_4, 40% CO_2	Default: (50% CH_4, 40% CO_2
Methane generation rate constant (k)	Default: 0.04 $year^{-1}$ (wet), 0.02 $year^{-1}$ (dry)	Default: 0.04 $year^{-1}$ (wet), 0.02 $year^{-1}$ (dry)
Methane generation potential (L_0)	Default: 25 m^3 $tonne^{-1}$ (2.0ft^3 lb^{-1})	Default: 25 m^3 $tonne^{-1}$ (2.0ft^3 lb^{-1})

Field Results:

Note for Landfill A: The summer emissions were lower than the winter. However, the emissions sampling was not done at the same sites during both seasons (all sites collected in winter were collected in summer, but summer also included 16 sites not collected in winter). A calculation of the mean and standard deviation for summer using only the same sites as sampled during the winter was completed to see if the additional 16 sites in summer had affected the means – in fact, all the summer sites not sampled in winter had zero emissions, lowered the summer mean. Using summer results just for the 40 sites were also sampled in winter does increase the mean; however, the summer results are still lower than the winter results.

DAILY South Africa Field Results and Modeled Emissions (all shown in grams CH_4/m^2/day)

Landfill	Arith-metic Mean	Std Dev (Arithmetic mean)	Kriging Method Mean	Kriging Std Dev	Mini-mum	Maxi-mum	N =	Non-zero N =	Comments
Field Results									
Landfill A – summer (hot, wet) March, 1999	32.8	63.14	26.7	1.63	0	285	56	17	
Landfill A – summer – using same collection points as winter – March 1999	46.0	70.8	n/a	n/a	0	285	40	17	
Landfill A – winter (cold, dry) August, 1999	56.5	128.46	40.7	2.04	-45	638	40	14	One negative flux
Landfill B Total – summer	46.1	82.88	28.1	1.71	0	410	46	21	
Landfill B New only – summer	52.7	87.23	43.9	1.12	0	410	40	20	
Landfill C – summer	12.7	55.25	16.2	2.91	0	347	43	6	
Landfill D – summer	15.7	70.49	17.9	2.83	0	385	32	2	
Landfill E – summer	< 5				0	0	41	0	(not modeled)
Landfill F - winter	< 5				0	0	40	0	(not modeled)
Modeled (CALMIM 5.4 Results)									
Landfill A	1822.6	542.1	n/a	n/a	306.3	2565.9	8760	n/a	
Landfill B (new only)	255.0	159.1	n/a	n/a	00.0	544.7	8760	n/a	
Landfill C	1559.9	331.4	n/a	n/a	469.3	2193.4	8760	n/a	
Landfill D	447.9	166.1	n/a	n/a	141.1	778.0	8760	n/a	
E-PLUS Model (g/m^2/day)									
Landfill A Summer	55.34								

(wet) *									
Landfill A Winter (dry) *	30.14								
Landfill B (wet) *	214.33								
Landfill B (dry) *	118.96								

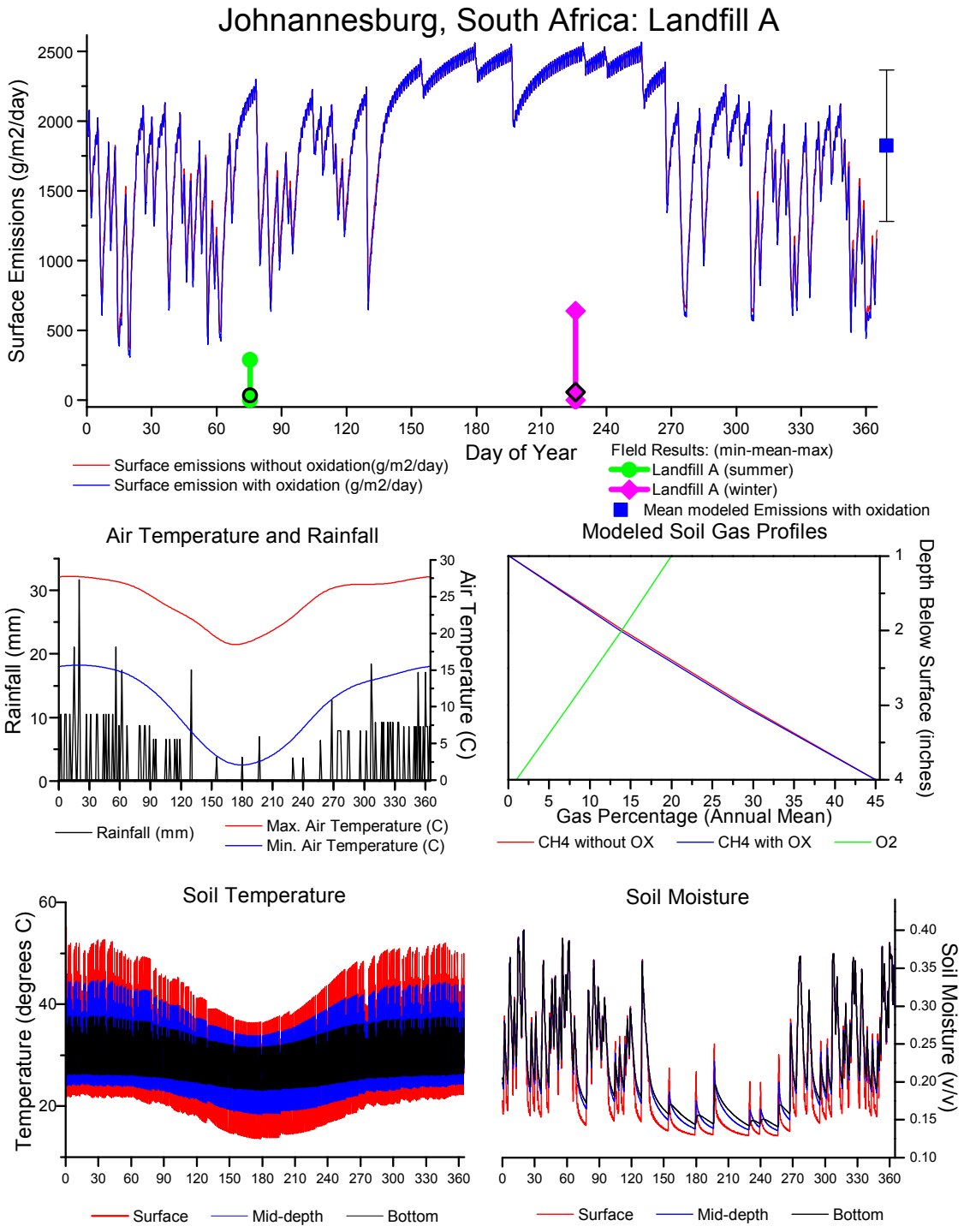
* Only available for Landfills A and B; Calculated from E-PLUS results as kg/day divided by number of hectares and converted to g and m^2

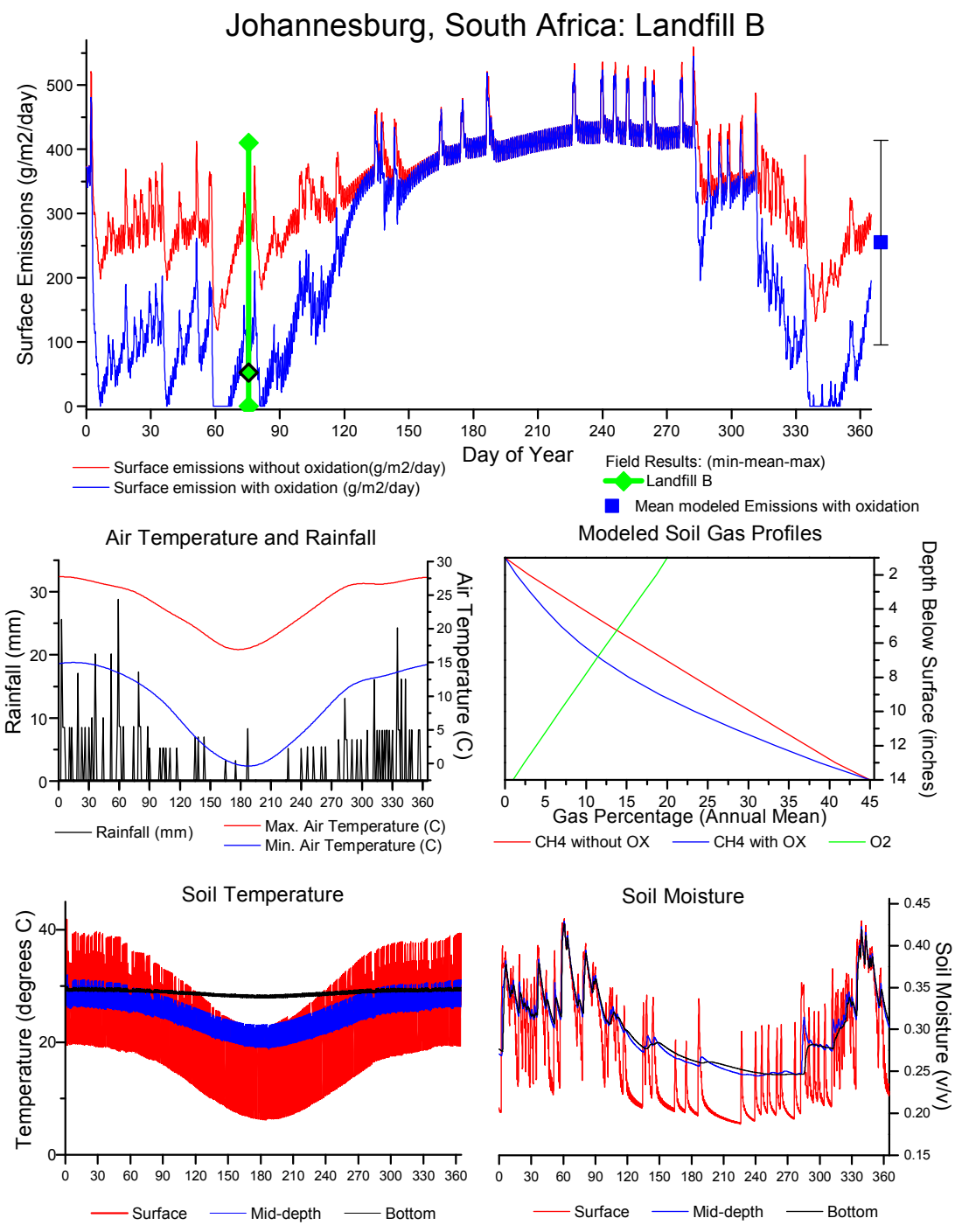
ANNUAL South Africa Field Results and Modeled Emissions (kg/year)

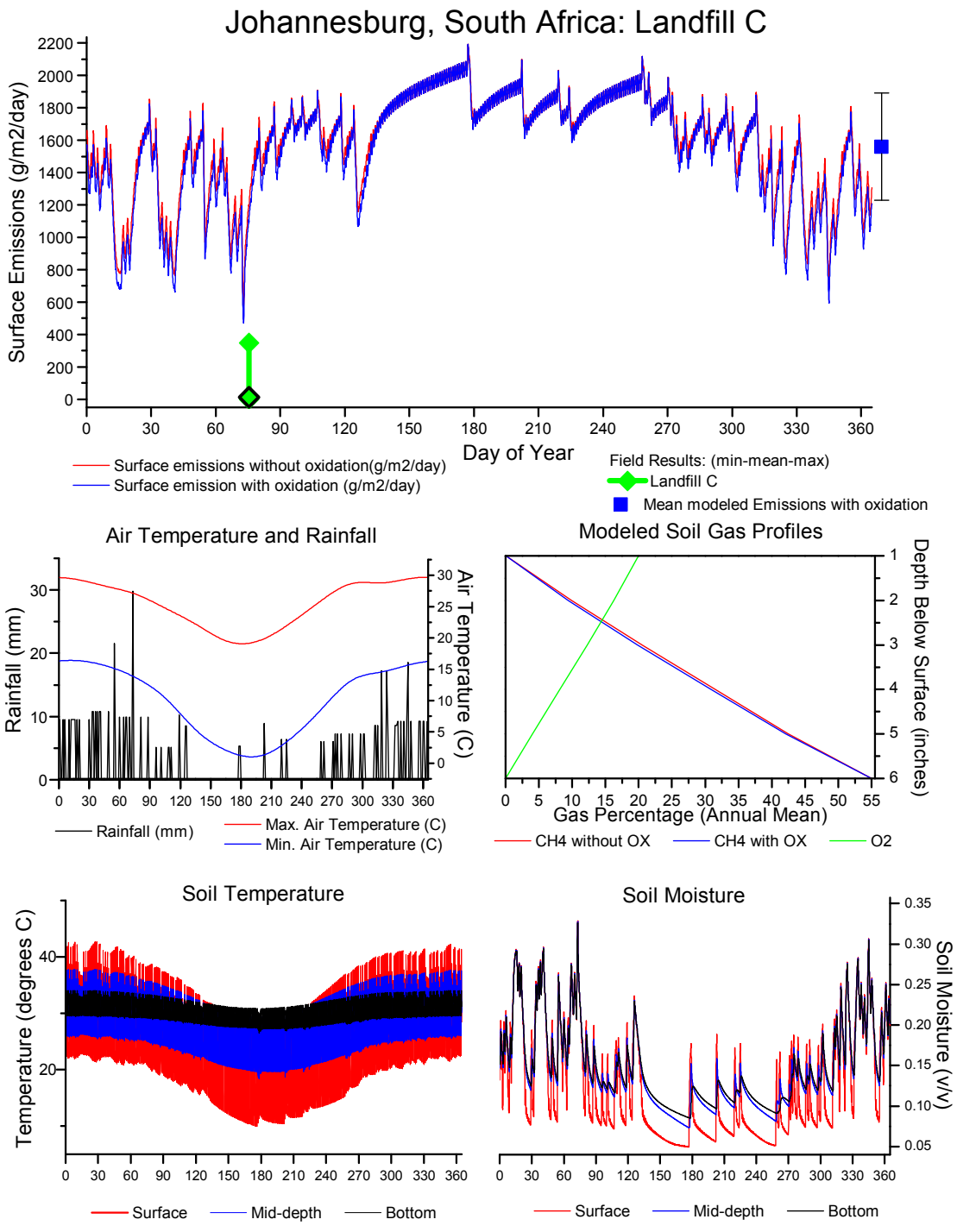
Landfill:	CALMIM (kg/year kg/day)	Study Results using Arithmetic method (kg/day)	Study Results using Kriging method (kg/day)	Study results Wet season using EPLUS model (kg/day)	Study results Dry season using EPLUS model (kg/day)
Landfill A – summer (hot, wet) March, 1999	51,149,548 kg/yr 140,136 kg/day	2,528.4	2,059.9	4,040	n/a
Landfill A – winter (cold, dry) August, 1999		4,351.5	3,137.2	n/a	2,200
Landfill B Total – summer	n/a	5,898.0	3,594.5	14,360	7,970
Landfill B New only – summer	6,214,401 kg/yr 17,026 kg/day	3,519.8	2,933.6	8,820	4,690
Landfill C – summer	82,945,138 kg/yr 227,247 kg/day	1,848.8	2,363.2	n/a	n/a
Landfill D – summer	20,244,610 kg/yr 55,465 kg/day	1,949.1	2,218.4	n/a	n/a

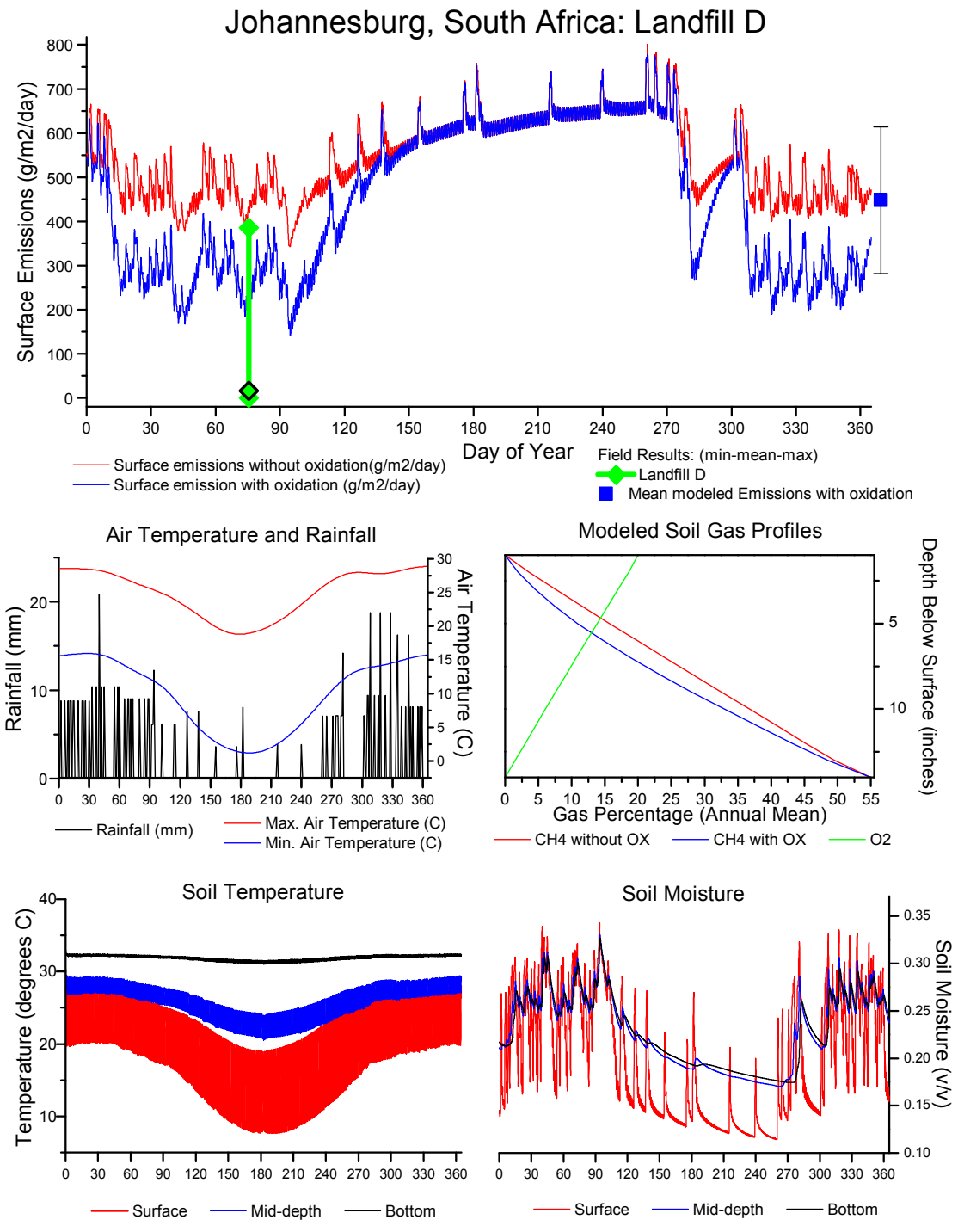
References:

Morris, J.W.F., "Effects of Waste Composition on Landfill Processes in Semi-Arid Climates," PhD thesis, University of the Witwatersrand, Johannesburg, South Africa, 2001.


Johannesburg, South Africa: Landfill A
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
Landfill A (summer)
Landfill A (winter)
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Johannesburg, South Africa: Landfill B
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
Landfill B
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Johannesburg, South Africa: Landfill C
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
Landfill C
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Johannesburg, South Africa: Landfill D
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
Landfill D
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

9-11. Sweden sites, including:

Site Name	Latitude	Longitude	Size
Helsingborg	56.0	12.4	Unknown
Malmo	55.4	13.0	Unknown
Stockholm (Högbytorp)	59.2	18.0	Unknown

Site Description:

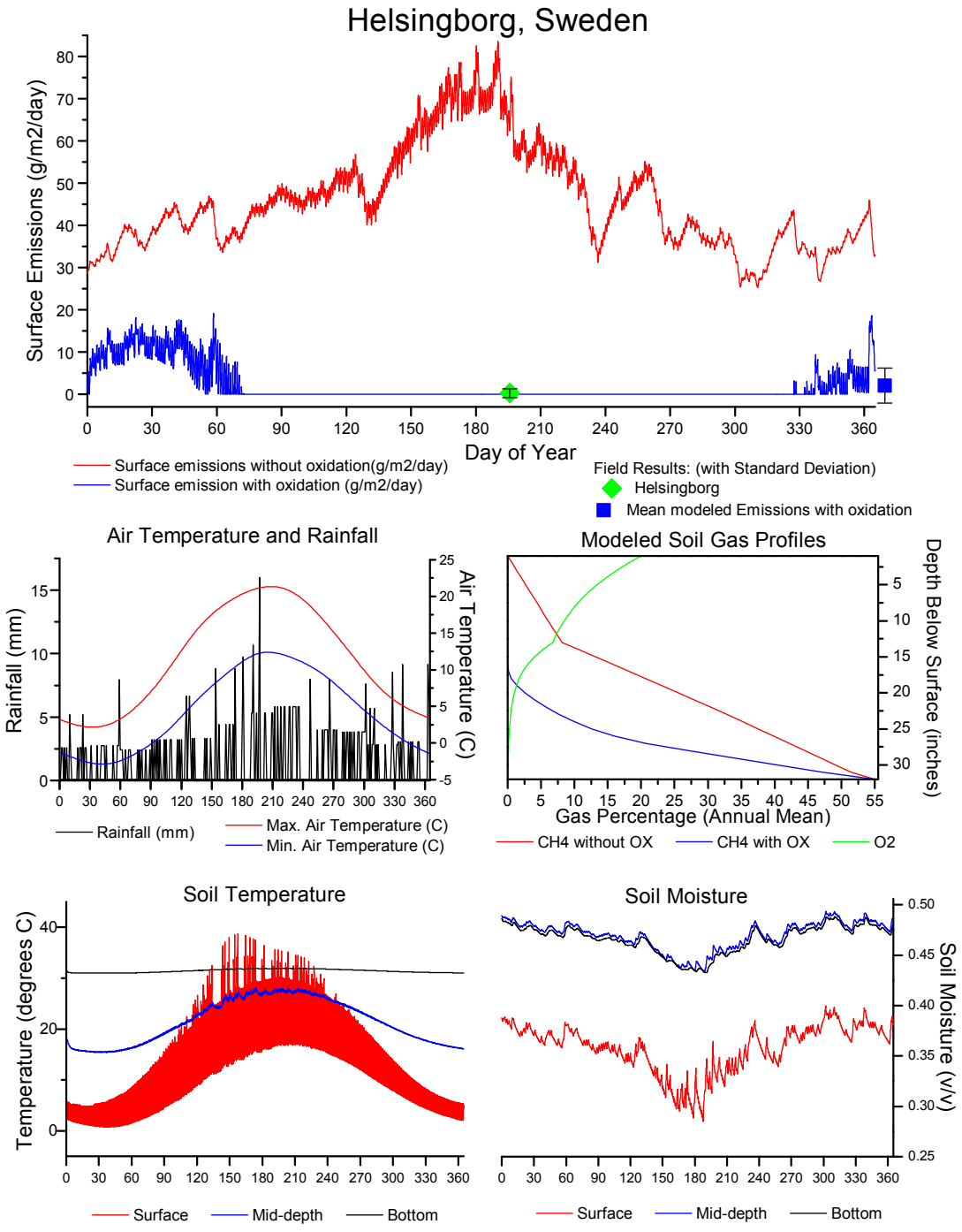
Three sites were studied in the summer of 1994 by Christian Maurice and colleagues at Lulea University of Technology. Each consisted of a test cell constructed for an integrated test cell program. Final cover had been placed on the test cells during the last three years. As limited information was available, some assumptions were made in order to run CALMIM (as described below).

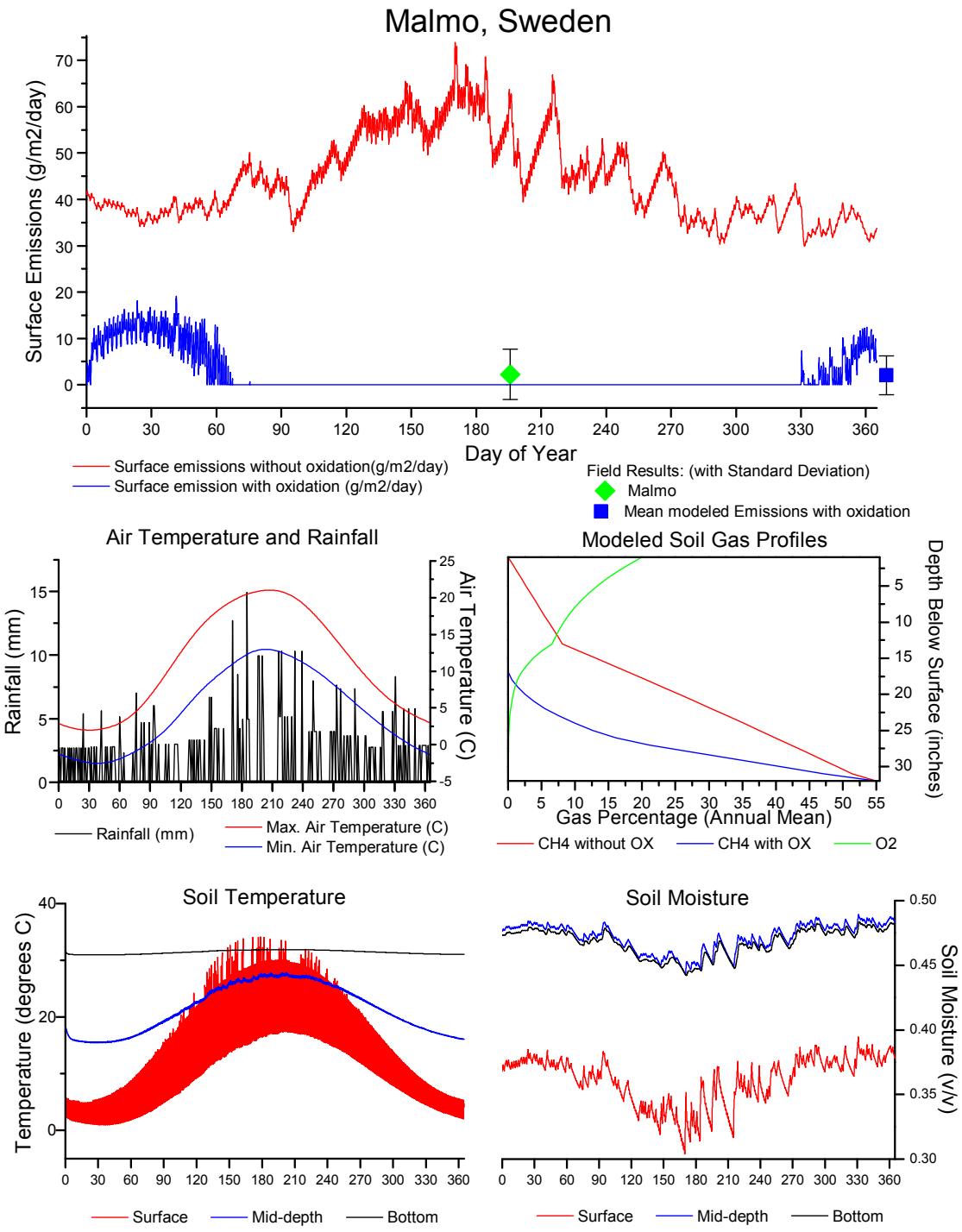
Covers	**Helsingborg**	**Malmo**	**Stockholm (Högbytorp)**
Hectares (Acres)	40 (100)	40 (100)	40 (100)
Cover Type	Final	Final	Final
Coverage % *	100%	100%	100%
Organic Matter %	Mid (2.5%)	Mid (2.5%)	Mid (2.5%)
Gas Recovery %	None	None	None
Vegetation %	None	None	None

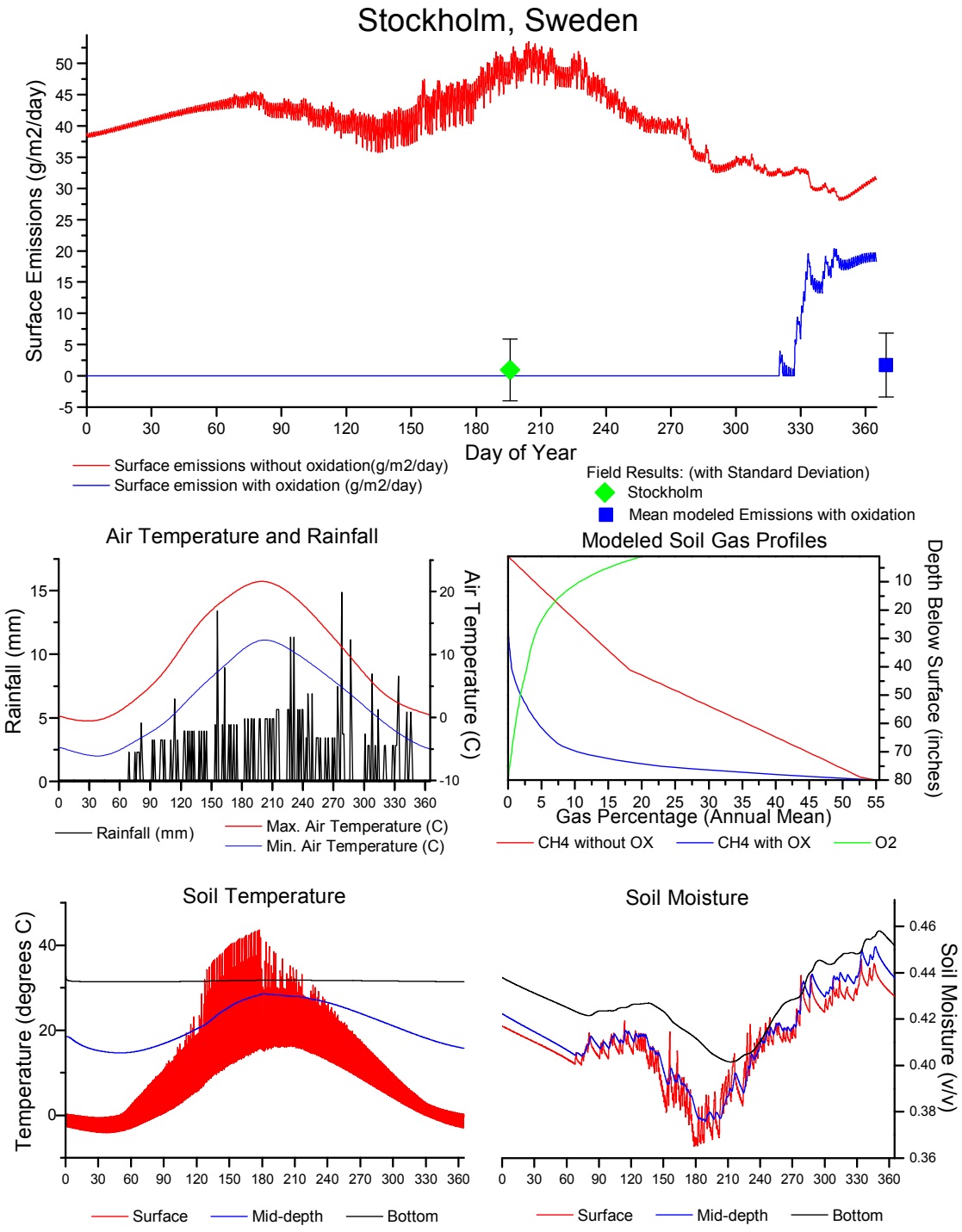
* Coverage % is for use by CALMIM

Layers		**Helsingborg**	**Malmo**	**Stockholm (Högbytorp)**
1	**Material**	Loam	Loam	ADC Sludge
	Thickness	30 cm (12 inches)	30 cm (12 inches)	1 m (40 inches)
2	**Material**	Clay	Clay	Silty clay loam
	Thickness	50 cm (20 inches)	50 cm (20 inches)	1 m (40 inches)

(no gas profile data available)


Helsingborg, Sweden
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (with Standard Deviation)
Helsingborg
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Malmo, Sweden
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (with Standard Deviation)
Malmo
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Stockholm, Sweden
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (with Standard Deviation)
Stockholm
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

12. Taylors Road Park Landfill

Site Location: Melbourne, VIC, Australia

Latitude: -37.7833 **Longitude: 144.9667**

Total Size: 0.02 hectares (0.05 acres)

Site Description: This study is part of the Australian Alternative Covers Assessment Program (A-ACAP) to evaluate phytocap performance at reducing landfill methane emissions. Small side by side cells were constructed using phytocaps and conventional covers. The cells in this study were located on top of existing landfill waste on the eastern slope of landfill cell C11, which closed in 2004. There is a gas recovery system at this landfill.

Covers	**Default**	**Custom Boundaries**	**Default, Gas Off**
Hectares (Acres)	0.02 (0.05)	0.02 (0.05)	0.02 (0.05)
Cover Type	Final	Final	Final
Coverage % *	33%	33%	34%
Organic Matter %	0%	0%	0%
Gas Recovery %	100%	100%	0%
Vegetation %	100%	100%	100%

* Coverage % is for use by CALMIM

Layers		**Default**	**Custom Boundaries**	**Default, Gas Off**
1	**Material**	Sandy-loam	Sandy-loam	Sandy-loam
	Thickness	70 inches	70 inches	70 inches
Custom Boundaries				
CH_4 Lower Boundary		Default (38.5%)	0.1%	Default (55%)
O_2 Lower Boundary		Default (0%)	10%	Default (0%)

Additional Notes:

Static flux chamber measurements were performed on the Phytocap and on the adjacent conventional cover. Only the Phytocap was modeled using CALMIM.

Three scenarios were run in CALMIM, all using the same cover parameters. The differences between the scenarios are in the lower gas boundaries for CH_4 and O_2.

Field Results:

Only the Static Flux Chamber measurements on the Phytocap are presented here, the conventional cover results are not presented.

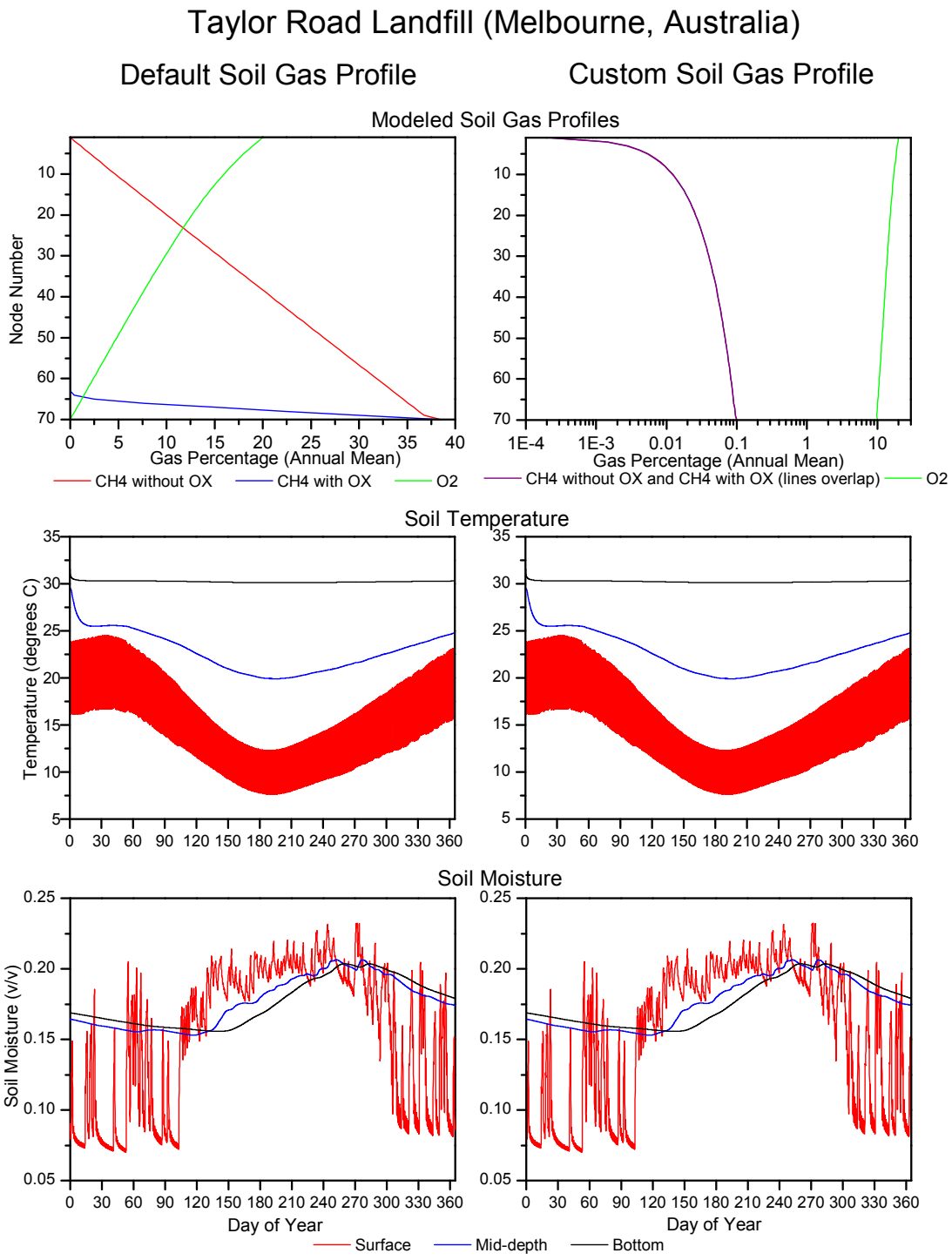
Of the 52 Static Flux Chamber measurements on the Phytocap, 43 showed measurements between -0.002 and 0.003 g CH_4/m^2/day, which are considered negligible.

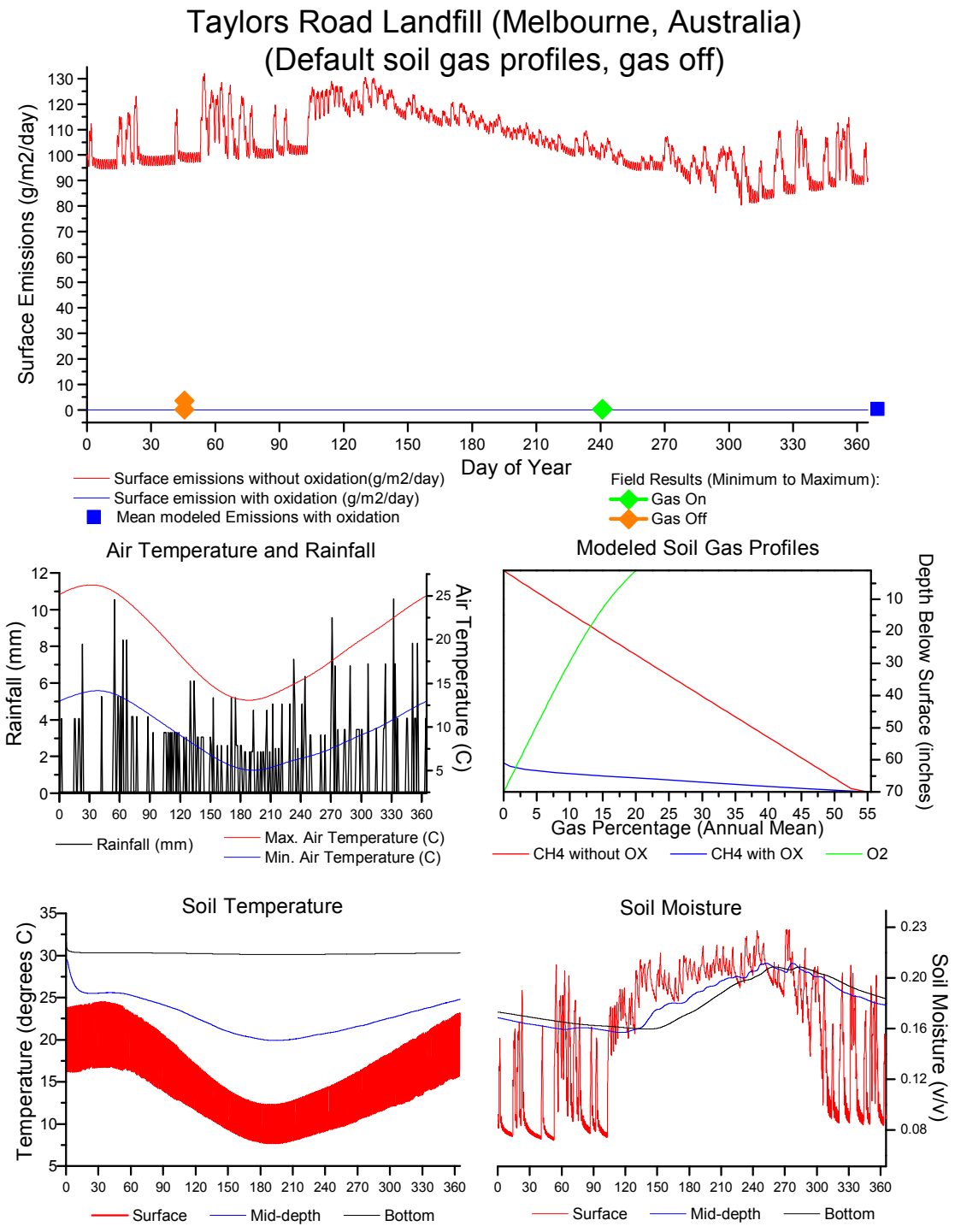
Source	Mean	Std Dev	Median	Minimum	Maximum	N=
Field Results (Sun, 2013) (CH_4 g/m^2/day)						
Phytocap (Gas recovery system on)	n/a	n/a	n/a	-0.024	0.020	29
Phytocap (Gas recovery system off)	n/a	n/a	n/a	-0.010	3.24	23
Modeled (CALMIM 5.4) Results (CH_4 g/m^2/day						
"Default": Phytocap surface emissions with oxidation (default lower gas boundaries)	0.0	0.0	0.0	0.0	0.0	8760
"Custom": Phytocap surface emissions with oxidation (custom lower gas boundaries)	0.183	0.036	0.185	0.0	0.239	8760
"Gas Off": Phytocap surface emissions with oxidation (default lower gas boundaries, gas off)	0.0	0.0	0.0	0.0	0.0	8760

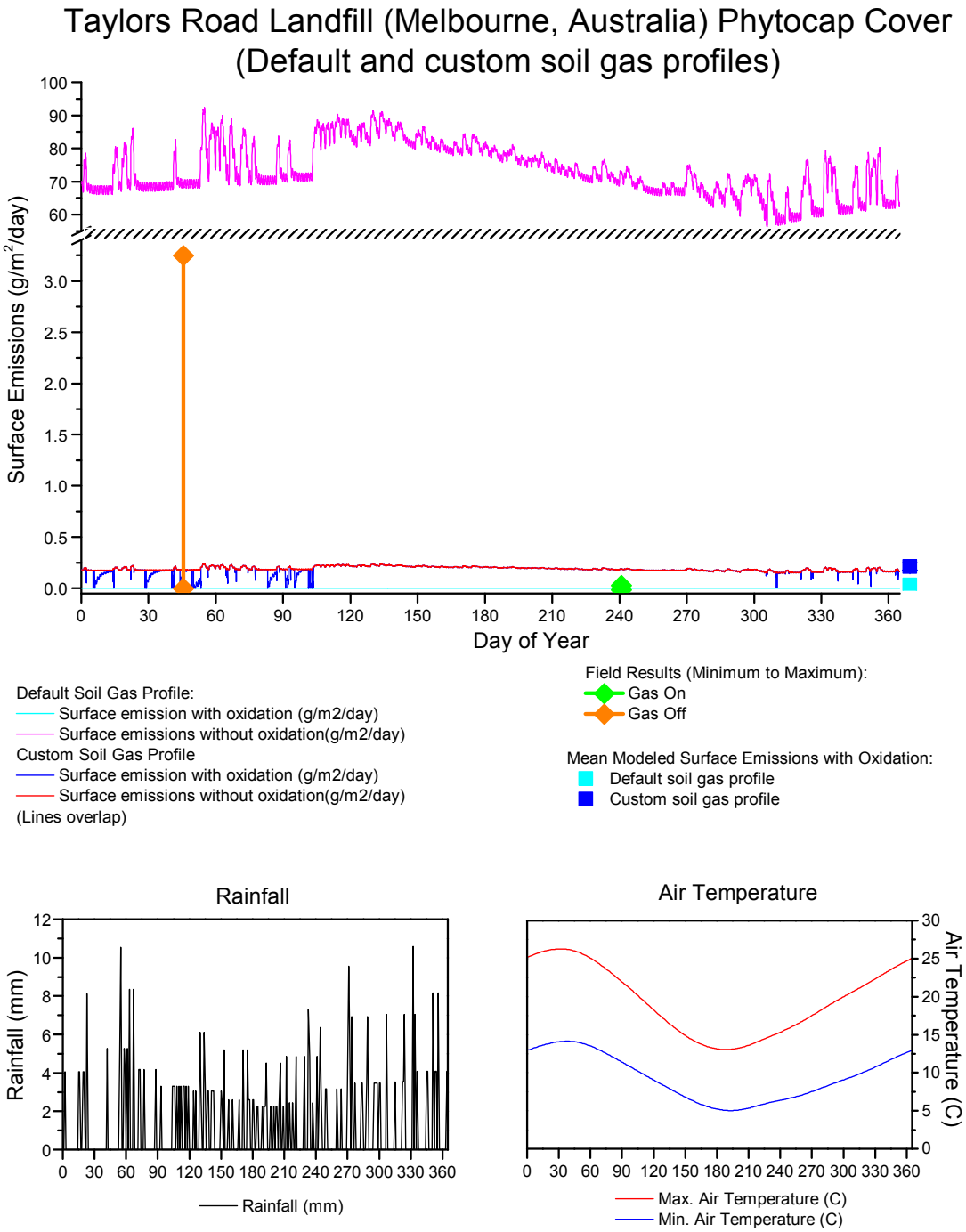
Discussion:

References:

Sun, J., 2013. Phytocaps as Biotic Systems to Mitigate Landfill Methane Emissions. Dept. of Infrastructure Engineering and Dept. of Agriculture and Food Systems. The University of Melbourne, Melbourne, Victoria, Australia.


Taylor Road Landfill (Melbourne, Australia)
Default Soil Gas Profile
Custom Soil Gas Profile
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
CH4 without OX and CH4 with OX (lines overlap)
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom


Taylors Road Landfill (Melbourne, Australia)
(Default soil gas profiles, gas off)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results (Minimum to Maximum):
Gas On
Gas Off
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Taylors Road Landfill (Melbourne, Australia) Phytocap Cover
(Default and custom soil gas profiles)
Surface Emissions (g/m2/day)
Day of Year
Default Soil Gas Profile:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Custom Soil Gas Profile
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
(Lines overlap)
Field Results (Minimum to Maximum):
Gas On
Gas Off
Mean Modeled Surface Emissions with Oxidation:
Default soil gas profile
Custom soil gas profile

Rainfall
Rainfall (mm)
Rainfall (mm)

Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)

13. Shan-Chu-Ku Landfill

Site Location: Taipei City, Taiwan

Latitude: 25.027425N **Longitude:** 121.625192E

Total Size: 30 hectares (75 acres)

Site Description:

This is an active landfill near Taipei City, Taiwan where 30 ha are in use for landfilling. This study was designed to compare the methane and carbon dioxide emissions from the landfill from three ages of waste: 1-2 year old, 2-3 year old, and 5 year old. There is a gas recovery system in place, but it is not clear if it covers the area where the field measurements were performed. CALMIM was modeled with 100 % gas recovery.

Covers	**1-2 Final**	**2-3 Final**	**5 Final**
Hectares (Acres)	10 (25)	10 (25)	10 (25)
Cover Type	Final	Final	Final
Coverage % *	33	33	34
Organic Matter %	high	high	high
Gas Recovery %	100%	100%	100%
Vegetation %	100%	100%	100%

* Coverage % is for use by CALMIM

Layers		**1-2 Final**	**2-3 Final**	**5 Final**
1	**Material**	Sandy Loam (paper shows "Loam, sandy loam")	Clay Loam (paper shows "Loam, clay loam")	Loam
	Thickness	130 cm	140 cm	180 cm

Custom Boundaries

(no gas profile data available)

Additional Notes:

The site location is listed as 25˚02'N, 120˚32'E, however CALMIM found that to be in the ocean, and CALMIM cannot properly model the weather over the ocean. The CALMIM model was run using the geographical coordinates listed at the top of the page based on a search in Google Maps.

Organic carbon was reported for the 1-2 year old, 2-3 year old, and 5 year old covers as 6.73, 8.4, and 6.3% respectively. CALMIM was modeled using "high" organic carbon, the maximum available in CALMIM, which is 5%.

Field Results:

The field measurements were performed in February 1998 (2-3 year old cover) and May 1998 (1-2 year old cover and 5 year old cover).

Field Results were published in units of $mg/m^2/hr$ and converted to $g/m^2/day$ by multiplying by 0.024.

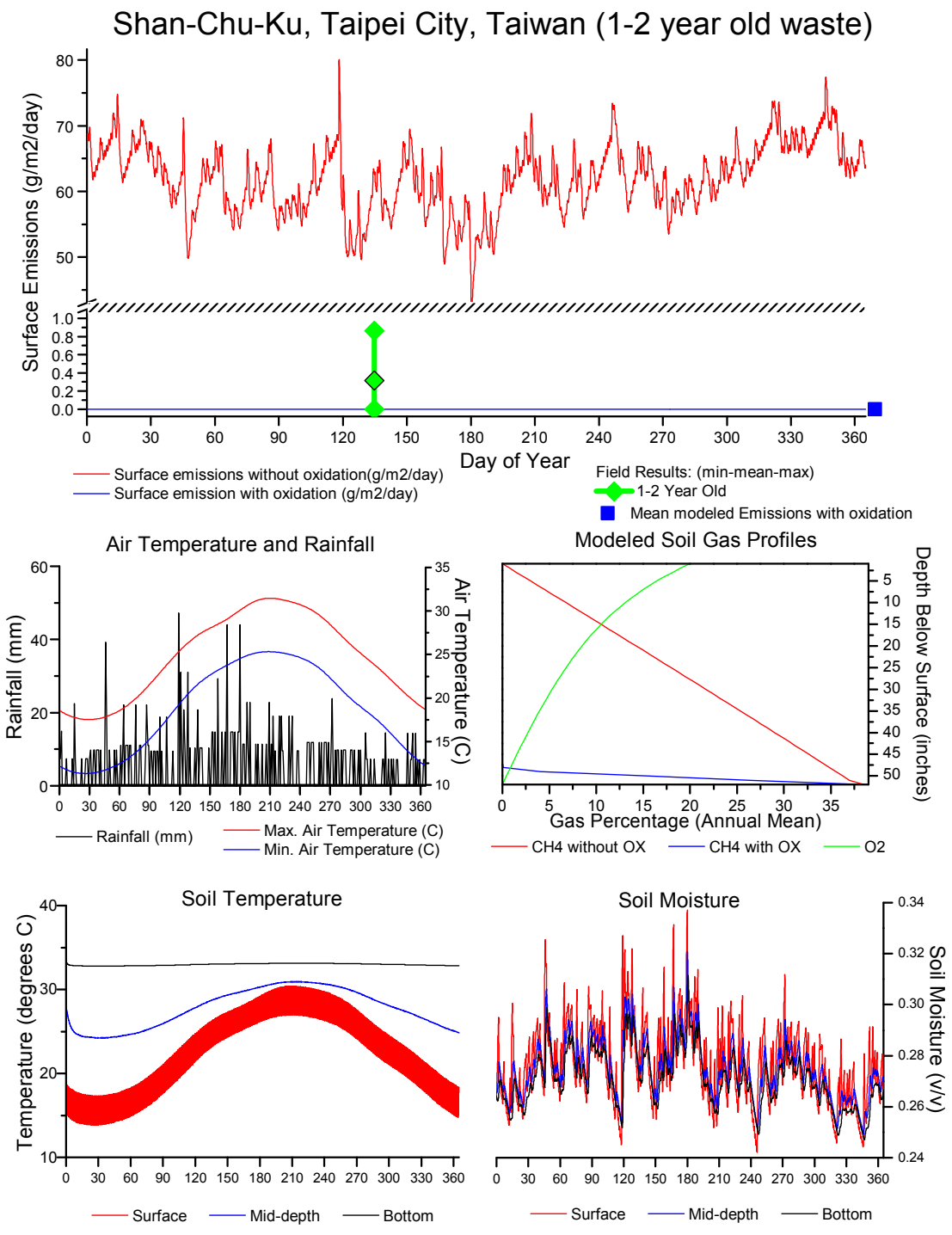
No errors were available in the published literature.

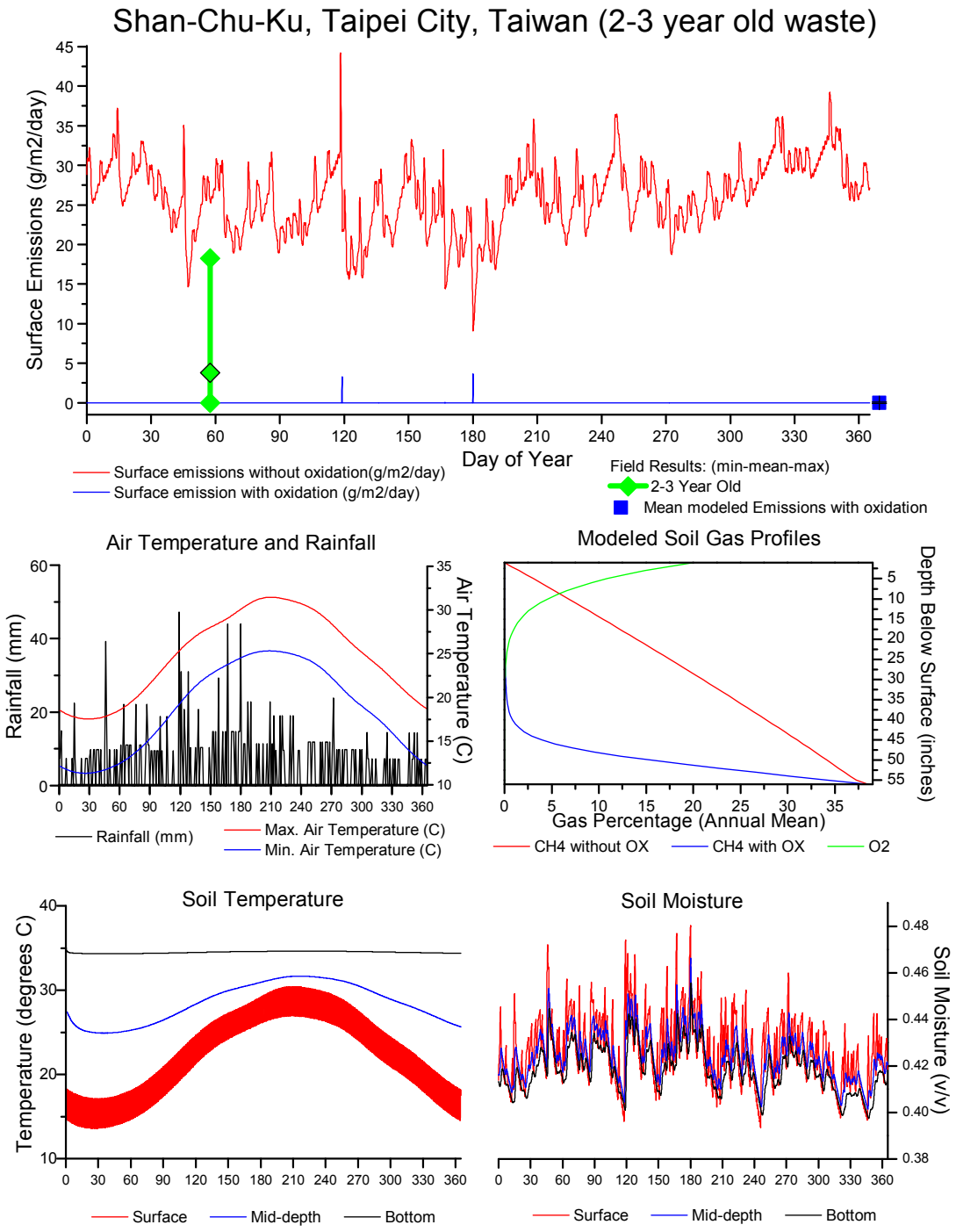
Results (all in)						
Source	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Published Results (Hegde et al., 2003) $g/m^2/day$ ($mg/m^2/hr$) *						
1-2 year old waste	0.32 (13.17)	n/a	n/a	0	0.86 (36.01)	9
2-3 year old waste	3.78 (157.56)	n/a	n/a	0	18.24 (759.82)	18
5 year old waste	0.024 (0.99)	n/a	n/a	0	0.13 (5.55)	9
Modeled (CALMIM) Results $g/m^2/day$						
1-2 year old waste	0.0	0.0	0.0	0.0	0.0	8760
2-3 year old waste	0.0017	0.0678	0.0	0.0	3.6589	8760
5 year old waste	0.0	0.0	0.0	0.0	0.0	8760
* Published results in mg/m^2/hour are converted to g/m^2/day by multiplying by 0.024						

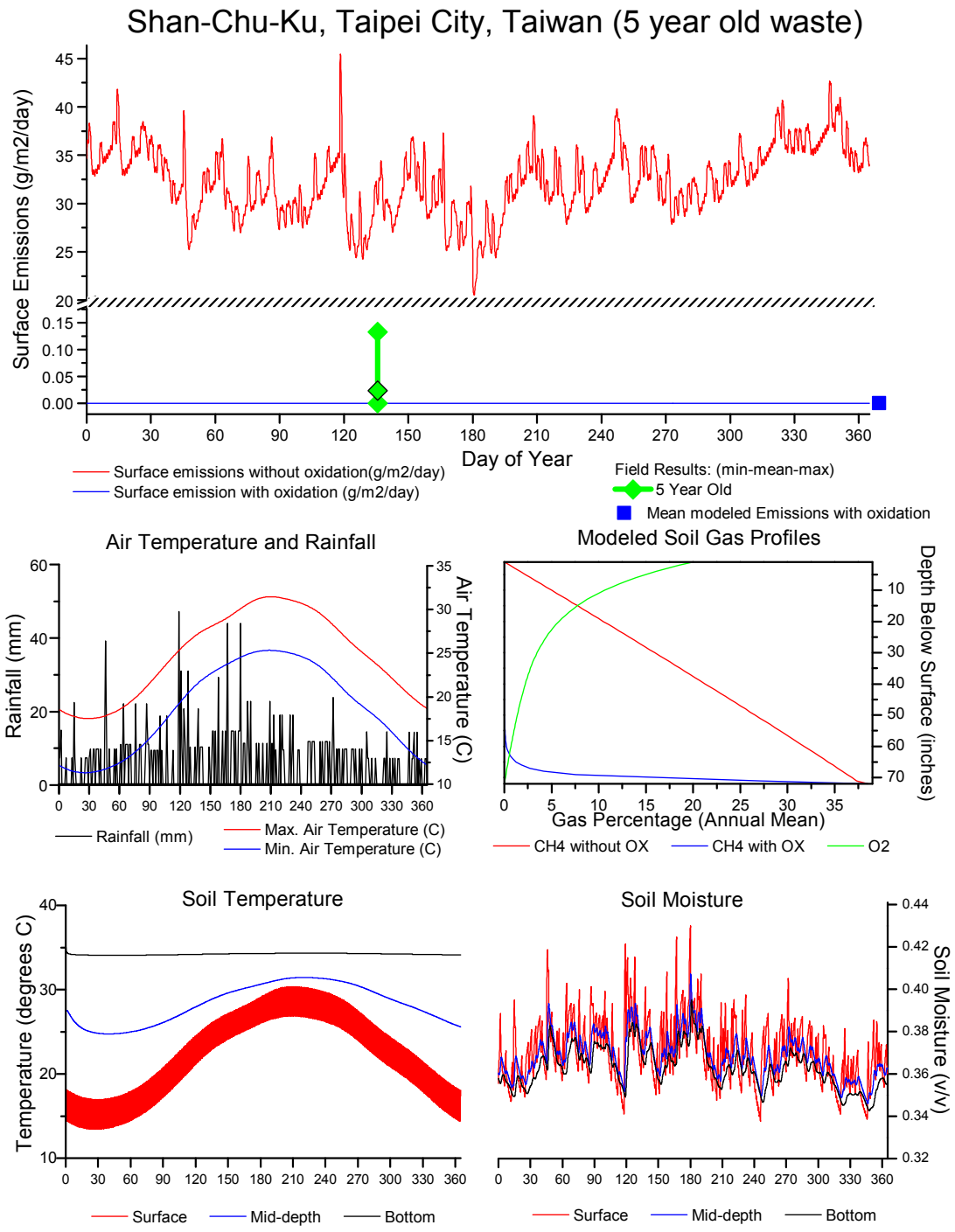
Discussion:

References:

Hegde, U., Chang, T.-C., Yang, S.-S., 2003. Methane and carbon dioxide emissions from Shan-Chu-Ku landfill site in northern Taiwan. Chemosphere, 52(8), 1275-1285.


Shan-Chu-Ku, Taipei City, Taiwan (1-2 year old waste)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
1-2 Year Old
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Shan-Chu-Ku, Taipei City, Taiwan (2-3 year old waste)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
2-3 Year Old
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Shan-Chu-Ku, Taipei City, Taiwan (5 year old waste)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results: (min-mean-max)
5 Year Old
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

14. Emerald Park Landfill, Franklin, **WI**

(near Milwaukee)

Latitude: 42.85 **Longitude: -88.06**

Total Size: 33 hectares (82 acres)

Site Description:

This landfill was studied in 2008. Cover soils were not analyzed so standard cover types were used in CALMIM with a Clay-silt-loam soil type typical of the local area. Static chambers were used in addition to other measurement methods.

Covers	Daily 6 (permitted minimum depth)	Daily 12 (double permitted minimum depth)	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)	Final ***
Hectares (Acres)	17 (42) **	17 (42) **	5 (13)	5 (13)	11 (27)
Cover Type	Daily	Daily	Intermediate	Intermediate	Final
Coverage % *	25%	25%	25%	25%	n/a
Organic Matter %	Mid	Mid	Mid	Mid	Mid
Gas Recovery %	100%	100%	100%	100%	100%
Vegetation %	100%	100%	100%	100%	100%

* Coverage % is for use by CALMIM

** Combined area of daily cover areas in A&B and C&D

*** Not run in CALMIM

Layers		Daily 6 (permitted minimum depth)	Daily 12 (double permitted minimum depth)	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)	Final ***
1	**Material**	Clay-silt-loam	Clay-silt-loam	Clay-silt-loam	Clay-silt-loam	Clay-silt-loam
	Thickness	6	12	12	36	36
2	**Material**					Geomembrane
	Thickness					

*** Not run in CALMIM

Custom Boundaries

(no gas profile data available)

Additional Notes:

Chambers were placed at these sites:

Area A. located on the western slope adjacent to the fluff covered daily cover areas, but in soil.

Area B, located on the eastern slope adjacent to the fluff covered daily cover areas, but in soil.

Area C was an intermediate covered area on the south facing slope on the C&D landfill.

Area D was at the top of the C&D area in daily soil cover.

For CALMIM modeling, each cover was run as 25% of the total area. To calculate total surface emissions, the CALMIM results must be adjusted from 25% to the correct

percentage for each cover type (Daily: 52% of total, Intermediate: 15% of total.) Because of the impermeable Geomembrane in the Final Cover the surface emissions for Final Cover are assumed to be zero.

Field Results:

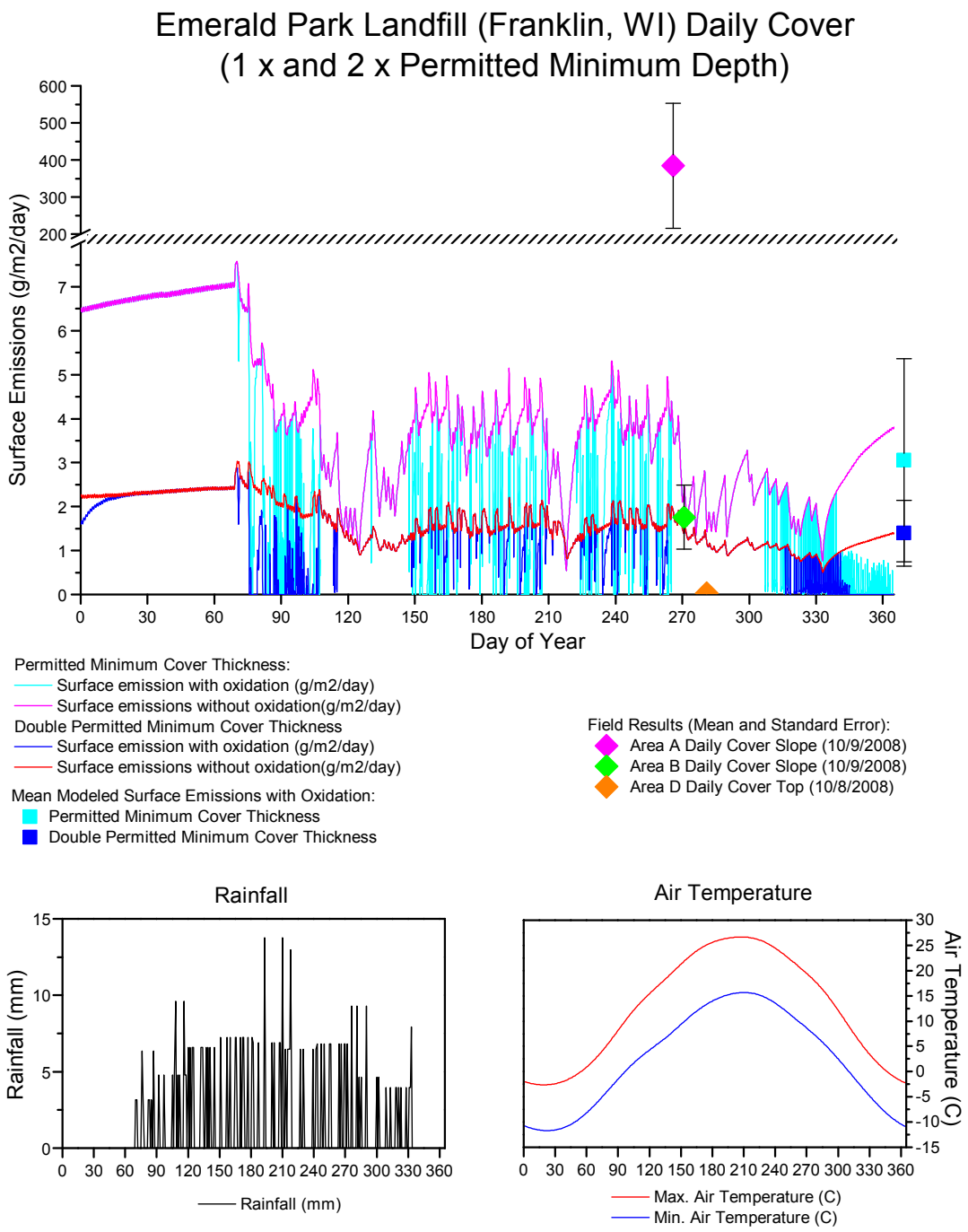
Source	Mean	Std Error	Median	Minimum	Maximum	N=
Published Results (Chanton and Bogner, 2008)						
Area A Daily Cover Slope 9-Oct-08	381.9	169.1	299.2	n/a	n/a	8
Area B Daily Cover Slope 9-Oct-08	1.74	0.73	1.00	n/a	n/a	8
Area C Intermediate Slope 8-Oct-08	13.4	10.0	0.000	n/a	n/a	7
Area D Daily Cover Top 8-Oct-08	0.005	0.005	0.00	n/a	n/a	7
Modeled (CALMIM 5.4) Results (CH_4 $g/m^2/day$	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Daily 6 (Permitted Minimum Thickness)	2.99	2.32	2.63	0.00	7.57	8760
Daily 12 (Double Permitted Minimum Thickness)	1.33	0.75	1.39	0.00	2.88	8760
Intermediate 12 (Permitted Minimum Thickness)	169.56	113.71	128.45	0.00	446.57	8760
Intermediate 36 (Triple Permitted Minimum Thickness)	0.00	0.00	0.00	0.00	0.00	8760

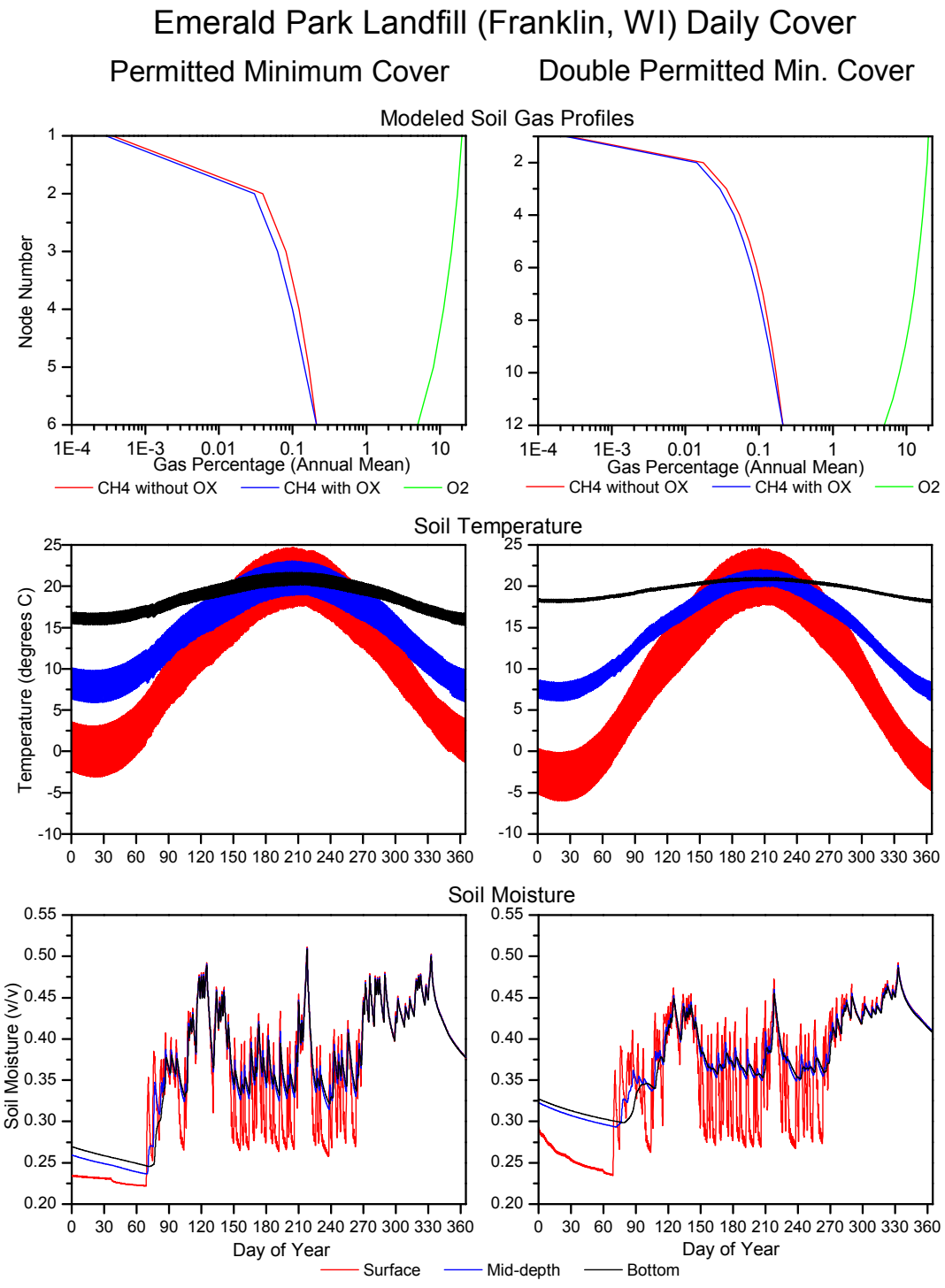
CALMIM 5.4 Results (Surface Emissions with Oxidation)	Gas Recovery %	Permitted Minimum Cover CH_4 kg/year	Doubled or Tripled Permitted Minimum Cover CH_4 kg/year	Hectares (Acres)
Daily Cover	100%	188,557	(Doubled) 83,981	17 (42) (52% of total)
Intermediate Cover	100%	3,080,491	(Tripled) 0	5 (13) (15% of total)
Final Cover	100%	(Assumed) 0	(Assumed) 0	11 (27) (33% of total)
Total CH_4 emissions with oxidation (kg/year) [Assumes Final Cover 0]		**(Minimum) 3,269,048**	**(Doubled/Tripled) 83,981**	**33 (82)**

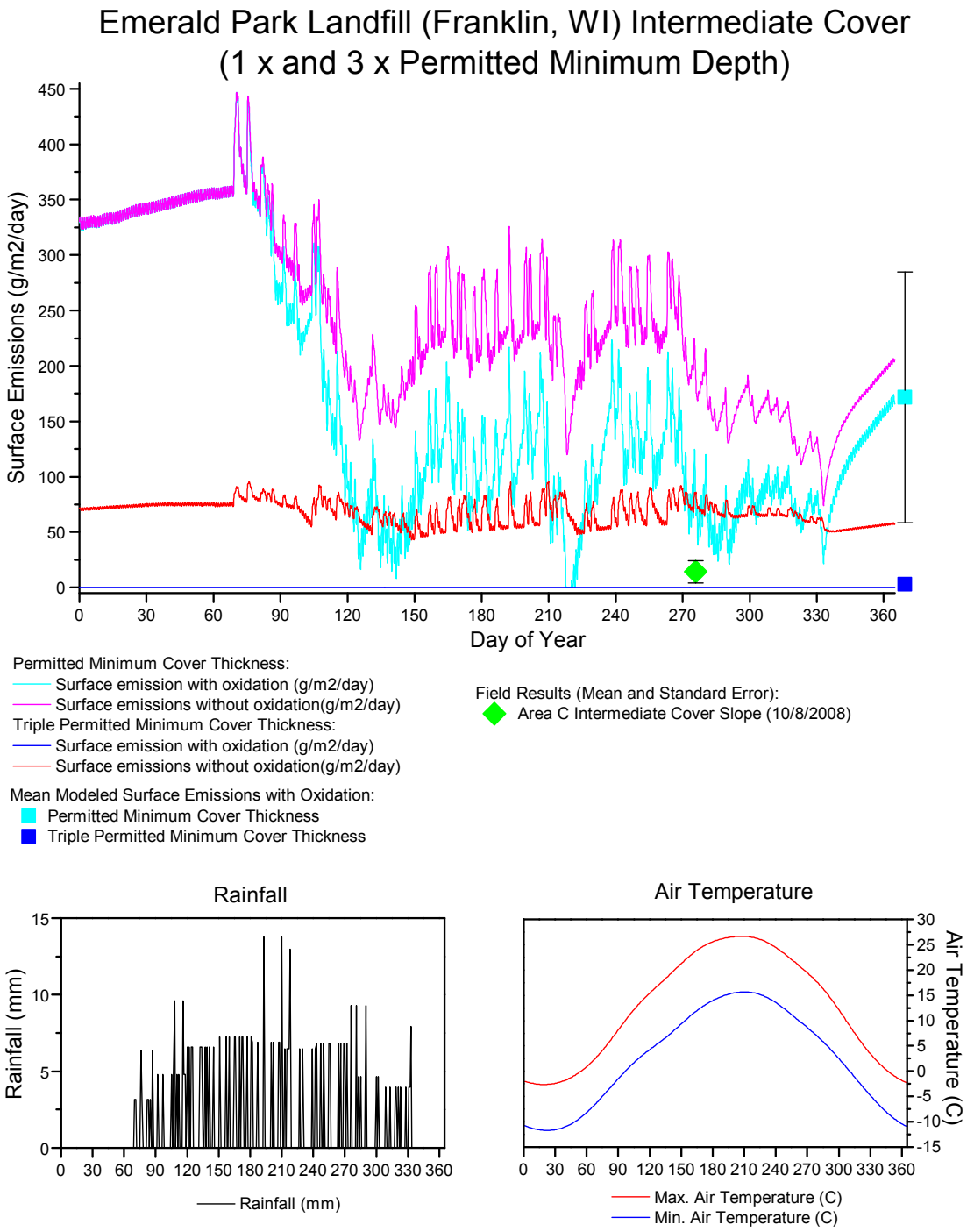
Discussion:

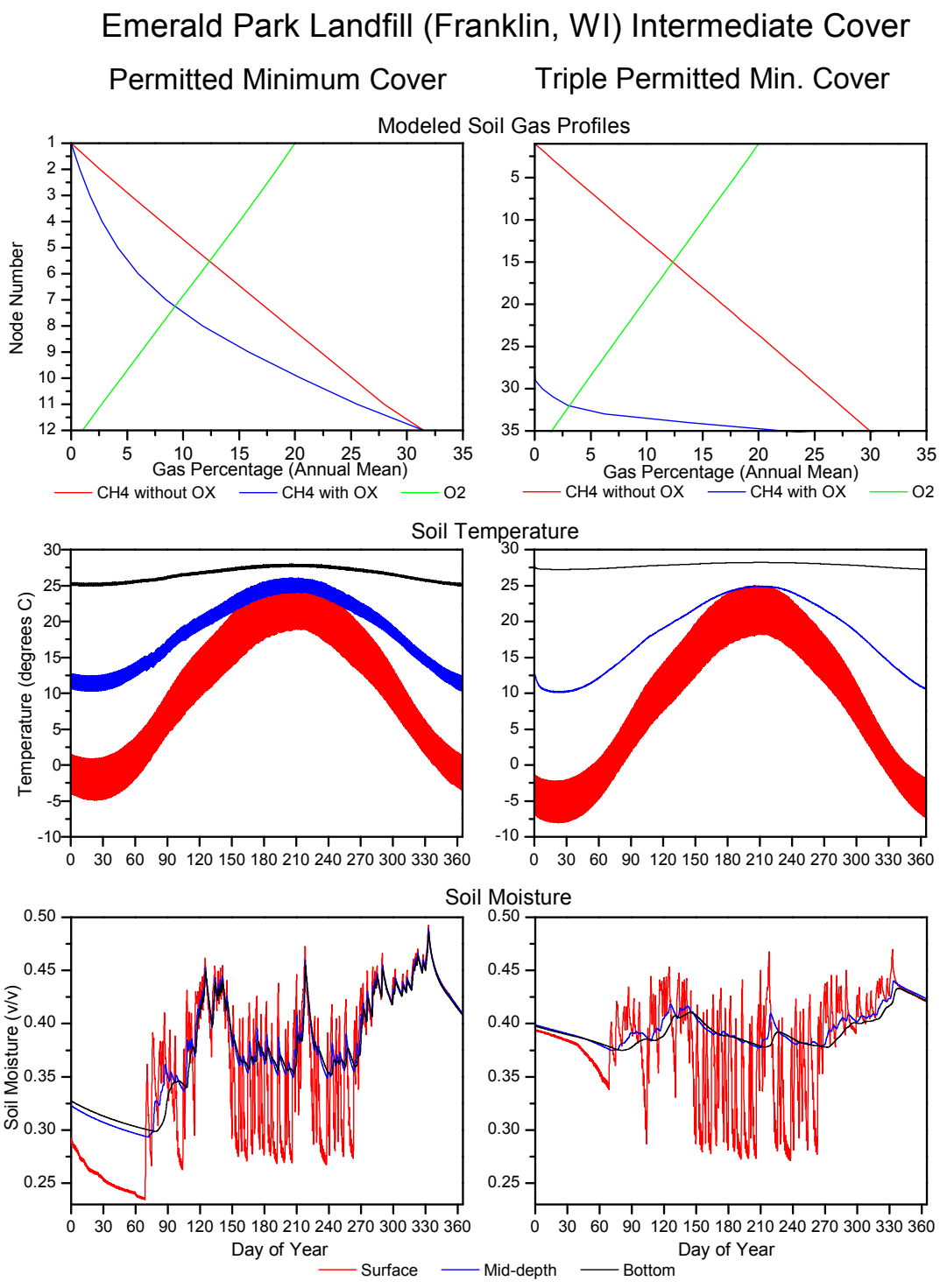
References:

Chanton, J., Bogner, J., 2008. Final Report: Chamber Measurements at USA Waste Management and Veolia Landfill Fugitive Emission Study, Wisconsin, USA.


Emerald Park Landfill (Franklin, WI) Daily Cover
(1 x and 2 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Double Permitted Minimum Cover Thickness
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Mean Modeled Surface Emissions with Oxidation:
Permitted Minimum Cover Thickness
Double Permitted Minimum Cover Thickness
Field Results (Mean and Standard Error):
Area A Daily Cover Slope (10/9/2008)
Area B Daily Cover Slope (10/9/2008)
Area D Daily Cover Top (10/8/2008)
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


Emerald Park Landfill (Franklin, WI) Daily Cover
Permitted Minimum Cover
Double Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom


Emerald Park Landfill (Franklin, WI) Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Triple Permitted Minimum Cover Thickness:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Mean Modeled Surface Emissions with Oxidation:
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results (Mean and Standard Error):
Area C Intermediate Cover Slope (10/8/2008)
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


Emerald Park Landfill (Franklin, WI) Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom

15. Site WI1

Site Location: Muskego, WI (near Milwaukee)

Latitude: 42.85 **Longitude: -88.06**

Total Size: 64.5 hectares (160 acres)

Site Description:

This landfill is located in Southeast Wisconsin, and was studied in 2008. Cover soils were not analyzed so emissions were modeled in CALMIM with a Clay-silt-loam soil type typical of the local area. Static chambers were used in addition to other measurement methods.

Covers	**Daily 6 (permitted minimum depth)**	**Daily 12 (double permitted minimum depth)**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**	**Final ****
Hectares (Acres)	9.8 (24)	9.8 (24)	9.2 (23)	9.2 (23)	45.5 (113)
Cover Type	Daily	Daily	Intermediate	Intermediate	Final
Coverage % *	25%	25%	25%	25%	n/a
Organic Matter %	Mid	Mid	Mid	Mid	Mid
Gas Recovery %	100%	100%	100%	100%	100%
Vegetation %	100%	100%	100%	100%	100%

* Coverage % is for use by CALMIM
** Not run in CALMIM

Layers		**Daily 6 (permitted minimum depth)**	**Daily 12 (double permitted minimum depth)**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**	**Final ****
1	**Material**	Clay-silt-loam	Clay-silt-loam	Clay-silt-loam	Clay-silt-loam	Clay-silt-loam
	Thickness	6	12	12	36	36
2	**Material**					Geomembrane
	Thickness					

** Not run in CALMIM

Custom Boundaries

(no gas profile data available)

Additional Notes:

Chambers were placed at these sites:
Area designated MS, a slope with vegetated clay cover on final cover. Note the final cover was not run in CALMIM due to the presence of the Geomembrane.
Area A, a vegetated southern slope on the working area with intermediate cover.
Area B, the top of the working area which had a daily cover.
Area C, the north slope of the working area, which had a vegetated intermediate cover.
For CALMIM modeling, each cover was run as 25% of the total area. To calculate total surface emissions, the CALMIM results must be adjusted from 25% to the correct percentage for each cover type (Daily: 15% of total, Intermediate, 14% of total.) Because of the impermeable Geomembrane in the Final Cover the surface emissions for Final Cover are assumed to be zero.

Field Results:

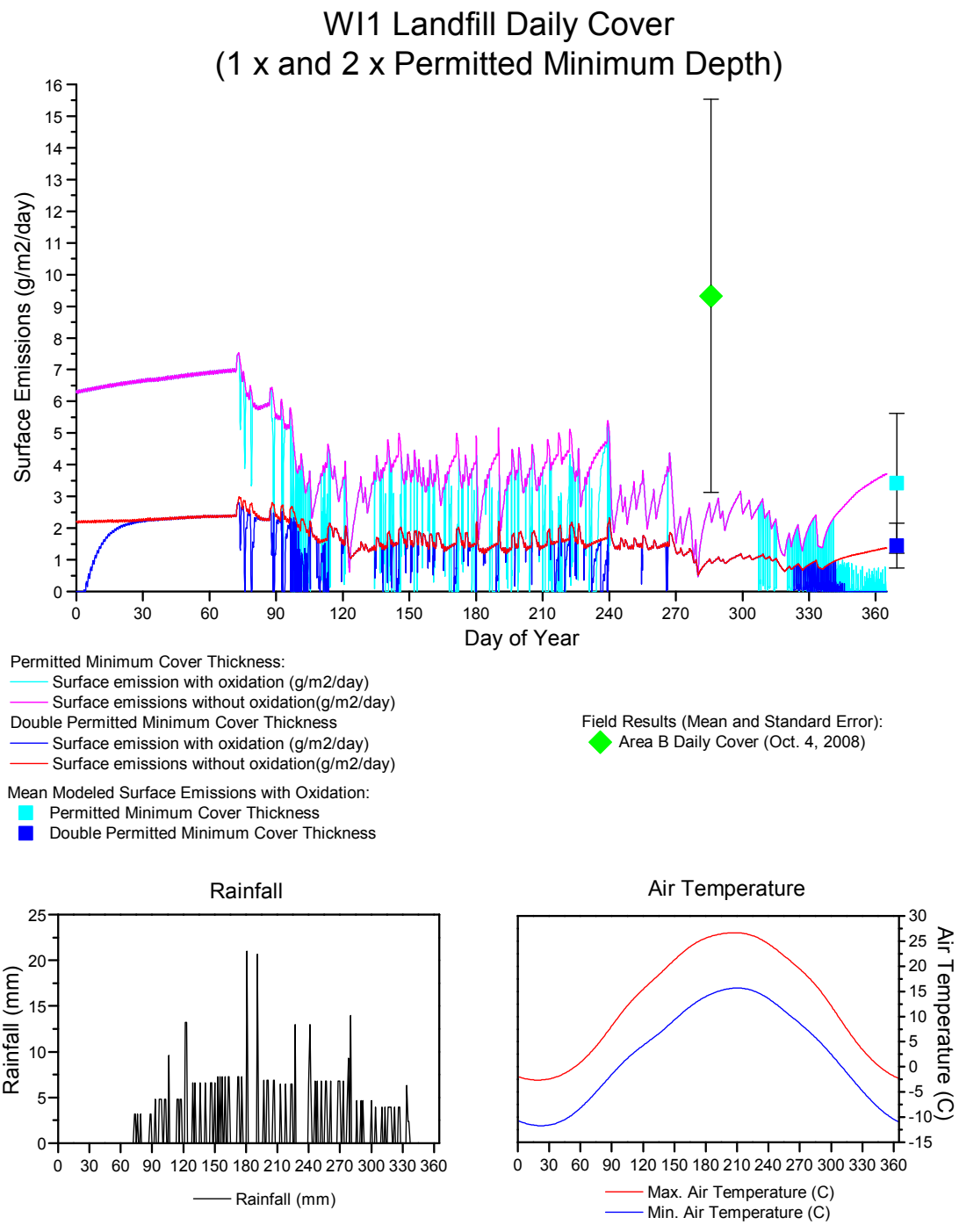
Source	Mean	Std Error	Median	Minimum	Maximum	N=
Published Results (Chanton and Bogner, 2008)						
Area B Daily Cover (10/4/2008)	9.3	6.2	4.5	n/a	n/a	7
Area A Intermediate Cover South Slope (10/3/2008)	116.6	114.4	0.050	n/a	n/a	8
Area A Intermediate Cover South Slope (10/4/2008)	74.1	69.8	0.170	n/a	n/a	8
Area C Intermediate Cover North Slope (10/4/2008)	36.4	28.2	0.970	n/a	n/a	8
Area MS Final Cover (10/1/2008)	-0.001	0.001	0.000	n/a	n/a	20
Area MS Final Cover (10/2/2008)	0.006	0.005	0.000	n/a	n/a	22
Modeled (CALMIM 5.4) Results (CH_4 $g/m^2/day$	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Daily 6 (Permitted Minimum Thickness)	3.33	2.22	3.10	0.0	7.52	8760
Daily 12 (Double Permitted Minimum Thickness)	1.35	0.71	1.41	0.0	2.82	8760
Intermediate 12 (Permitted Minimum Thickness)	170.65	115.83	125.36	0.0	439.99	8760
Intermediate 36 (Triple Permitted Minimum Thickness)	0.0	0.0	0.0	0.0	0.0	8760

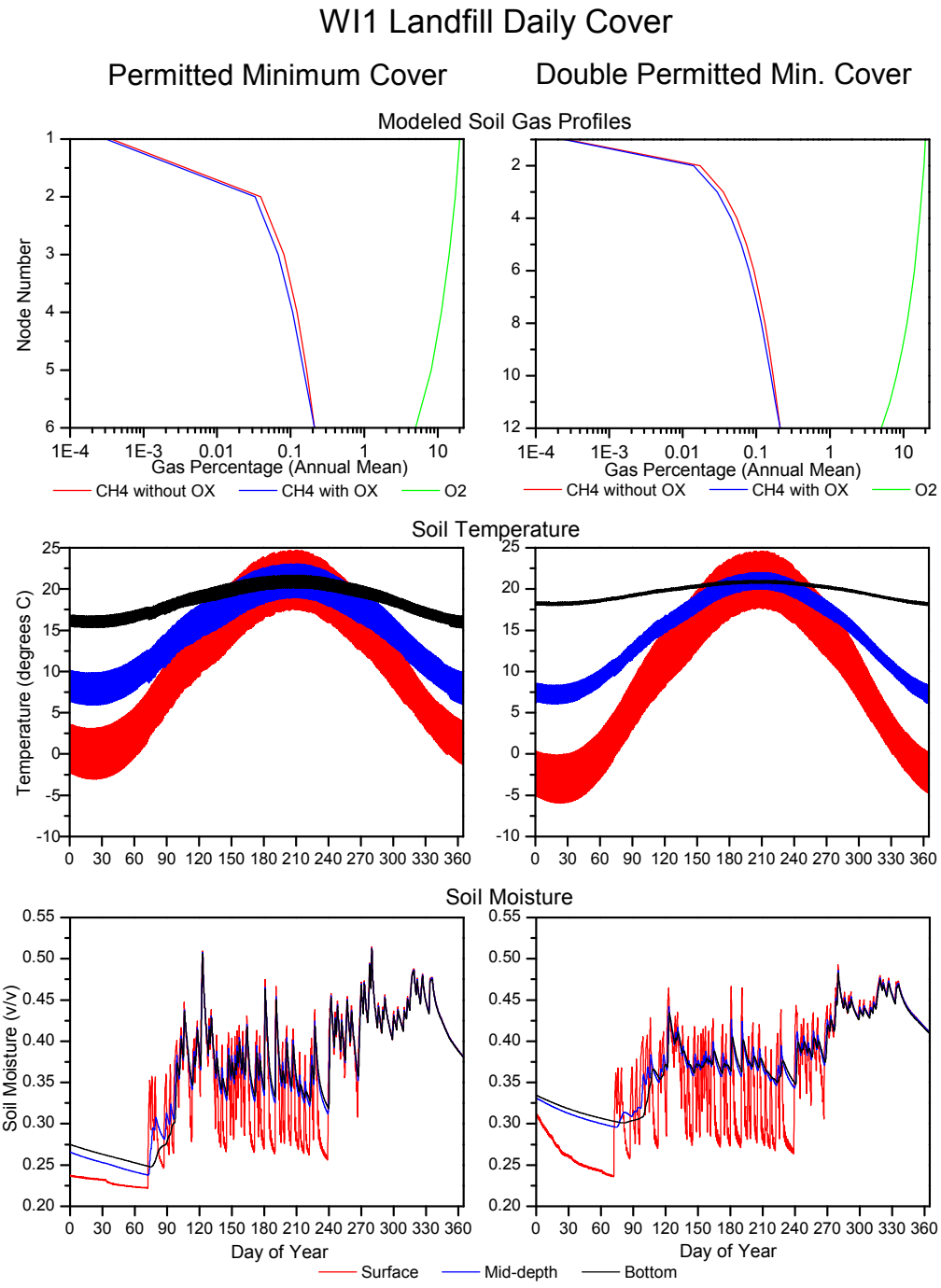
CALMIM 5.4 Results (Surface Emissions with Oxidation)	**Gas Recovery %**	**Permitted Minimum Cover CH_4 kg/year**	**Doubled or Tripled Permitted Minimum Cover CH_4 kg/year**	**Hectares (Acres)**
Daily Cover	100%	118,109	(Doubled) 47,970	9.8 (24) (15% of total)
Intermediate Cover	100%	5,645,926	(Tripled) 0	9.2 (23) (14% of total)
Final Cover	100%	(Assumed) 0	(Assumed) 0	45.5 (113) (71% of total)
Total CH4 emissions with oxidation (kg/year) [Assumes Final Cover 0]		**(Minimum) 5,764,035**	**(Doubled/Tripled) 47,970**	**64.5 (160)**

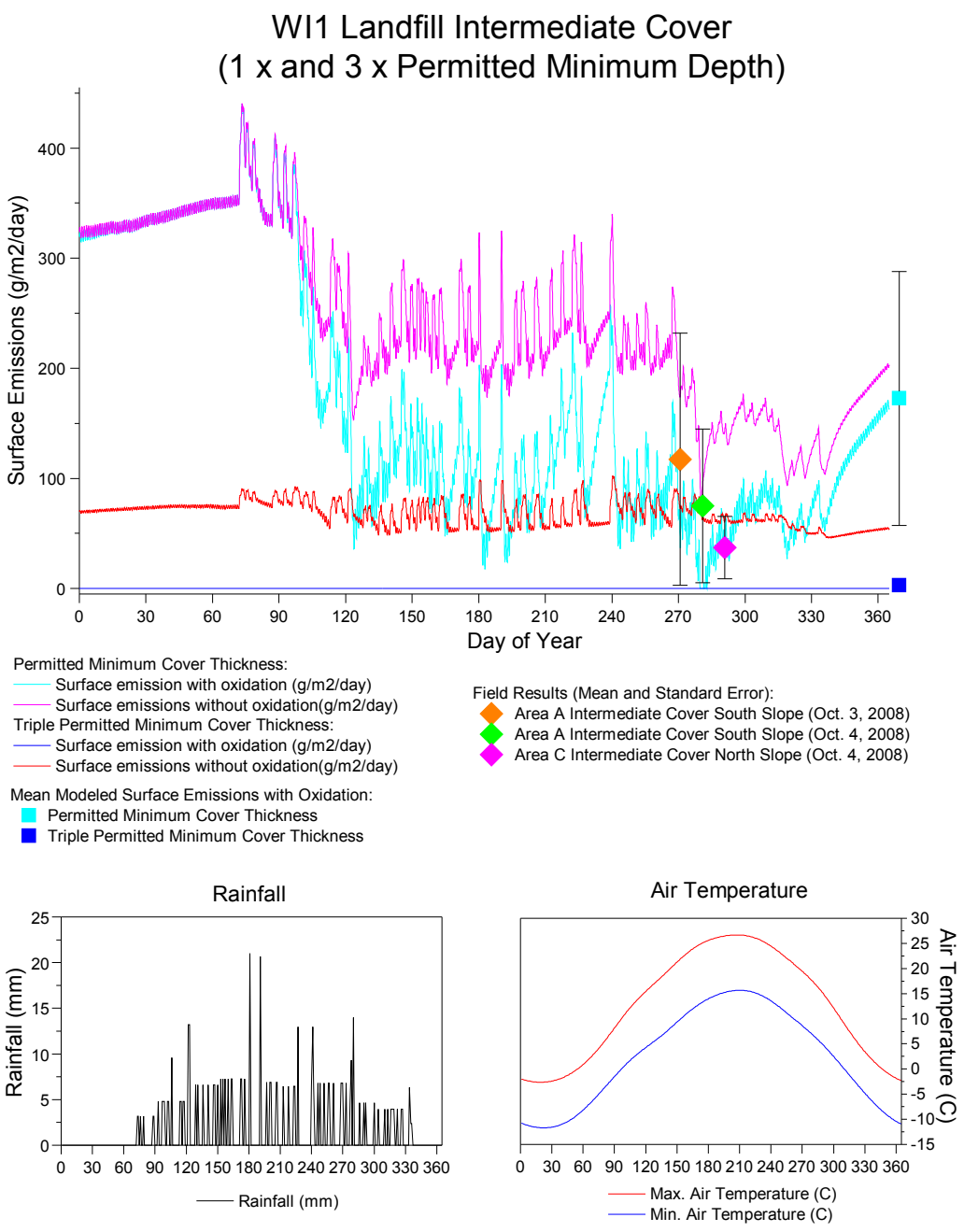
Discussion:

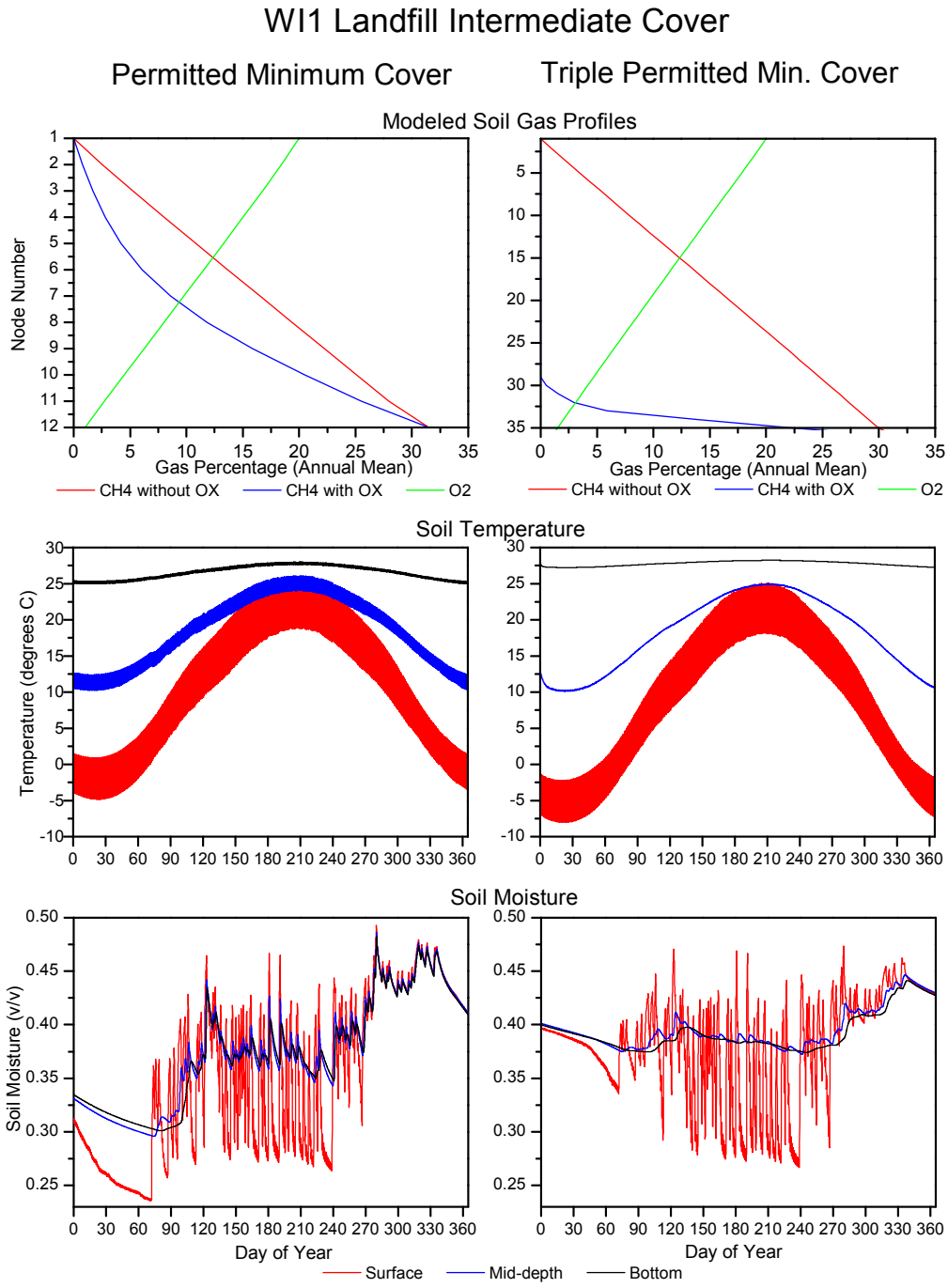
References:

Chanton, J., Bogner, J., 2008. Final Report: Chamber Measurements at USA Waste Management and Veolia Landfill Fugitive Emission Study, Wisconsin, USA.


WI1 Landfill Daily Cover
(1 x and 2 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Double Permitted Minimum Cover Thickness
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Mean Modeled Surface Emissions with Oxidation:
Permitted Minimum Cover Thickness
Double Permitted Minimum Cover Thickness
Field Results (Mean and Standard Error):
Area B Daily Cover (Oct. 4, 2008)
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


WI1 Landfill Daily Cover
Permitted Minimum Cover
Double Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom


WI1 Landfill Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Triple Permitted Minimum Cover Thickness:
Surface emission with oxidation (g/m2/day)
Surface emissions without oxidation(g/m2/day)
Mean Modeled Surface Emissions with Oxidation:
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results (Mean and Standard Error):
Area A Intermediate Cover South Slope (Oct. 3, 2008)
Area A Intermediate Cover South Slope (Oct. 4, 2008)
Area C Intermediate Cover North Slope (Oct. 4, 2008)
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


W11 Landfill Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom

16. Mallard Lake Landfill

Site Location: Hanover Park, IL

Latitude: 42°N

Longitude: 88°W

Total Size: 17 hectares (42 acres)

Site Description: This landfill, located in the Chicago suburb of Hanover Park, IL, operated from 1975 to 1999. The location in the landfill used in this study had final cover placed in the late 1980s. The landfill has an active gas recovery system. Chamber measurements and soil gas profiles were taken proximal and distal to the gas wells. The field study was during 1995.

Covers	**Default**	**Proximal**	**Distal**
Hectares (Acres)			
Cover Type	Final	Final	Final
Coverage % *	34%	33%	33%
Organic Matter %	Default	Default	Default
Gas Recovery %	100%	100%	100%
Vegetation %	100%	100%	100%

* Coverage % is for use by CALMIM

Layers		**Default**	**Proximal**	**Distal**
1	**Material**	Loam	Loam	Loam
	Thickness	25 cm	25 cm	25 cm
2	**Material**	Silty-clay	Silty-clay	Silty-clay
	Thickness	100 cm	100 cm	100 cm

Custom Boundaries	**Proximal**	**Distal**
Methane Lower	0.001%	10%

Additional Notes:

Proximal gas profile measured the lower methane boundary at 2ppm. CALMIM can only go down to 10ppm, so will use 10ppm (0.001%).
Three covers were run in the same CALMIM run so weather data is the same.
Note CALMIM cannot model a negative methane flux, while field measurements can record a negative flux.

Field Results:

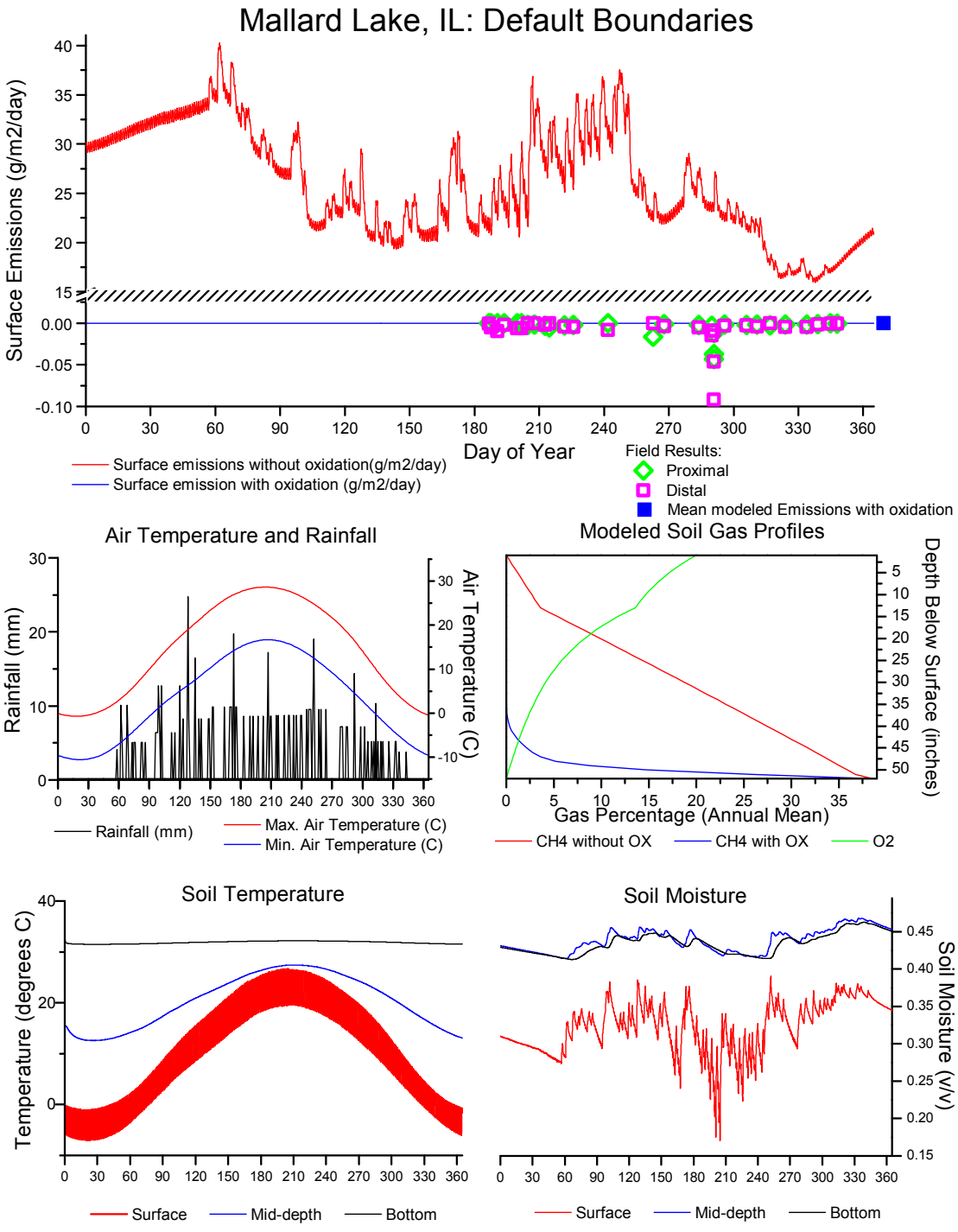
Two studies were performed, one in 1994 and one in 1995. Only results from the 1995 study are shown. During the field study in 1995 the gas recovery system was shut down for two days. Results from this period show a greater uptake of atmospheric methane than while the gas recovery system was in operation. The maximum uptake for both proximal and distal are from the period when the gas recovery system was not operating.
Field results given below and in the graphs include the measurements during the gas recovery system shutdown.

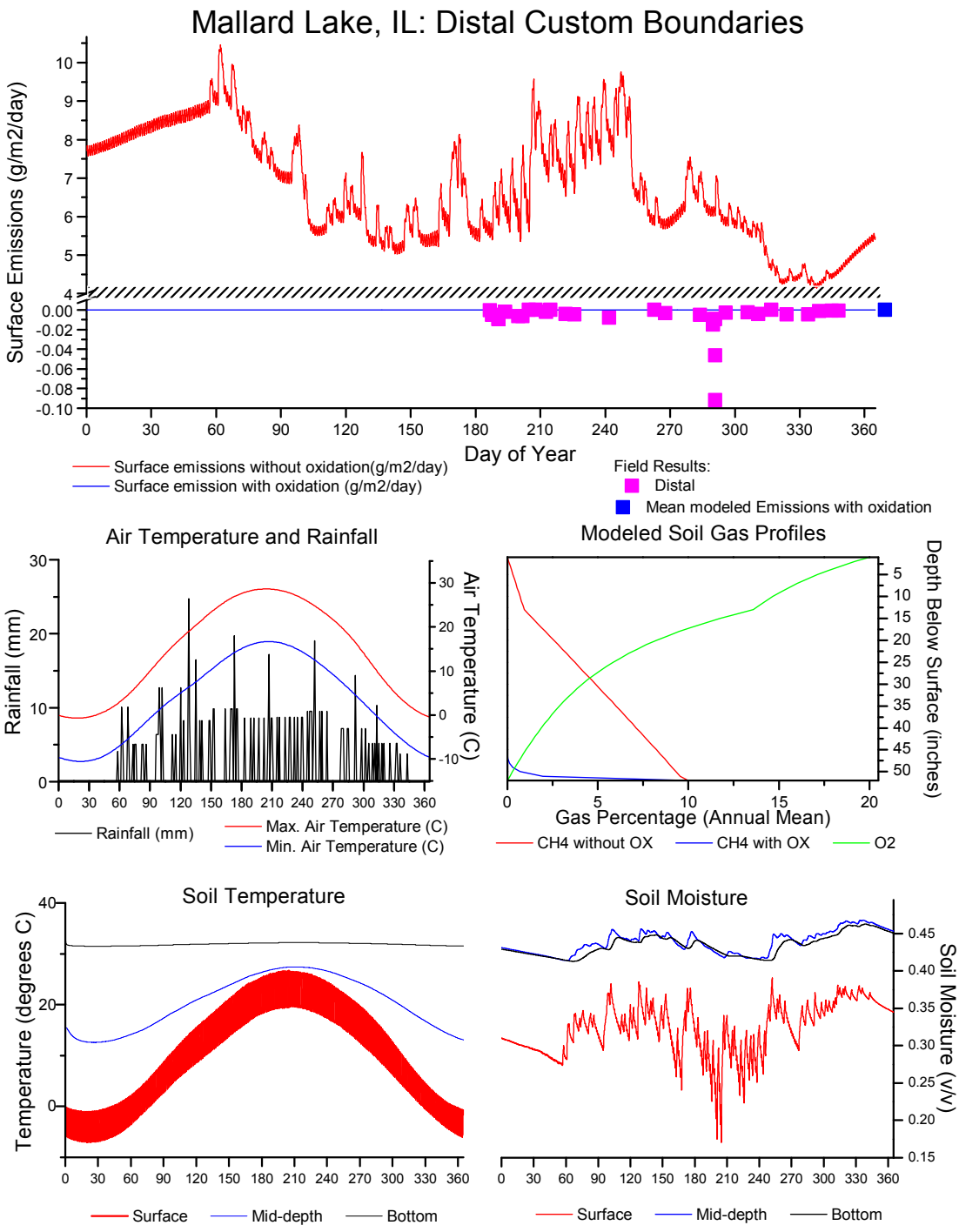
Field Results (in g/m^2/day)						
	Mean	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Published Results (Bogner et al., 1999b)						

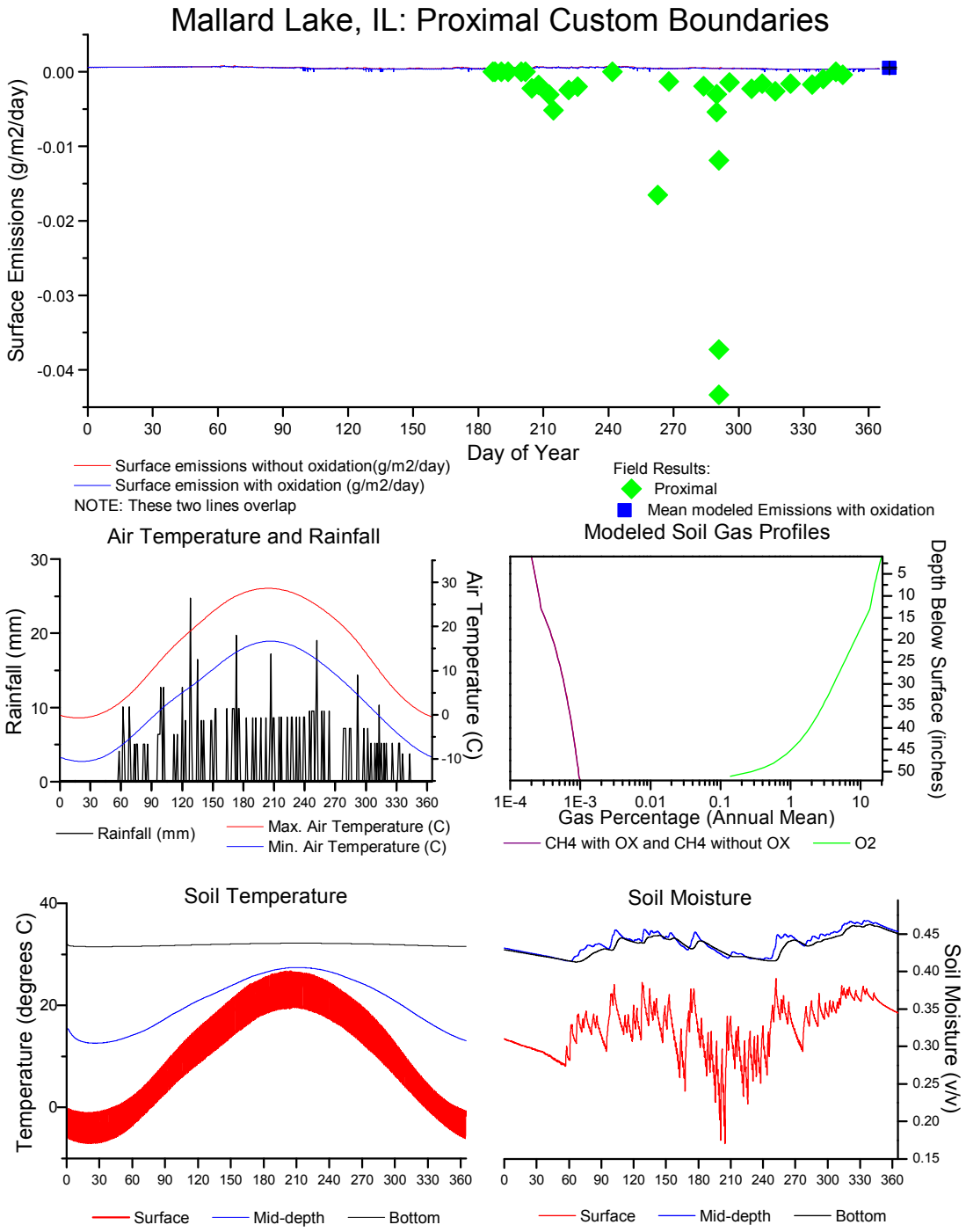
Mallard Lake Proximal (close to gas recovery wells)	-6.81×10^{-3}	1.15×10^{-2}	-2.26×10^{-3}	-4.07×10^{-4}	-4.33×10^{-2}	22
Mallard Lake Distal (far from gas recovery wells)	-1.05×10^{-2}	2.00×10^{-2}	-4.70×10^{-3}	-6.67×10^{-4}	-9.19×10^{-2}	25
Modeled (CALMIM) Results						
CALMIM 5.4 Default Boundaries	0	0	0	0	0	8760
CALMIM 5.4 Proximal (Custom boundaries)	0	0	0	0	0	8760
CALMIM 5.4 Distal (Custom boundaries)	0.0005	0.0001	0.0005	0.0	0.0008	8760

References:

Bogner, J., Spokas, K., Burton, E.A., 1999. Temporal Variations in Greenhouse Gas Emissions at a Midlatitude Landfill. Journal of Environmental Quality 28, 278-288.
Bogner, J.E., Spokas, K., Burton, E.A., 1997. Kinetics of Methane Oxidation in a Landfill Cover Soil: Temporal Variations, a Whole-Landfill Oxidation Experiment, and Modeling of Net CH_4 Emissions. Environmental Science and Technology 31, 2504-2514.


Mallard Lake, IL: Default Boundaries
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results:
Proximal
Distal
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Mallard Lake, IL: Distal Custom Boundaries
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results:
Distal
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Mallard Lake, IL: Proximal Custom Boundaries
Surface Emissions (g/m2/day)
0.00
-0.01
-0.02
-0.03
-0.04
0 30 60 90 120 150 180 210 240 270 300 330 360
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
NOTE: These two lines overlap
Field Results:
Proximal
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
1E-4 1E-3 0.01 0.1 1 10
Gas Percentage (Annual Mean)
CH4 with OX and CH4 without OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

17. Muribeca Experimental Cells

Site Location: Recife, Brazil

Latitude: -8.175 **Longitude: -35.00**

Total Size: 65 hectares (161 acres)

Site Description: Experimental cells were built at the Muribeca Landfill to investigate gas generation and emissions. Three experimental cells were constructed above newly placed waste: a Methanotrophic Cell including a soil/compost mixed layer, a Capillary Cell with a gravel gas distribution layer, and a Conventional Cell with a cover made of the local soil. Two new layers of waste, 6.0 m and 3.0 m were placed into the cells before placement of the experimental covers. There was no intermediate cover layer, and there was passive vertical gas venting. The cells were filled from April, 2007 to January, 2008, and emissions field testing was done from September to December, 2008.

Covers	**Methanotrophic Cell**	**Capillary Cell**	**Conventional Cell**
Hectares (Acres)	**0.06 (0.15)**	**0.05 (0.12)**	**0.05 (0.13)**
Cover Type	FInal	Final	Final
Coverage % *	33%	33%	34%
Organic Matter %	Default (mid)	Default (mid)	Default (mid)
Gas Recovery %	25%	25%	25%
Vegetation %	0%	0%	0%

* Coverage % is for use by CALMIM

Layers		**Methanotrophic Cell**	**Capillary Cell**	**Conventional Cell**
1	**Material**	Mixture of 75% sandy-clay and 25% composted materials Modeled as Sandy-clay-loam	Sandy-clay	Sandy-clay
	Thickness	25 cm	52.5 cm	70 cm
2	**Material**	Sandy-clay	Gravel	
	Thickness	30 cm	20 cm	

Custom Boundaries

(no gas profile data available)

Additional Notes:

Because there is a passive gas venting system, the CALMIM model was run using 25% gas recovery.

Field Results:

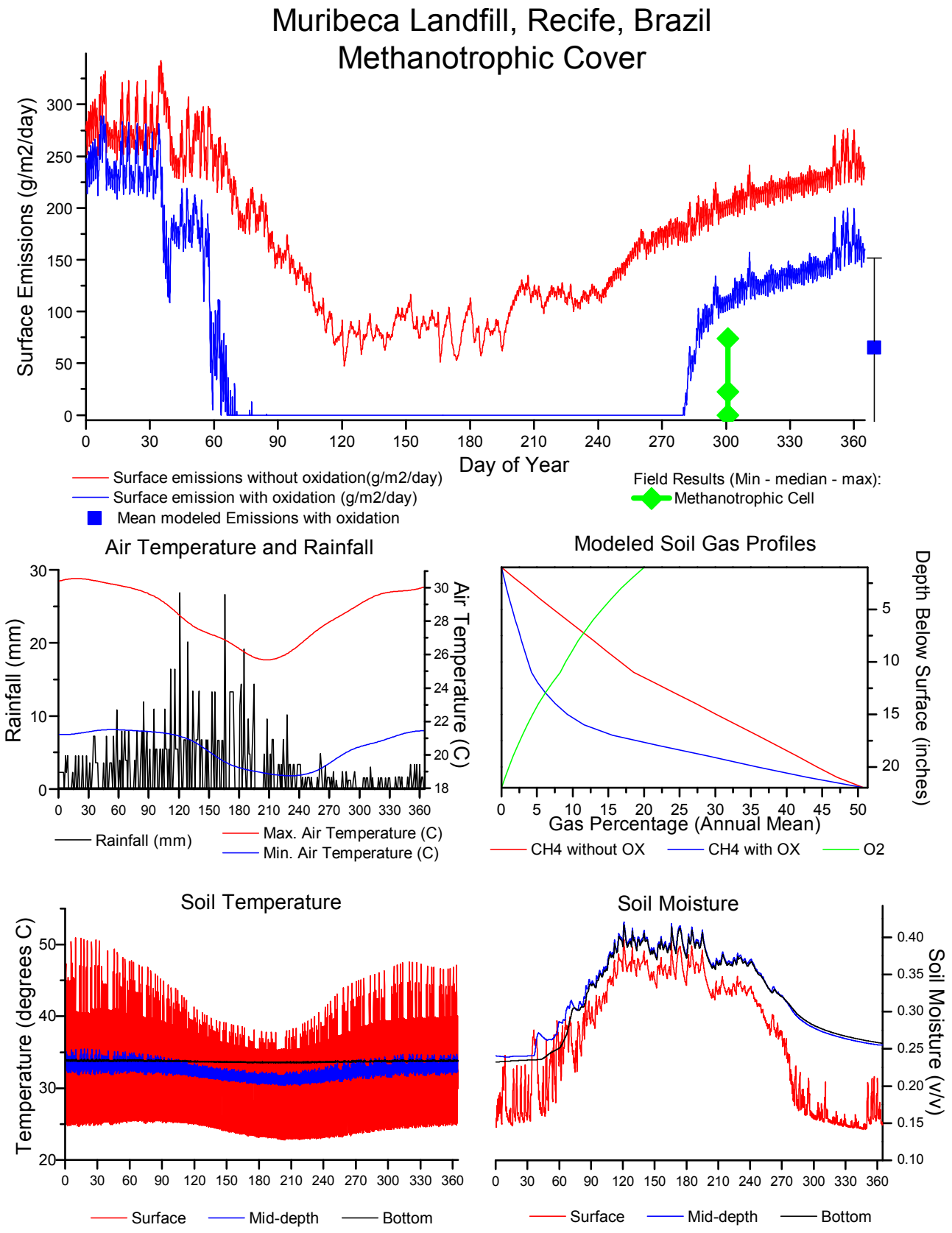
Methane emissions were measured using static chambers in the dry season, September to December, 2008

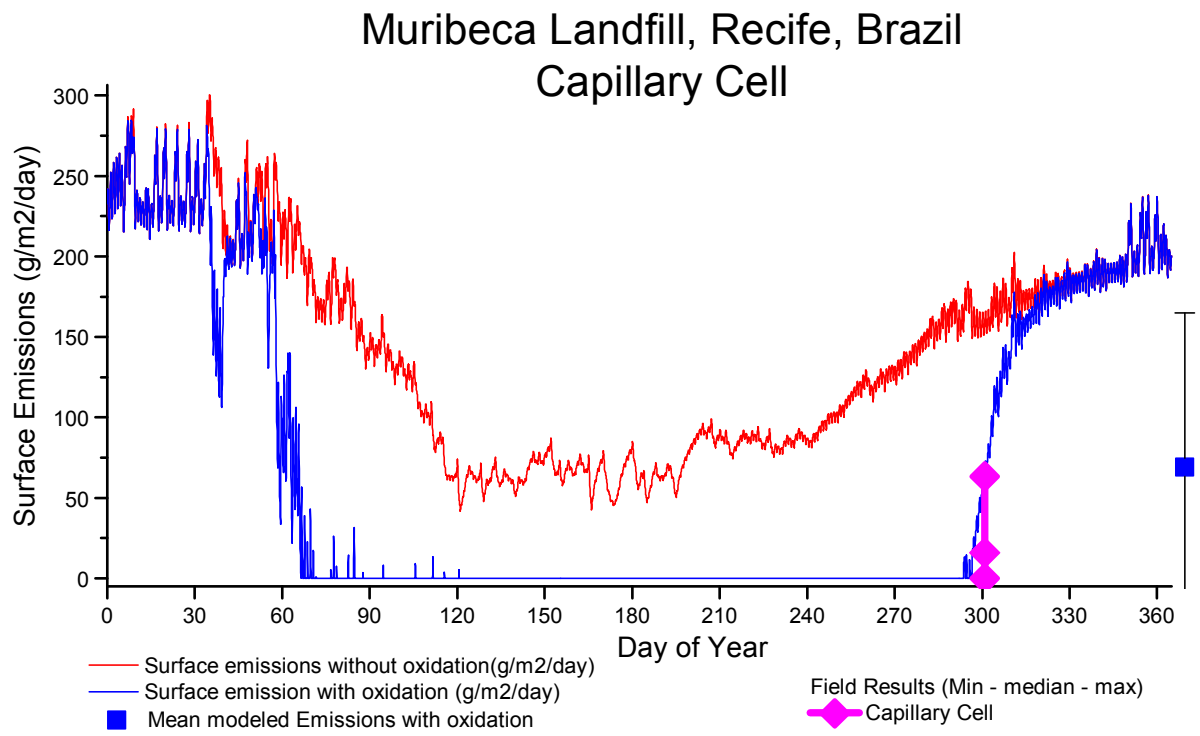
Source	Mean	Std Dev	Median	Minimum	Maximum	N=
Published Results (CH_4 g/m^2/day) (Maciel and Juca, 2011)						
Methanotrophic Cell	n/a	n/a	22.2	0.0	74.1	10
Capillary Cell	n/a	n/a	15.9	0.0	63.4	10
Conventional Cell	n/a	n/a	161.5	2.1	984.7	10
Modeled (CALMIM) Results: Surface emissions with oxidation (CH_4 g/m^2/day)						
Methanotrophic Cell	64.94	86.49	0.00	0.00	288.94	8760
Capillary Cell	68.95	95.87	0.00	0.00	284.44	8760
Conventional Cell	62.38	83.55	0.00	0.00	249.65	8760

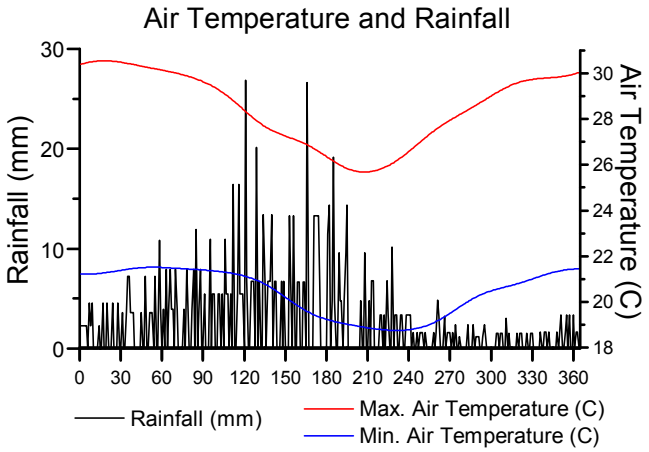
Discussion:

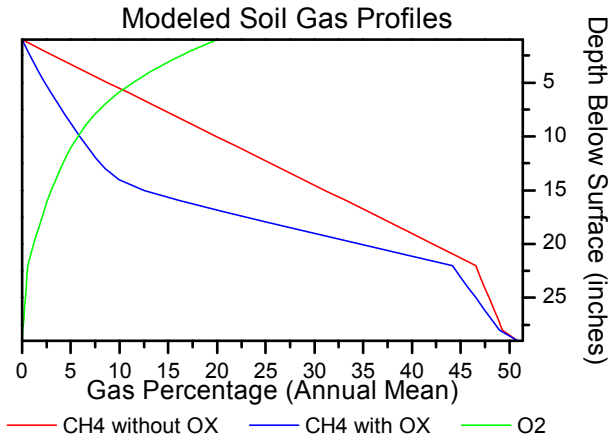
References:

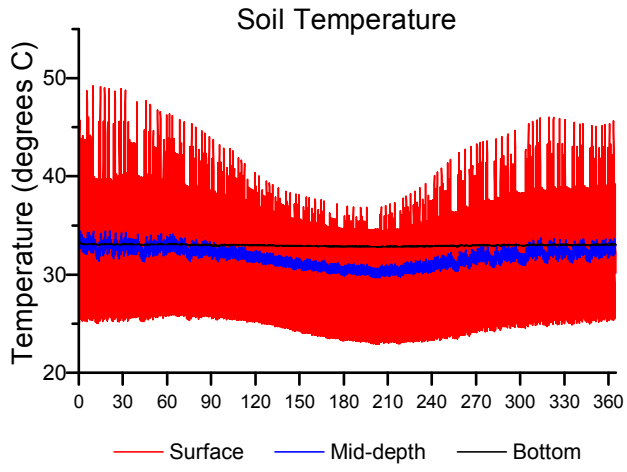
Maciel, F.J., Juca, J.F.T., 2011. Evaluation of landfill gas production and emissions in a MSW large-scale Experimental Cell in Brazil. Waste Management 31, 966-977.

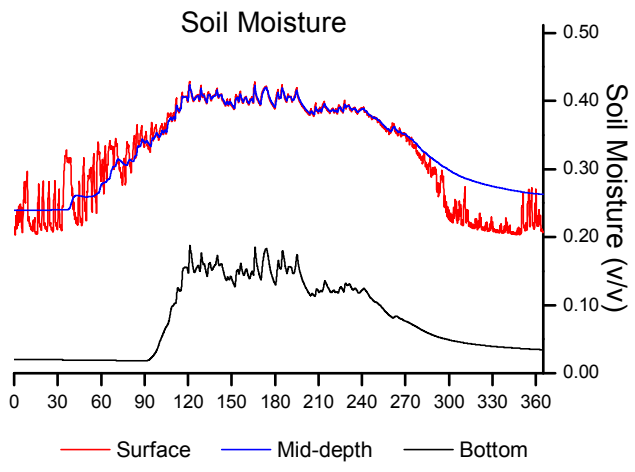

Muribeca Landfill, Recife, Brazil
Methanotrophic Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results (Min - median - max):
Methanotrophic Cell
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Gas Percentage (Annual Mean)
Depth Below Surface (inches)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

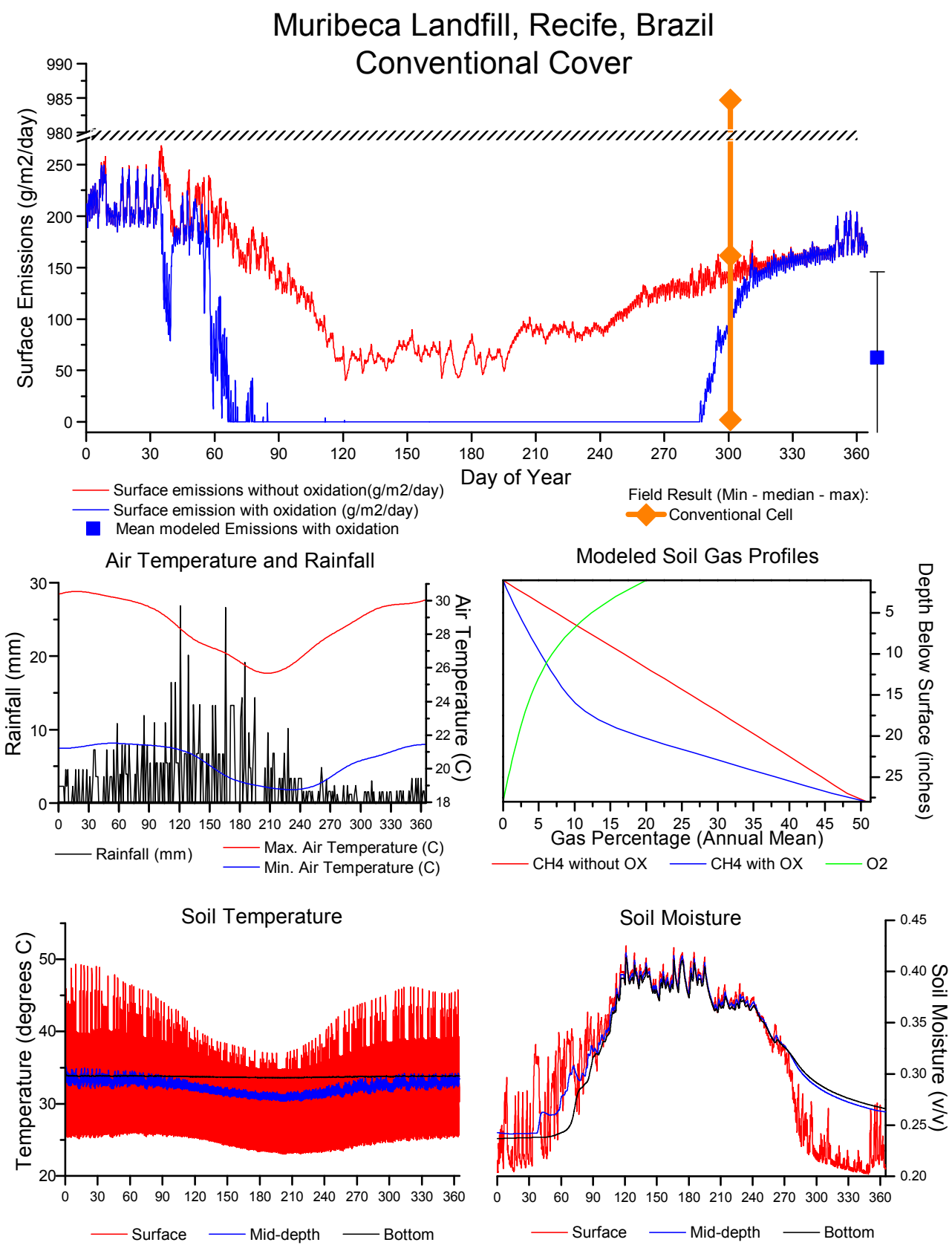

Muribeca Landfill, Recife, Brazil
Capillary Cell
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results (Min - median - max)
Capillary Cell


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Muribeca Landfill, Recife, Brazil
Conventional Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Result (Min - median - max):
Conventional Cell
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

18. Scholl Canyon

Location: Glendale, CA

Latitude: +34.158

Longitude: 118.196

Total Size: 178 hectares **(**440 acre)

Site Description: Scholl Canyon Landfill is located in the northern part of the Los Angeles area. The site has an inland climate. Cover soils are made up of local materials. Field measurements were done using static chambers as well as soil gas profiles. Soil gas profiles were limited due to the high compaction of the intermediate and final covers. The field study focused in the following areas: collecting flux measurements for use in validating the flux results of the CALMIM model; collecting soil gas profiles for use in validating the CALMIM models results; collecting gas samples for stable carbon isotope analysis to determine oxidation fractions; and collecting field samples for use in laboratory incubations for use in calibrating the oxidation rate in the CALMIM model. Measurements were taken in 2007 and 2008 during the wet season (March) and the dry season (August).

Covers	**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**	**Final**
Acres	4 (10)	123 (304)	123 (304)	51 (126)
Cover Type	Daily	Intermediate	**Intermediate**	Final
Coverage % *	25%	25%	25%	25%
Organic Matter %	2.5% (default)	2.5% (default)	2.5% (default)	2.5% (default)
Gas Recovery %	100%	100%	100%	100%
Vegetation %	0%	0%	0%	0%

* For use in CALMIM model

Layers		**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**	**Final**
1	**Material**	ADC Composted Organic Materials	Sandy Loam	Sandy Loam	Loam
	Thickness	6 inches	12 in	36 in	12 inches
2	**Material**				Clay
	Thickness				12 inches
3	**Material**				Silty clay loam
	Thickness				24 inches

Custom Boundaries

No custom boundaries were used in this CALMIM model

Additional Notes:

The cover descriptions are the standard California covers used for CALMIM modeling.
In order to ensure all covers used the same generated weather the Daily, Intermediate 12, Intermediate 36, and Final covers were entered into one CALMIM file, each with 25% coverage in CALMIM. To get correct total modeled emissions the totals for each cover must be adjusted from the 25% coverage to the appropriate actual percentages (2% daily, 69% for the selected intermediate cover, and 29% for the Final cover).

Field Results						
Source	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Published Results: Spokas 2011 Paper (Spokas et al., 2011a) (CH_4 g/m^2/day)						
Wet Season (+ CH_4) Daily	4.52E-02	4.91E-02	3.28E-02	1.52E-03	1.73E-01	na
Wet Season (+ CH_4) Final	2.46E-02	2.27E-02	1.74E-02	2.64E-03	8.84E-02	na
Dry Season (+ CH_4) Daily	1.87E-02	1.70E-02	1.37E-02	1.11E-03	7.04E-02	na
Dry Season (+ CH_4) Intermediate	1.02E-02	1.25E-02	5.45E-03	3.32E-04	7.04E-02	na
Dry Season (+ CH_4) Final	7.65E-03	7.09E-03	5.42E-03	4.67E-05	1.86E-02	na
Wet Season (- CH_4) Daily *	-3.76E-02	2.48E-02	-3.44E-02	-7.40E-02	-9.31E-03	na
Wet Season (- CH_4) Intermediate *	-1.05E-02	1.18E-02	-5.75E-03	-2.79E-02	-2.49E-03	na
Wet Season (- CH_4) Final *	-2.34E-02	3.24E-02	-5.91E-03	-8.96E-02	-5.18E-04	na
Dry Season (- CH_4) Daily *	-7.12E-03	3.10E-03	-7.12E-03	-9.31E-03	-4.93E-03	na
Dry Season (- CH_4) Intermediate *	-1.08E-02	9.36E-03	-6.60E-03	-2.57E-02	-1.17E-03	na
Dry Season (- CH_4) Final *	-1.07E-02	7.36E-03	-8.82E-03	-2.30E-02	-1.15E-03	na
Modeled (CALMIM 5.4) Emissions with oxidation (CH_4 g/m^2/day)						
Daily Cover	6.06	2.27	6.82	0.0	9.13	8760
Intermediate (permitted min. depth)	355.52	160.38	440.68	11.89	585.58	8760
Intermediate (3 x permitted min. depth)	15.76	29.27	0.0	0.0	114.48	8760
Final Cover	0.0	0.0	0.0	0.0	0.0	8760

Field Results: Inverse Distance Weighting (Bogner et al., 2011a) (CH_4 g/m^2/day)

	March 2007	August 2007	March 2008	August 2008
Daily *	0.006	0.015	0.019	0.022
Intermediate *	-0.006	0.002	0.013	-0.003
Final *	0.003	0.004	0.008	-0.001

* Not Graphed

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**CH4 kg/year**
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)		
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)		

CALMIM Results:	**Gas Recovery %**	**Permitted Minimum Cover CH_4 kg/year**	**3 x Permitted Minimum Cover CH_4 kg/year**	**Hectares (Acres)**
Daily Cover	100%	78,828	n/a	4 (10)
Intermediate Cover	100%	159,418,465	7,068,478	123 (304)
Final Cover	100%	12	n/a	51 (126)
Total CH_4 emissions with oxidation (kg/year) (Sum of emissions for Permitted Daily Cover, selected Intermediate Cover, and Final Cover)		**159,497,305**	**7,147,306**	**178 (440)**

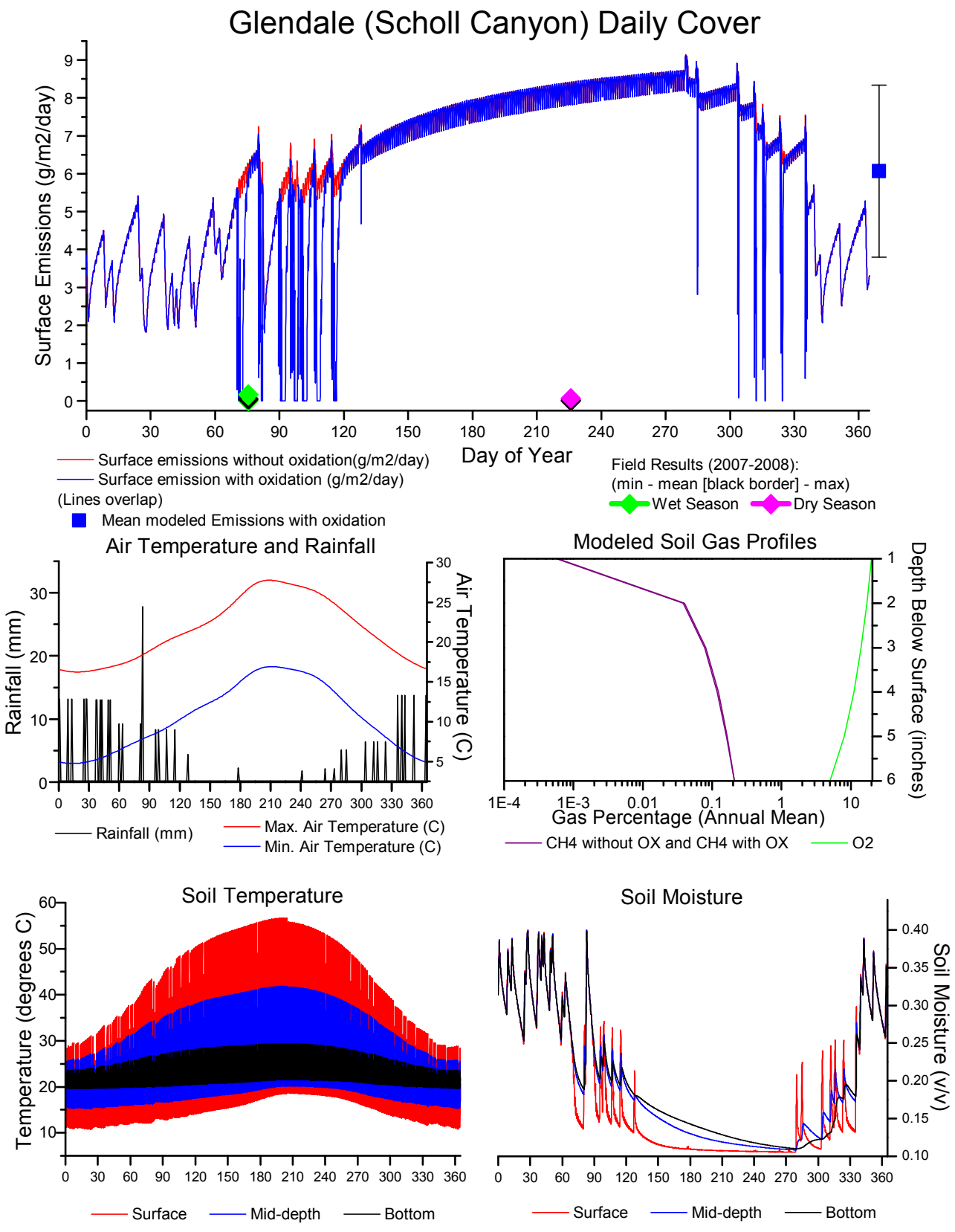
* www.ghgdata.epa.gov
** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21

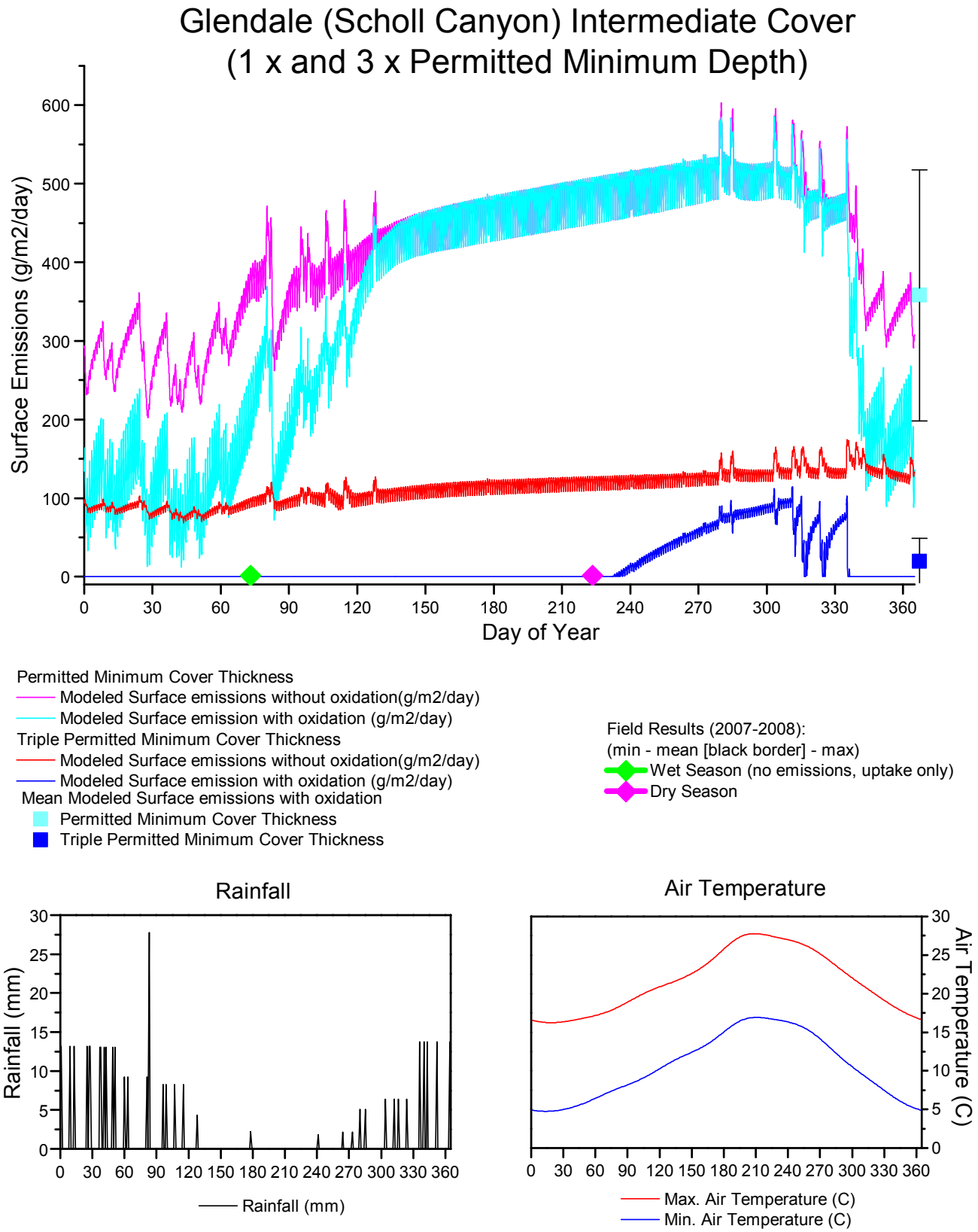
References:

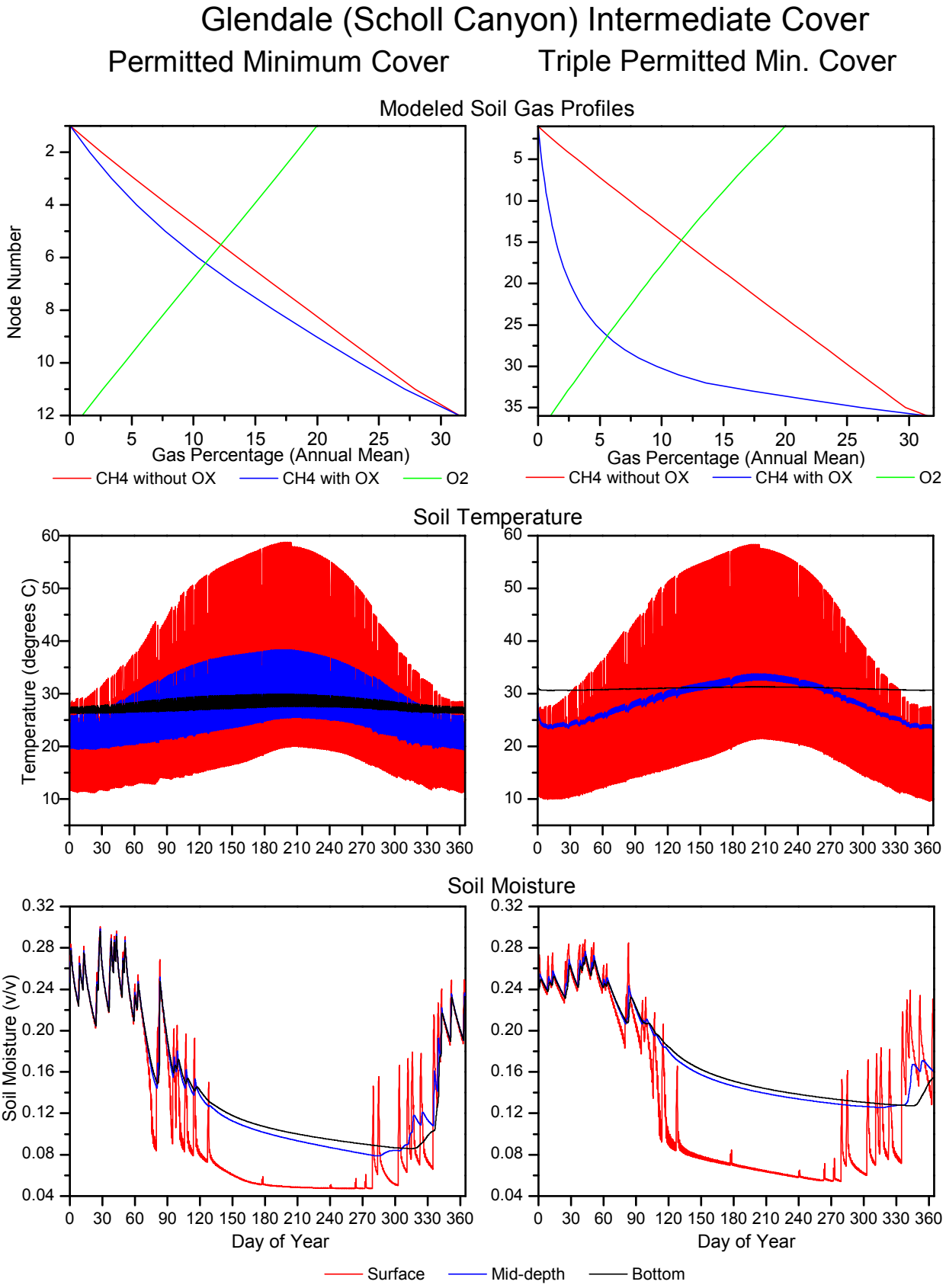
Bogner, J., Spokas, K., Chanton, J., 2011. Seasonal Greenhouse Gas Emissions (Methane, Carbon Dioxide, Nitrous Oxide) from Engineered Landfills: Daily, Intermediate, and Final California Cover Soils. Journal of Environmental Quality, 1-11.

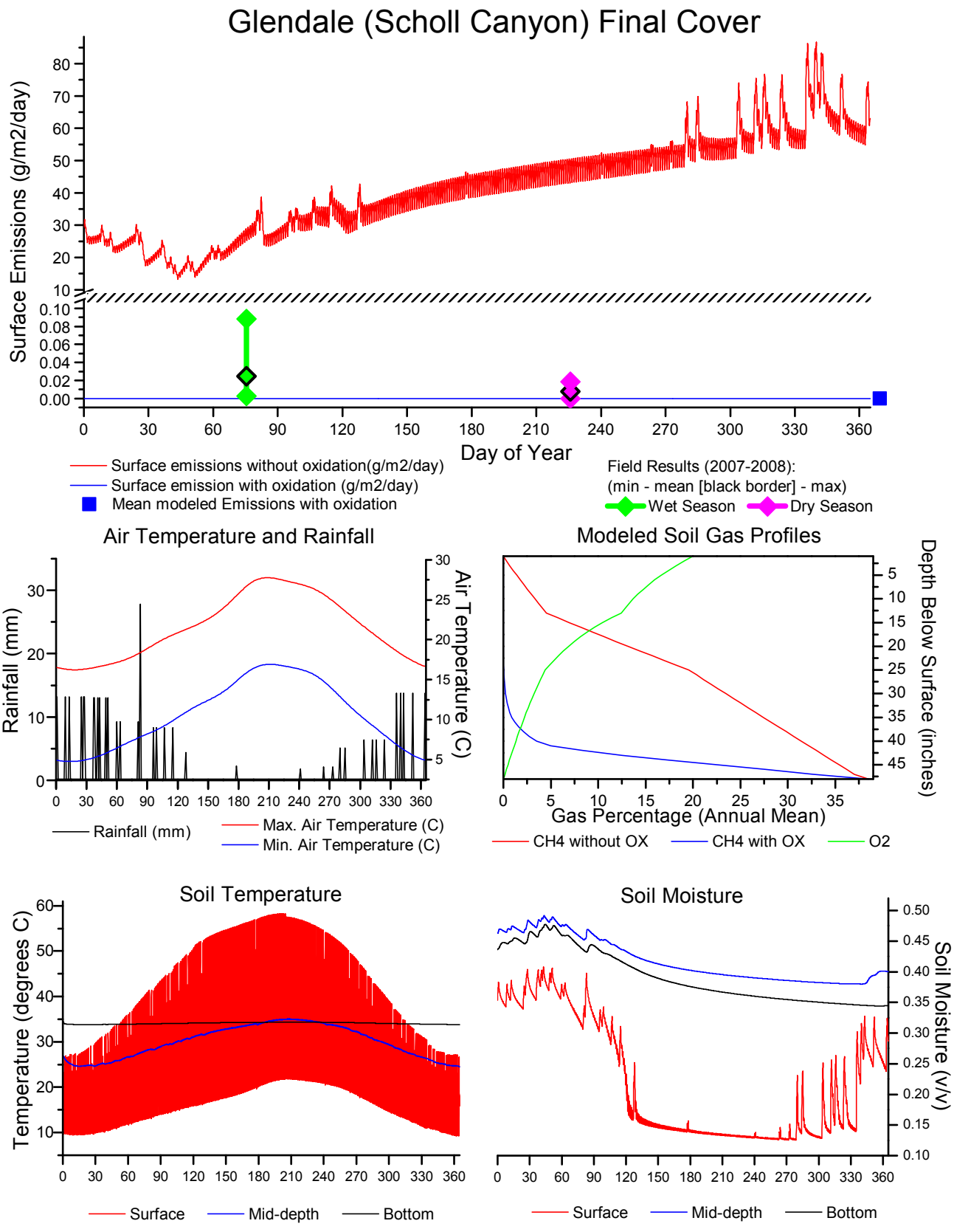
Spokas, K., Bogner, J., Chanton, J., 2011. A process-based inventory model for landfill CH4 emissions inclusive of seasonal soil microclimate and CH4 oxidation. Journal of Geophysical Research 116.

Data in: Summary Field Emissions Data CA.xls; SchollCanyon_All.xls (climate graphs); Spokas Probes 6_05_07.xlsx (soil gas profile for Scholl and Marina)]


Glendale (Scholl Canyon) Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Mean modeled Emissions with oxidation
Field Results (2007-2008):
(min - mean [black border] - max)
Wet Season
Dry Season
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Glendale (Scholl Canyon) Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results (2007-2008):
(min - mean [black border] - max)
Wet Season (no emissions, uptake only)
Dry Season
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


Glendale (Scholl Canyon) Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom


Glendale (Scholl Canyon) Final Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation
Field Results (2007-2008):
(min - mean [black border] - max)
Wet Season
Dry Season
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

19. Calabasas Landfill

Site Location: Agoura, CA

Latitude: 34.15125

Longitude: -118.72005

Total Size: 168 hectares (416 acres)

Site Description:

This site has a daily cover area which was assumed to be 4 hectares (10 acres), and the remaining area is intermediate cover, 164 hectares (406 acres) using 2010 total cover areas (Walker, 2012). There is no final cover area.

Covers	**Daily**	**Intermediate 12**	**Intermediate 36**	**Intermediate 60**
Hectares (Acres)	4 (10)	164 (406)	164 (406)	164 (406)
Cover Type	Daily	Intermediate	Intermediate	Intermediate
Coverage % *	25%	25%	25%	25%
Organic Matter %	Mid (2.5%)	Mid (2.5%)	Mid (2.5%)	Mid (2.5%)
Gas Recovery %	100%	100%	100%	100%
Vegetation %	0%	0%	0%	0%

* Coverage % is for use by CALMIM

Layers		**Daily**	**Intermediate 12**	**Intermediate 36**	**Intermediate 60**
1	**Material**	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
	Thickness	12 inches	12 inches	36 inches	60 inches

Custom Boundaries

(no gas profile data available)

Additional Notes:

To test the effect of cover thickness on emissions the CALMIM model was run with three different thicknesses of intermediate cover: 12 inches (the permitted depth), 36 inches, and 60 inches. In order to ensure all covers used the same generated weather the four covers were entered into one CALMIM file, each with 25% coverage. To get correct total emissions the totals for each cover must be adjusted from the 25% coverage to the appropriate actual percentages (2.4% daily and 97.6% of a selected intermediate cover.)

Field Results:

Source	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**	**95% UCL**
Modeled (CALMIM) Results with oxidation							
Daily	2.50	1.05	2.69	0.0	4.25	8760	n/a
Intermediate (permitted depth)	361.12	156.43	442.29	2.43	613.98	8760	n/a
Intermediate (3 x permitted depth)	16.30	32.10	0.0	0.0	135.92	8760	n/a
Intermediate (5 x permitted depth)	0.0	0.0	0.0	0.0	0.0	8760	n/a
Published Field Results (11/2012 to 1/2013) (Shan et al., 2012)							
Daily	2.9	n/a	1.7	0.002	12.0	8	13.6
Intermediate	0.04	n/a	0.02	-0.002	0.2	32	0.05

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**CH4 kg/year**	**Hectares (Acres) ***
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)			
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)			

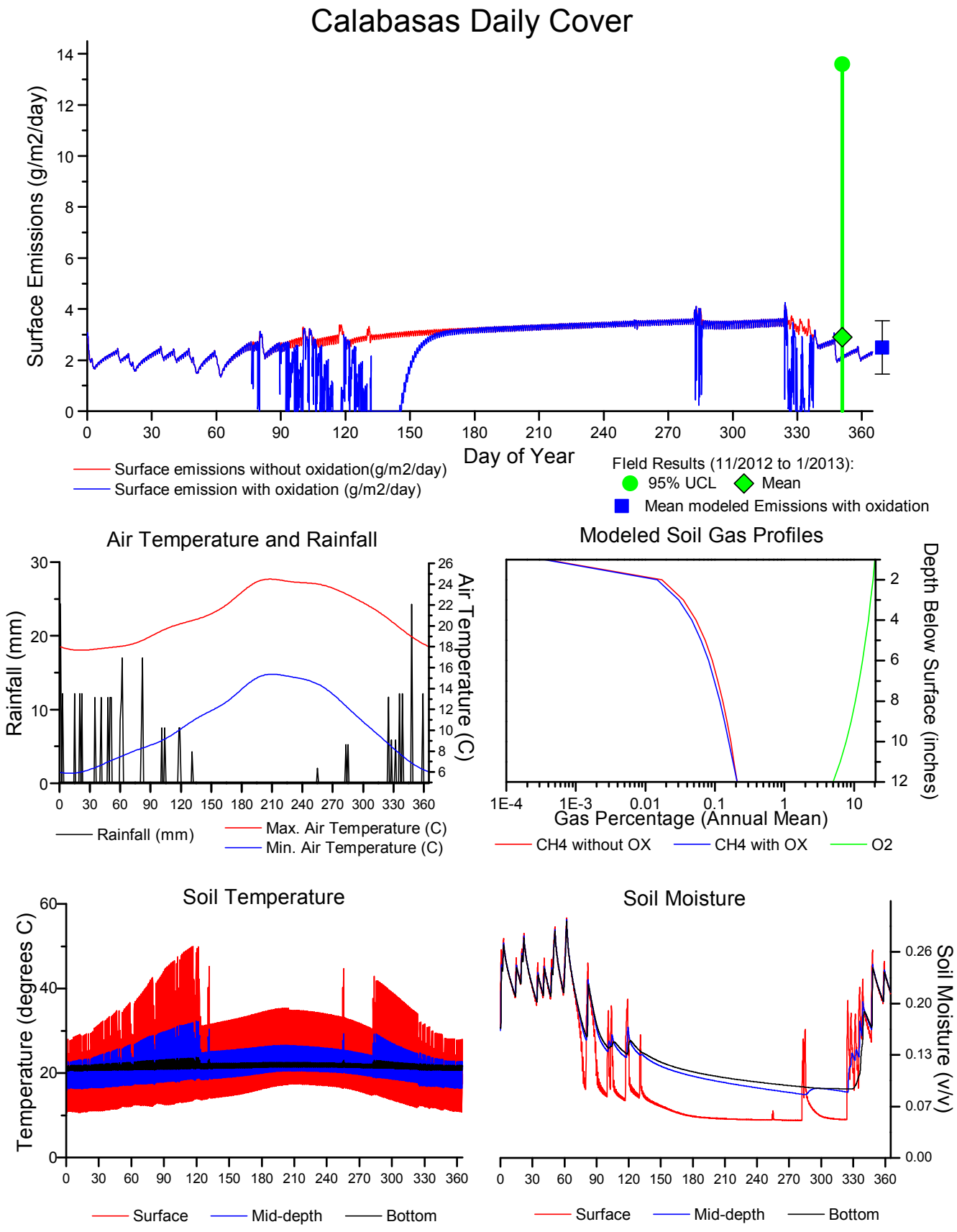
CALMIM Results:	**Gas**	**Permitted**	**3 x Permitted**	**5 x Permitted**	**Hectares**

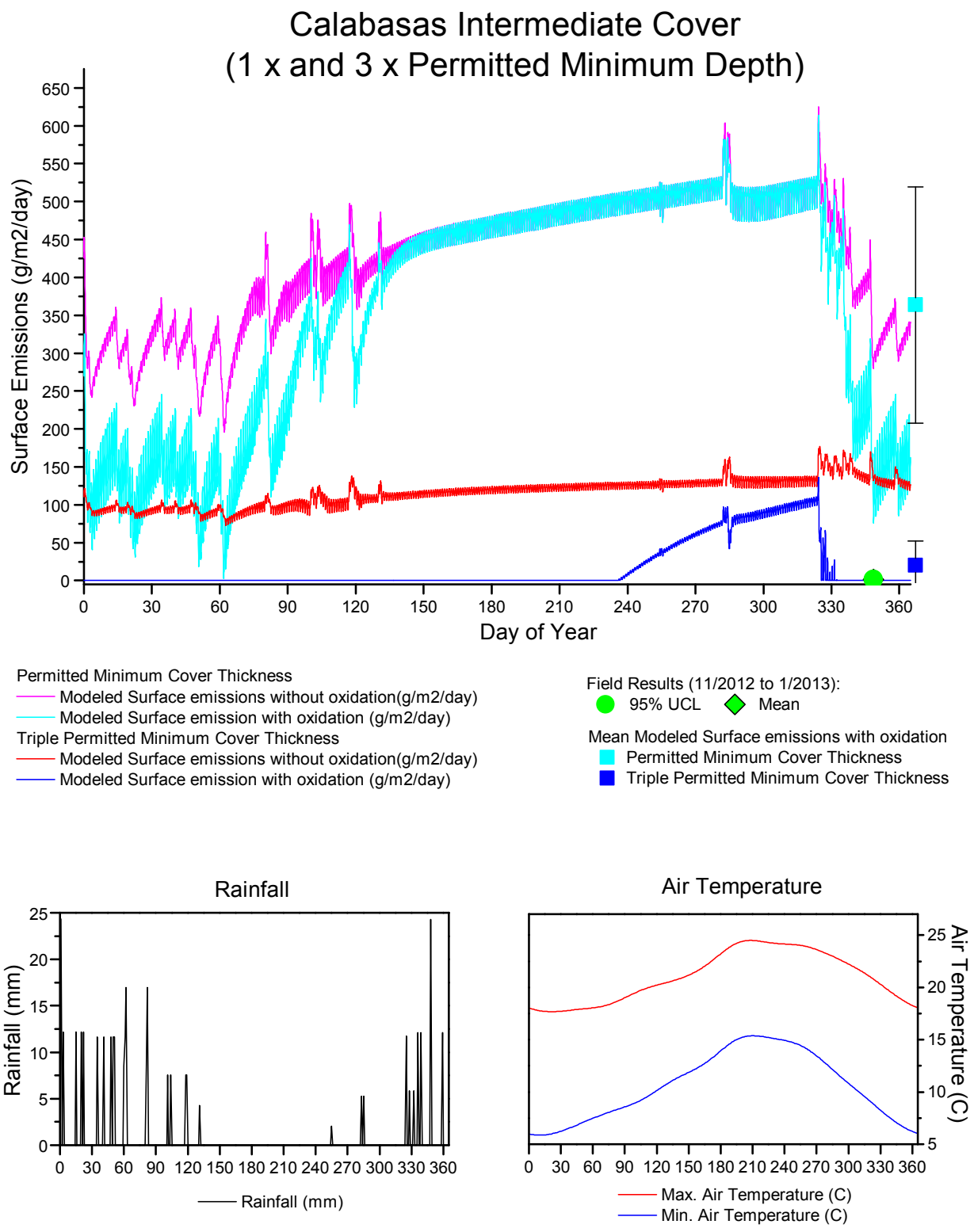
	Recovery %	Cover CH4 kg/year	Cover CH4 kg/year	Cover CH4 kg/year	(Acres)
Daily	100%	36,817	n/a	n/a	4 (10)
Intermediate	100%	216,554,935	9,773,789	0.0	164 (406)
Total CH4 emissions with oxidation (kg/year) (Sum of Permitted Daily Cover Emissions and selected Intermediate Cover)		**216,591,752**	**9,810,606**	**0.0**	**168 (416)**
* www.ghgdata.epa.gov. "Surface area containing waste" is given in m^2, converted to hectares and acres here. ** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21					

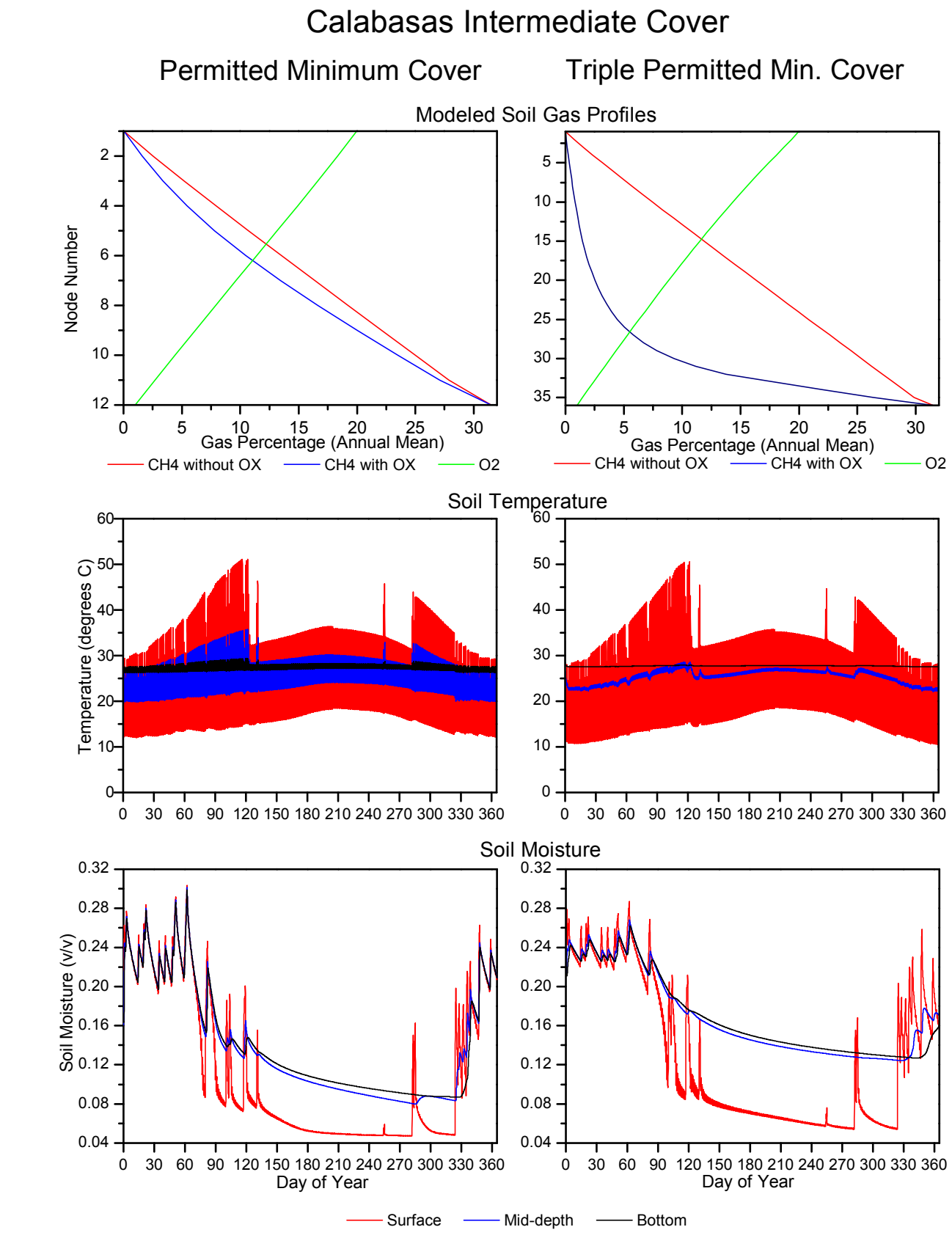
Discussion:

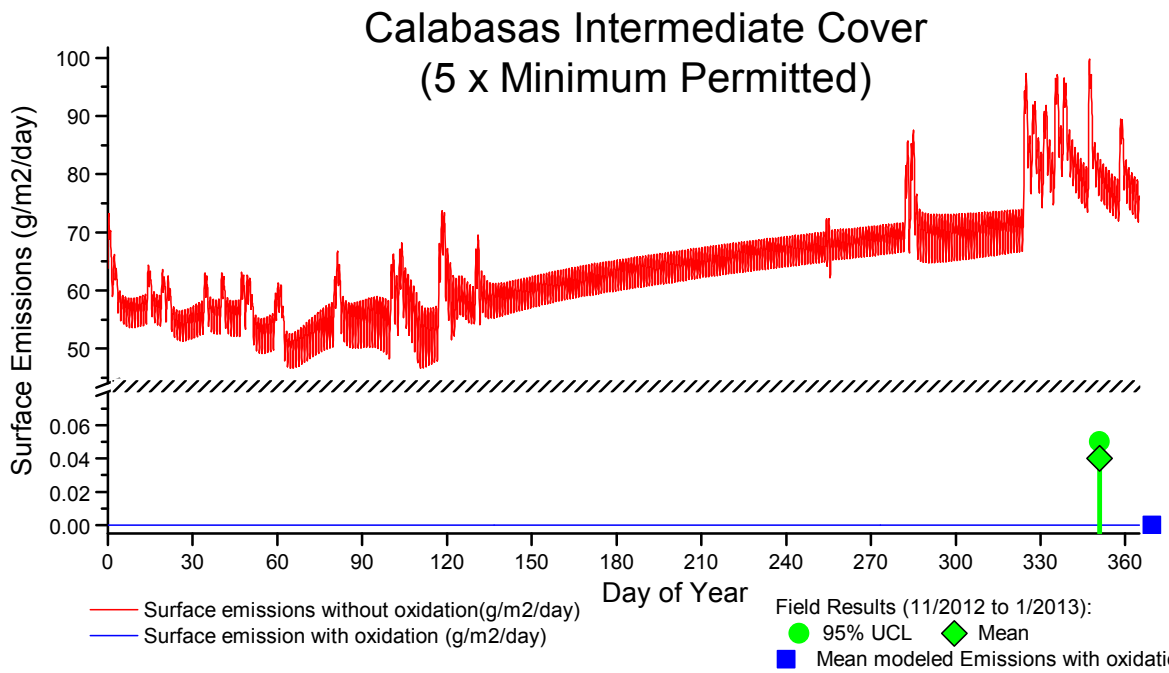
References:

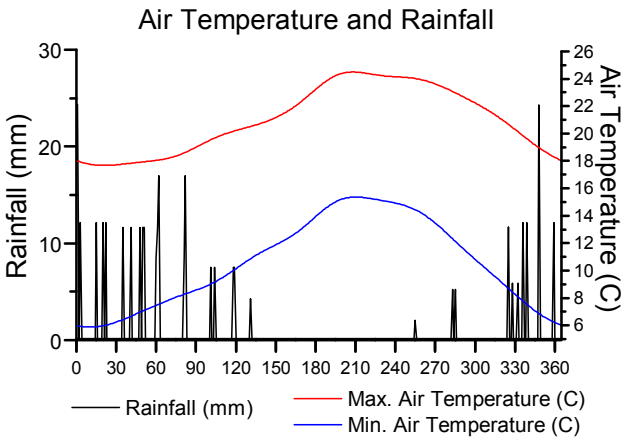
Shan, J., Kong, D., Do, N., Guillen, M., Iacoboni, M., Ferrante, R.F., 2012. Estimation of Landfill Gas Emissions and Collection System Efficiency Using Surface Flux Chamber Technology -- A Case Study of Puente Hills Landfill. 35th Annual Landfill Gas Symposium. Solid Waste Association of North America (SWANA) Landfill Gas Management Technical Division, Orlando, Florida, USA.

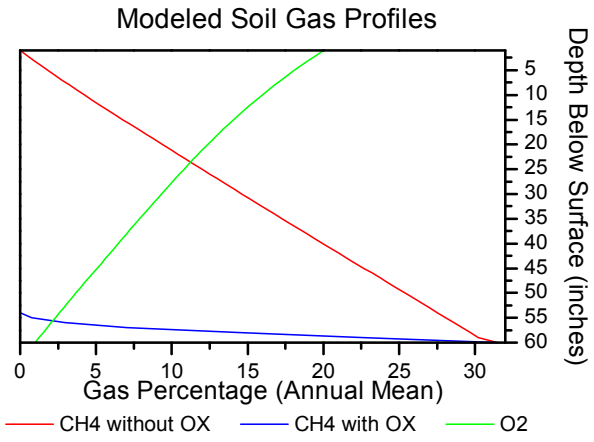

Calabasas Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Fleld Results (11/2012 to 1/2013):
95% UCL
Mean
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

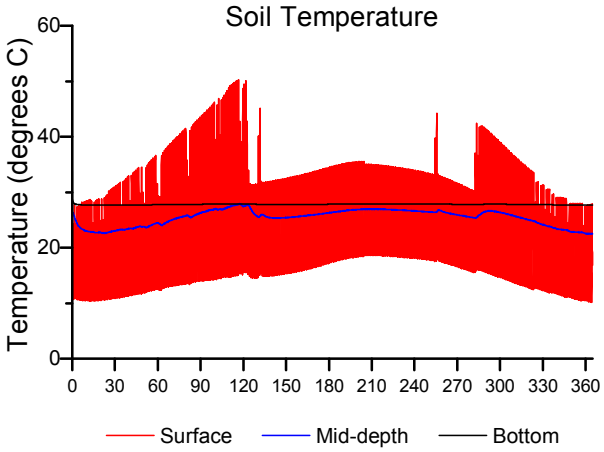

Calabasas Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Field Results (11/2012 to 1/2013):
95% UCL
Mean
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)

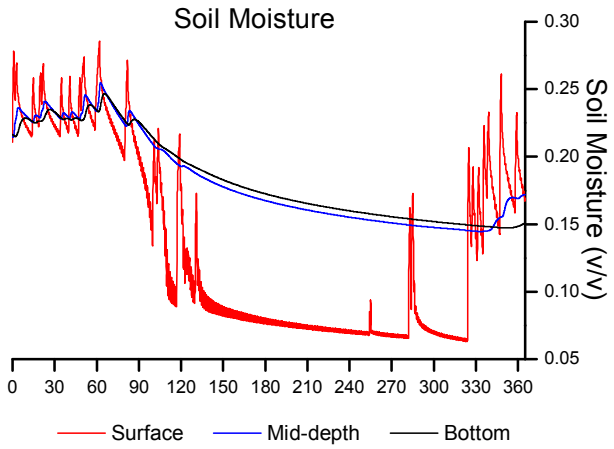

Calabasas Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom


Calabasas Intermediate Cover
(5 x Minimum Permitted)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results (11/2012 to 1/2013):
95% UCL
Mean
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

20. Puente Hills

Site Location: Industry, CA

Latitude: 34.02033

Longitude: -118.00604

Total Size: 243 hectares (600 acres)

Site Description:

This site is the largest landfill in the U.S. The daily cover area was assumed to be 4 hectares (10 acres), intermediate cover which is 42 hectares (104 acres), and a final cover area which is 197 hectares (486 acres). The site closed on Oct 31, 2013.

Covers

	Daily	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)	Intermediate 60 (5 x permitted minimum)	Final
Hectares (Acres)	4 (10)	42 (104)	42 (104)	42 (104)	197 (486)
Cover Type	Daily	Intermediate	Intermediate	Intermediate	Final
Coverage % *	20%	20%	20%	20%	20%
Organic Matter %	Mid (2.5%)	Mid (2.5%)	Mid (2.5%)	Mid (2.5%)	Mid (2.5%)
Gas Recovery %	100%	100%	100%	100%	100%
Vegetation %	0%	0%	0%	0%	0%

* Coverage % is for use by CALMIM

Layers

		Daily	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)	Intermediate 60 (5 x permitted minimum)	Final
1	**Material**	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Loam
	Thickness	12 inches	12 inches	36 inches	60 inches	12 inches
2	**Material**					Clay
	Thickness					12 inches
3	**Material**					Silty clay loam
	Thickness					24 inches

Custom Boundaries

(no gas profile data available)

Additional Notes:

To test the effect of cover thickness on emissions the CALMIM model was run with three different thicknesses of intermediate cover: 12 inches (the permitted depth), 36 inches (3 x permitted minimum depth), and 60 inches (5 x permitted minimum depth). In order to ensure all covers used the same generated weather the five covers were entered into one CALMIM file, each with 20% coverage. To get correct total emissions the totals for each cover must be adjusted from the 20% coverage to the appropriate actual percentages (1.7% daily, 17.3% for the selected intermediate cover, and 81.0% for the final cover).

Field Results:

Source	Mean	Std Dev	Median	Minimum	Maximum	N=	95% UCL
Modeled (CALMIM) Results with oxidation ($g/m^2/day$)							
Daily	2.41	1.04	2.58	0.00	4.11	8760	n/a
Intermediate (permitted min. depth)	351.18	157.67	431.71	0.00	592.59	8760	n/a
Intermediate (3 x permitted min. depth)	9.74	21.62	0.00	0.00	106.92	8760	n/a
Intermediate (5 x permitted min. depth)	0.00	0.00	0.00	0.00	0.00	8760	n/a
Final	0.00	0.00	0.00	0.00	0.00	8760	n/a
Published Field Results (11/2012 to 1/2013) ($g/m^2/day$) (Shan et al., 2012)							
Daily	3.2	n/a	0.3	0.001	20.0	14	12.1
Intermediate and Final	1.1	n/a	0.01	0.002	17.1	51	3.3

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**CH4 kg/year**	**Hectares (Acres) ***
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)			
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)			

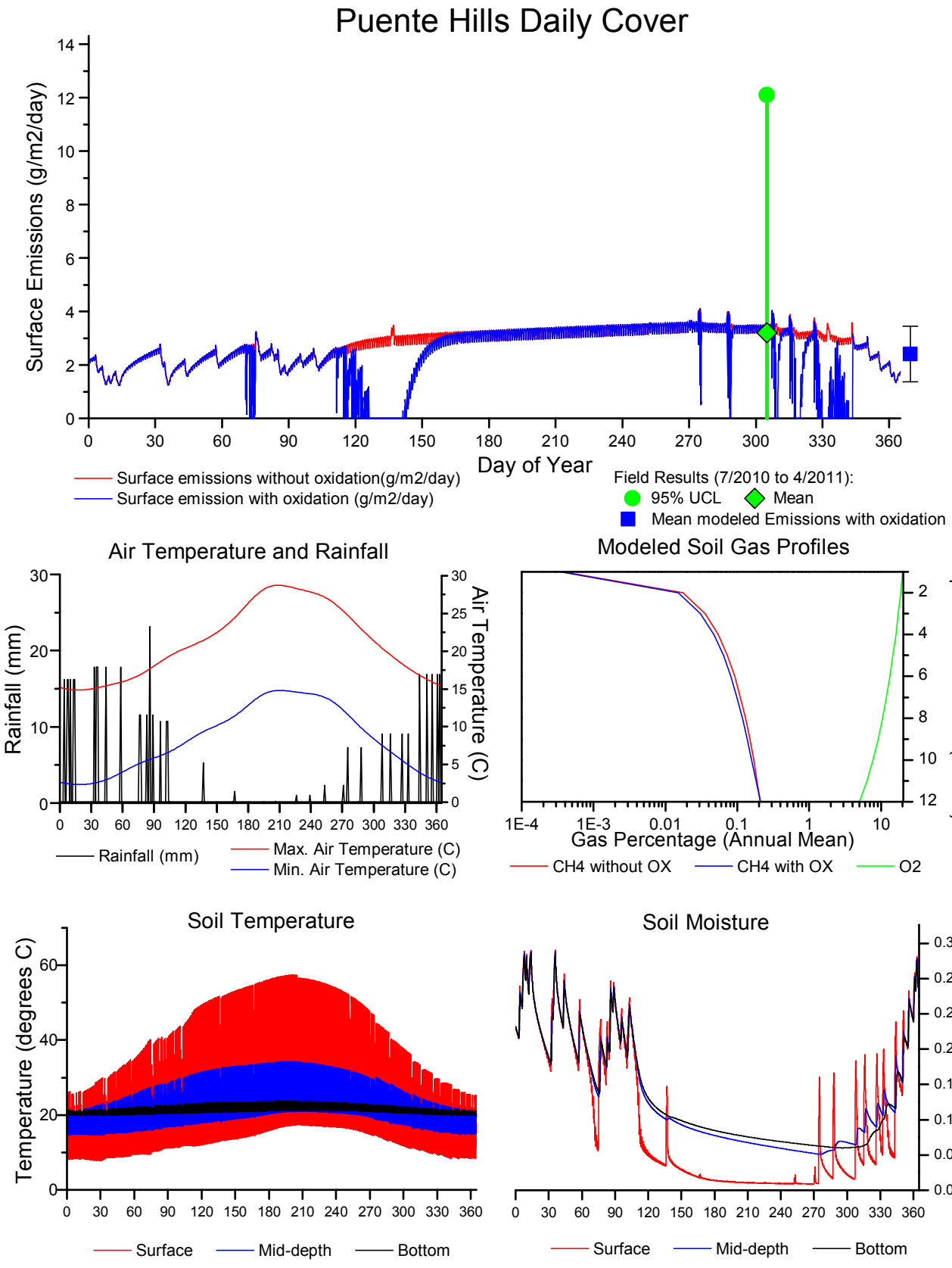
CALMIM Results:	**Gas Recovery %**	**Permitted Minimum Cover CH4 kg/year**	**3 x Permitted Minimum Cover CH4 kg/year**	**5 x Permitted Minimum Cover CH4 kg/year**	**Hectares (Acres)**
Daily	100%	36,357	n/a	n/a	4 (10)
Intermediate	100%	53,838,520	1,519,809	0.0	42 (104)
Final	100%	0	n/a	n/a	197 (486)
Total CH4 emissions with oxidation (kg/year) (Sum of emissions for Permitted Daily Cover, selected Intermediate Cover, and Final Cover)		**53,874,877**	**1,556,166**	**36,357**	**243 (600)**

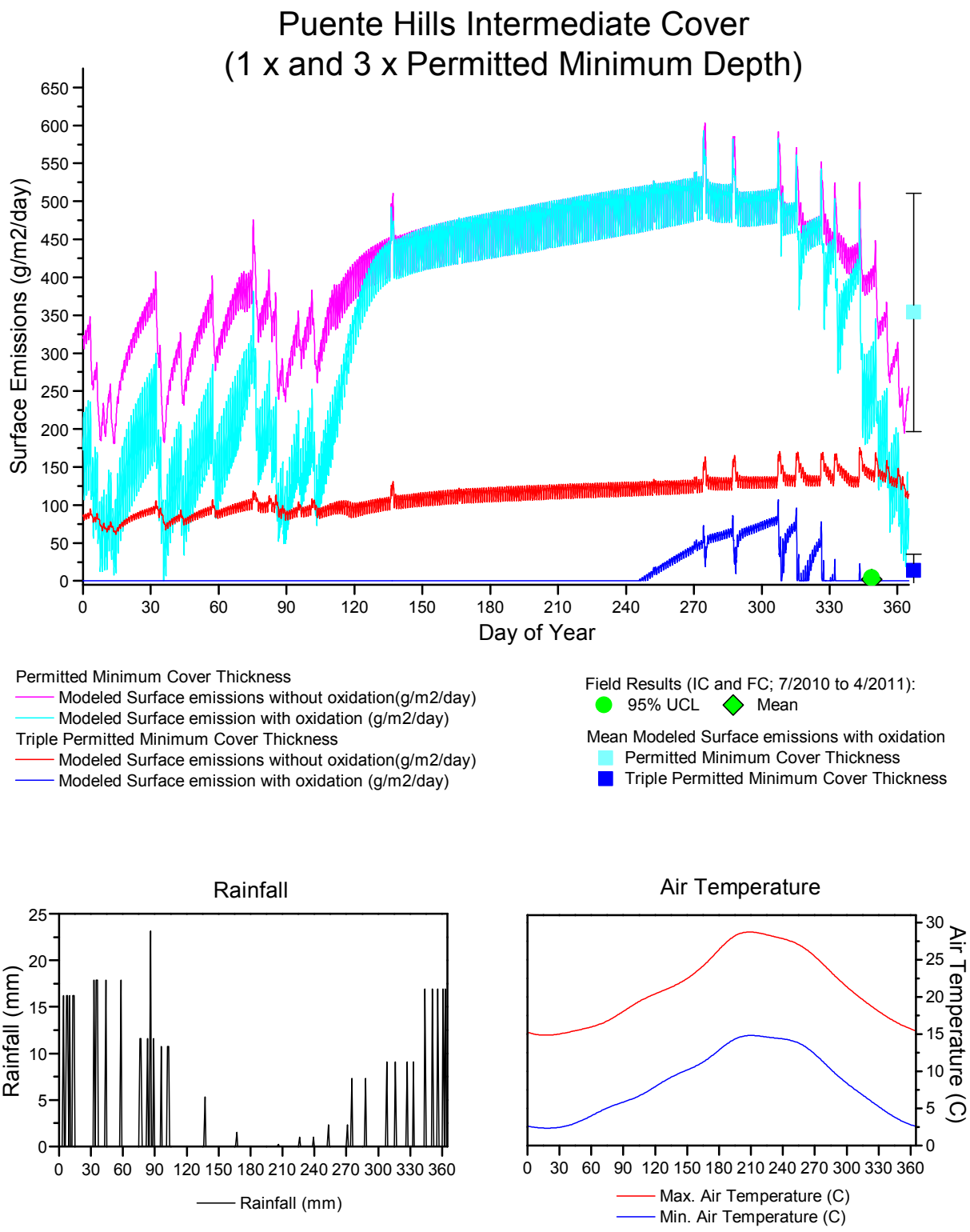
* www.ghgdata.epa.gov. "Surface area containing waste" is given in m^2, converted to hectares and acres here.

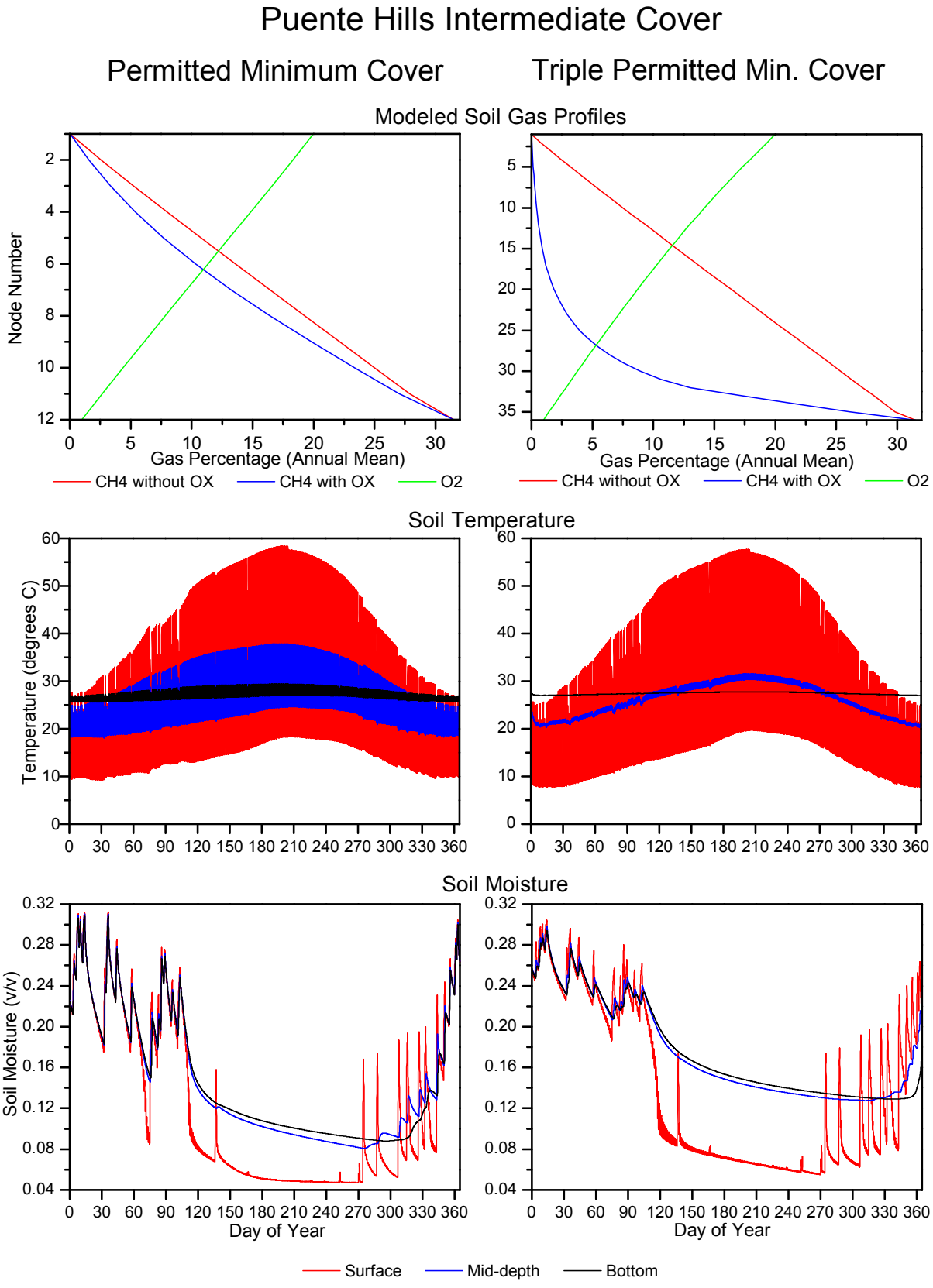
** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21

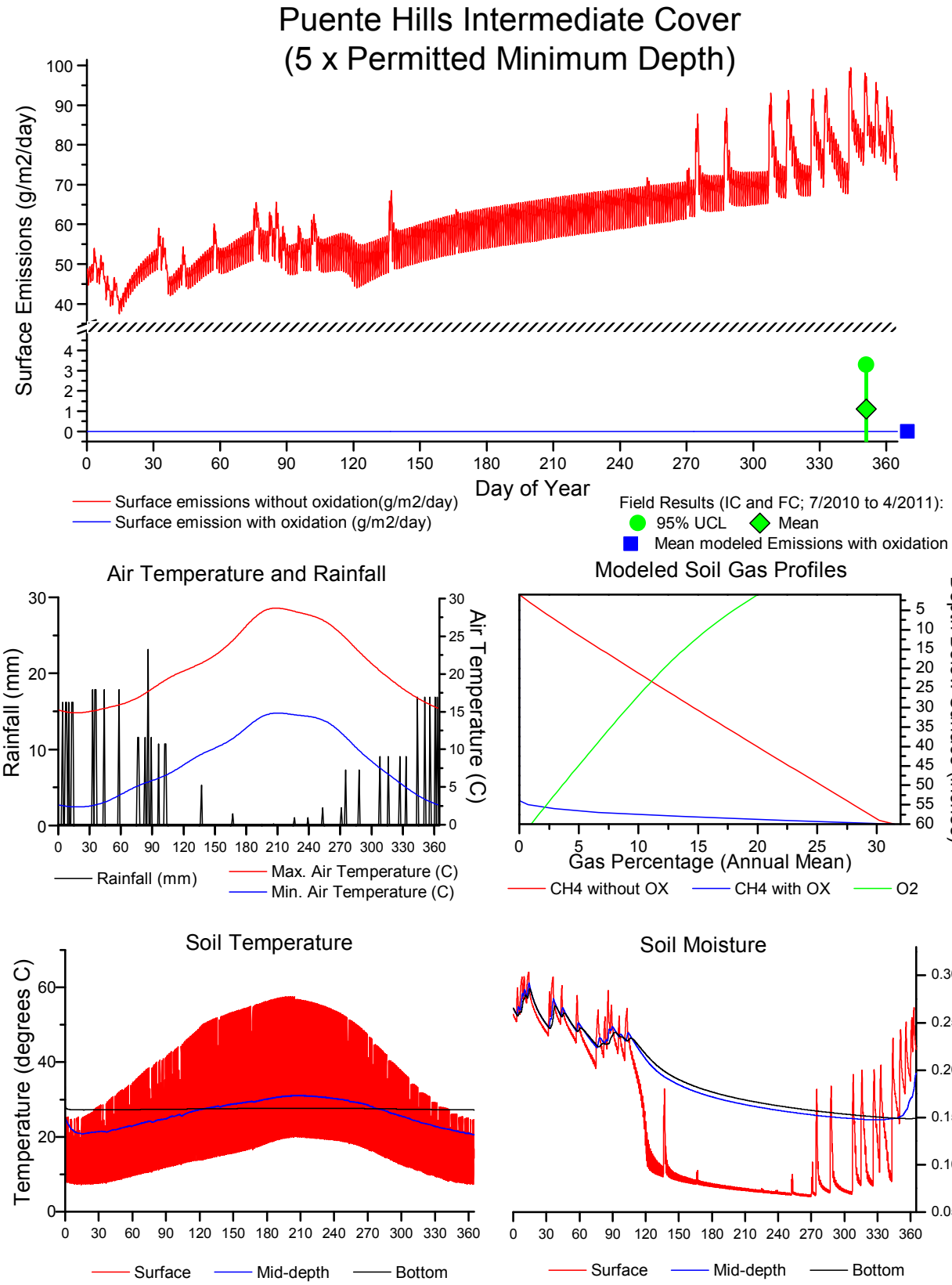
References:

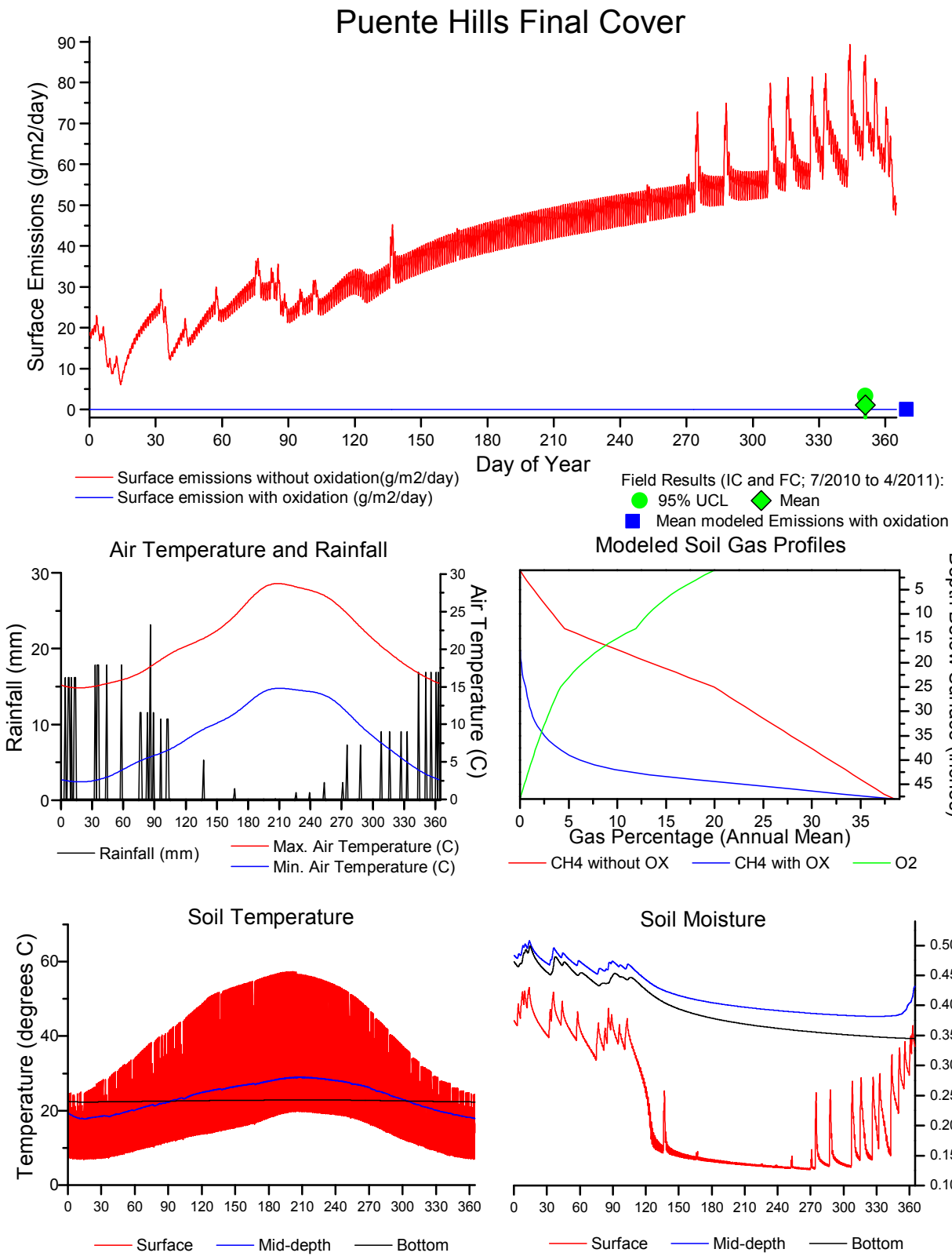
Shan, J., Kong, D., Do, N., Guillen, M., Iacoboni, M., Ferrante, R.F., 2012. Estimation of Landfill Gas Emissions and Collection System Efficiency Using Surface Flux Chamber Technology -- A Case Study of Puente Hills Landfill. 35th Annual Landfill Gas Symposium. Solid Waste Association of North America (SWANA) Landfill Gas Management Technical Division, Orlando, Florida, USA.


Puente Hills Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results (7/2010 to 4/2011):
95% UCL
Mean
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Puente Hills Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Field Results (IC and FC; 7/2010 to 4/2011):
95% UCL
Mean
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


Puente Hills Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom


Puente Hills Intermediate Cover
(5 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results (IC and FC; 7/2010 to 4/2011):
95% UCL
Mean
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Puente Hills Final Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results (IC and FC; 7/2010 to 4/2011):
95% UCL
Mean
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

21. Marina Landfill

Site Location: Monterey, CA

Latitude: +36.71

Longitude: -121.762

Total Size: 127.5 hectares (315 acres)

Site Description: Marina Landfill in northern California has a coastal climate. It uses onsite soils as well as composted sewage sludge and green waste for cover materials. Field measurements were completed using static chambers as well as soil gas profiles. The field study focused on the following areas: collecting flux measurements for use in validating the flux results of the CALMIM model; collecting soil gas profiles for use in validating the CALMIM models results; collecting gas samples for stable carbon isotope analysis to determine oxidation fractions; and collecting field samples for use in laboratory incubations for use in calibrating the oxidation rate in the CALMIM model. Measurements were taken in 2007 and 2008 during the wet season (March) and the dry season (August).

Covers

Cover Name	Daily	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)
Hectares (Acres)	4 (10)	123.5 (305)	123.5 (305)
Cover Type	Daily	Intermediate	Intermediate
Coverage % *	34%	33%	33%
Organic Matter %	2.5% (default)	2.5% (default)	2.5% (default)
Gas Recovery %	100%	100%	100%
Vegetation %	0%	0%	0%

* For use in CALMIM model

Layers

		Daily	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)
1	Material	ADC Composted organic material	Sandy Loam	Sandy Loam
	Thickness	6 in	12 in	36 in

Custom Boundaries

None.

Additional Notes:

The cover descriptions are the standard California covers used for CALMIM modeling.
In order to ensure all covers used the same generated weather the Daily, Intermediate 12 and Intermediate 36 were entered into one CALMIM file, with 34%, 33%, and 33% coverage in CALMIM respectively. To get correct total modeled emissions the totals for each cover must be adjusted from the 34% or 33% coverage to the appropriate actual percentages (3% daily and 97% for the selected intermediate cover).

Results						
Source	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**	**N=**
Published Results (Spokas et al., 2011a) (CH_4 g/m^2/day) (from Summary Field Emissions Data CA.xls)						
Wet Season (+ CH_4) Daily	1.02E+01	1.54E+01	2.15E+00	3.31E-02	5.22E+01	na
Wet Season (+ CH_4) Intermediate	2.17E+01	6.97E+01	3.85E+00	4.94E-03	3.53E+02	
Wet Season (+ CH_4) Final	1.74E-02	1.02E-02	1.58E-02	4.77E-03	3.85E-02	na
Dry Season (+ CH_4) Daily	1.06E+01	1.48E+01	2.27E+00	4.01E-02	4.16E+01	na
Dry Season (+ CH_4) Intermediate	9.11E+01	1.83E+02	1.30E+01	2.26E-03	7.94E+02	na
Dry Season (+ CH_4) Final	1.08E-01	2.49E-01	8.51E-03	1.99E-03	9.28E-01	na
Wet Season (- CH_4) Final *	-1.40E-02	1.31E-02	-8.89E-03	-3.90E-02	-7.08E-04	na
Dry Season (- CH_4) Final *	-0.0130	0.0145	-0.0056	-0.0447	-0.0027	na
Modeled Results (CALMIM 5.4, Emissions with oxidation) (CH_4 g/m^2/day)						
Daily Cover	5.65	2.27	6.24	0.0	8.98	8760
Intermediate (permitted min. depth)	321.95	164.28	370.45	9.03	579.33	8760
Intermediate (3 x permitted min. depth)	6.04	16.39	0.0	0.0	91.59	8760

Field Results: Inverse Distance Weighting (CH_4 g/m^2/day) (Bogner et al., 2011a) [not graphed]

	March 2007	August 2007	March 2008	August 2008
Daily	0.209	0.564	10.2	8.86
Intermediate	0.032	53.20	34.2	238
Final	0.003	0.002	0.007	0.099

* Negative flux field results are not graphed

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**CH4 kg/year**
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)		
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)		

CALMIM Results:	**Gas Recovery %**	**Permitted Minimum Cover CH_4 kg/year**	**3 x Permitted Minimum Cover CH_4 kg/year**	**Hectares (Acres)**
Daily Cover	100	80,511	n/a	4 (10)
Intermediate Cover	100	143,840,866	2,697,115	123.5 (305)
Total CH_4 emissions with oxidation (kg/year) (Sum of emissions for Permitted Daily Cover and selected Intermediate Cover)		**143,921,377**	**2,777,626**	**127.5 (315)**

* www.ghgdata.epa.gov

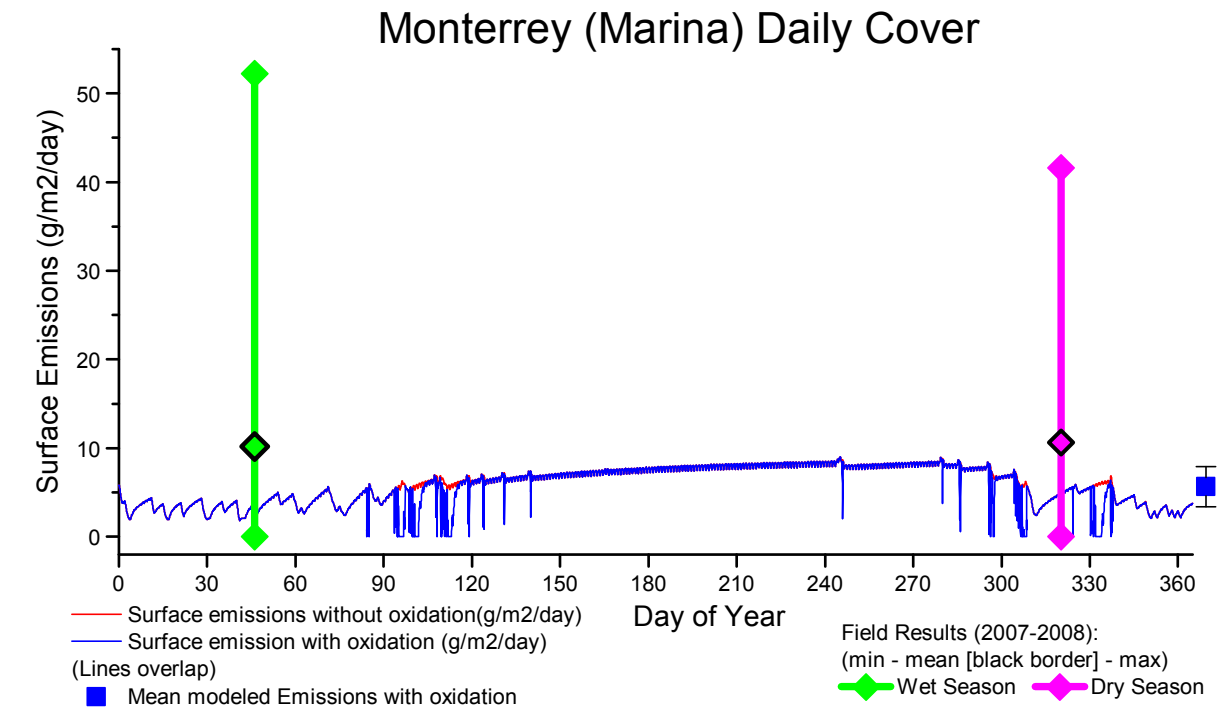
** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21

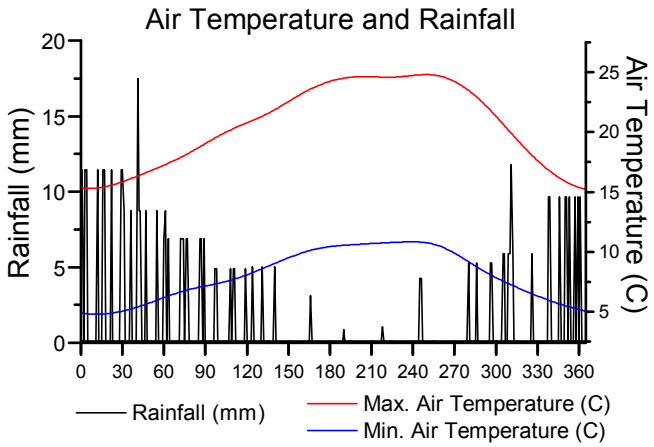
References:

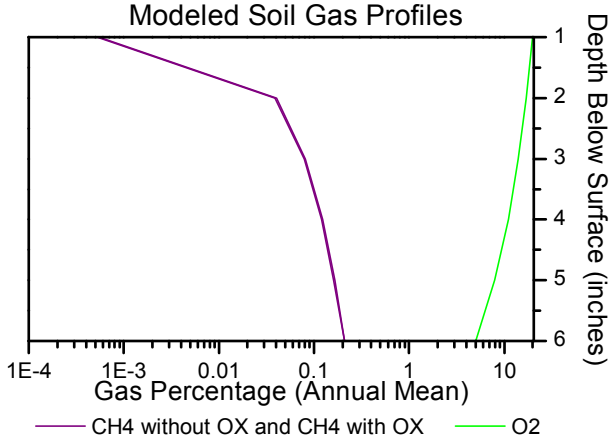
Data in: Summary Field Emissions Data CA.xls; Marina_All.xls (climate graphs); Spokas Probes 6_05_07.xlsx (soil gas profile for Scholl and Marina)

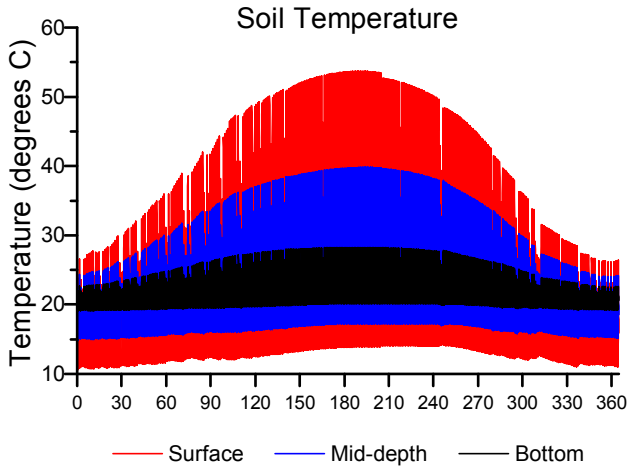
Bogner, J., Spokas, K., Chanton, J., 2011. Seasonal Greenhouse Gas Emissions (Methane, Carbon Dioxide, Nitrous Oxide) from Engineered Landfills: Daily, Intermediate, and Final California Cover Soils. Journal of Environmental Quality, 1-11.

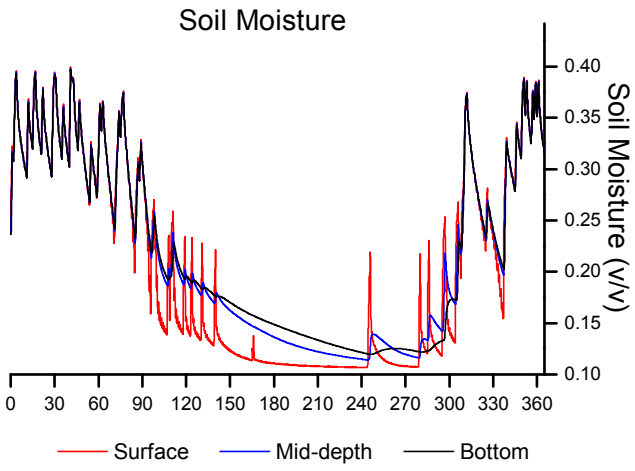
Spokas, K., Bogner, J., Chanton, J., 2011. A process-based inventory model for landfill CH4 emissions inclusive of seasonal soil microclimate and CH4 oxidation. Journal of Geophysical Research 116.

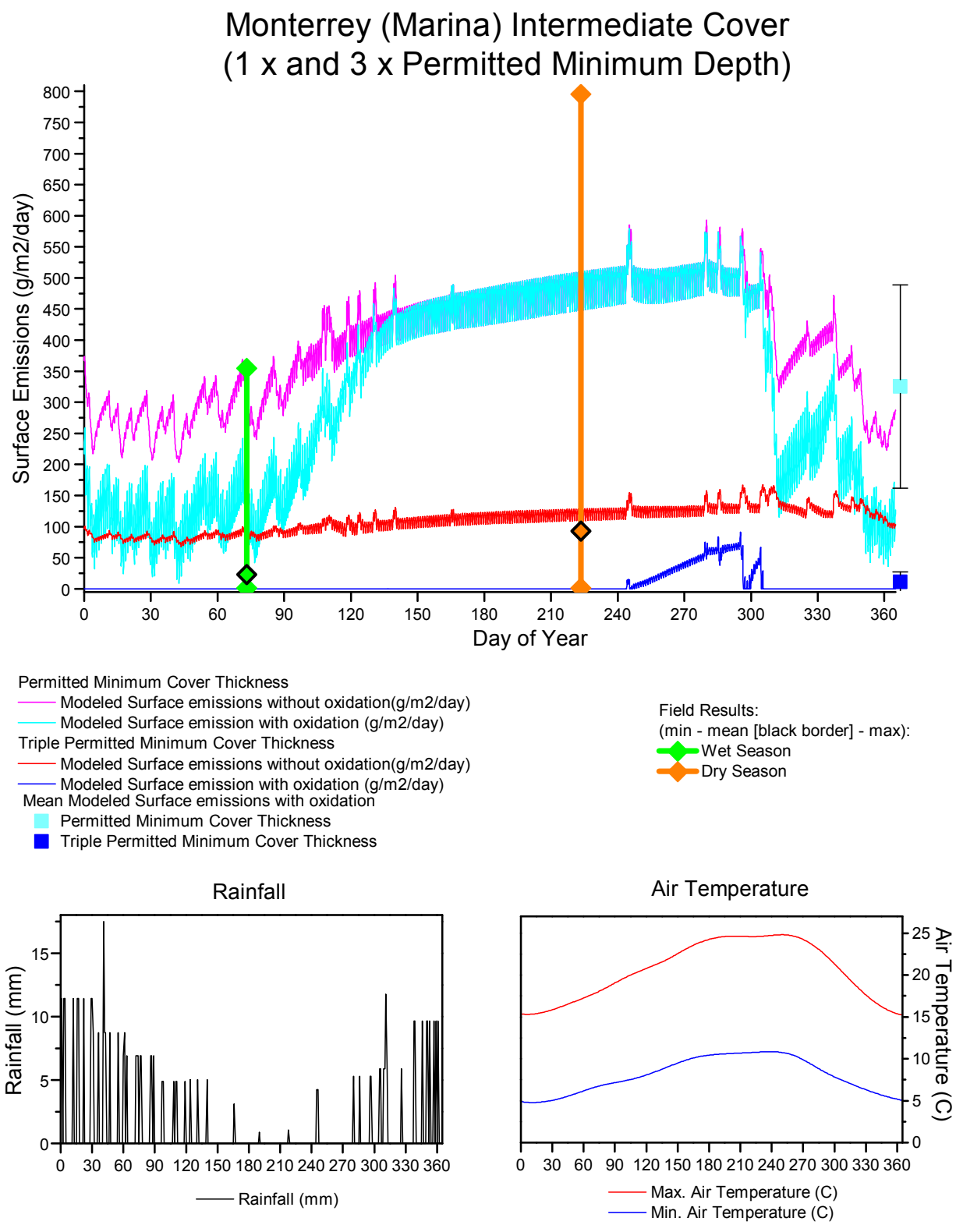

Monterrey (Marina) Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Mean modeled Emissions with oxidation
Field Results (2007-2008):
(min - mean [black border] - max)
Wet Season
Dry Season

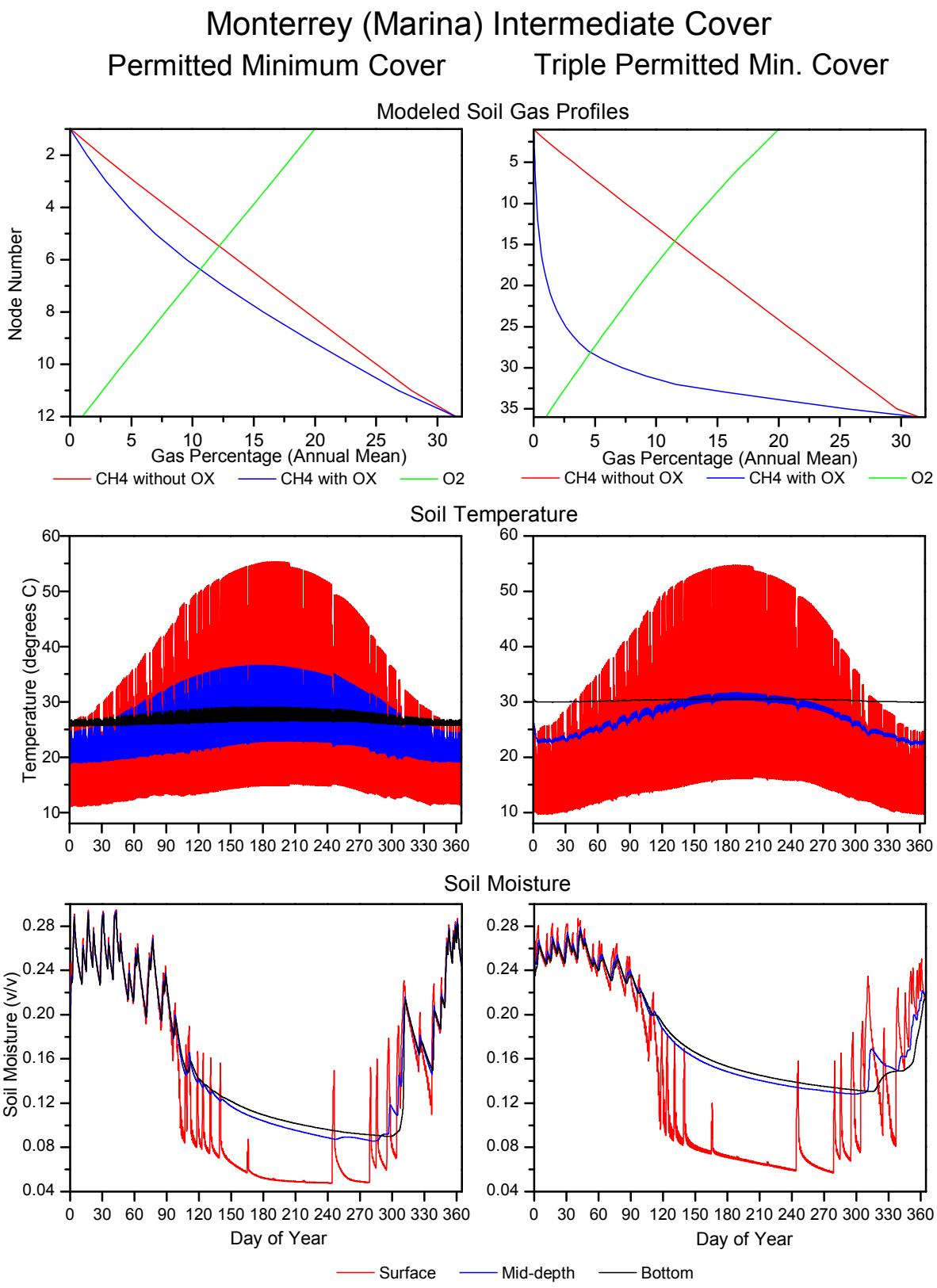

Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


Monterrey (Marina) Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results:
(min - mean [black border] - max):
Wet Season
Dry Season
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


Monterrey (Marina) Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom

22. Site CA-1

Site Location: CA

Latitude: +38.165064

Longitude: -122.563136

Total Size: 90 hectares (223 acres)

Site Description: This landfill is operated by Waste Management. Field studies were performed during June and Oct, 2009, using both TDL (by Waste Management) and chambers (samples analyzed by Jeff Chanton, Florida State University).

Covers	**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**
Acres	4 (10)	86 (213)	86 (213)
Cover Type	Daily	Intermediate	**Intermediate**
Coverage % *	34%	33%	33%
Organic Matter %	2.5% (default)	2.5% (default)	2.5% (default)
Gas Recovery %	100%	100%	100%
Vegetation %	0%	0%	0%

* For use in CALMIM model

Layers		**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**
1	**Material**	ADC Composted organic material	Sandy Loam	Sandy Loam
	Thickness	6 in	12 in	12 in

Custom Boundaries

(No gas profiles were available)

Additional Notes:

The cover descriptions are the standard California covers used for CALMIM modeling.
In order to ensure all covers used the same generated weather the Daily, Intermediate 12 and Intermediate 36 were entered into one CALMIM file, with 34%, 33%, and 33% coverage in CALMIM respectively. To get correct total modeled emissions the totals for each cover must be adjusted from the 34% or 33% coverage to the appropriate actual percentages (4% daily and 96% for the selected intermediate cover).

Field Results:

Field testing was performed only on the intermediate cover. All results are in grams/m^2/day.
The datafile from Jeff Chanton (Chanton, 2007-2009) contains static chamber and oxidation measurements for 17 sites. For this landfill, it contained 3 field results.
In the table below the reported CALMIM mean does not match the mean in the CALMIM Report due to rounding errors.

Source	Mean	Std Dev	Median	Minimum	Maximum	N=
Modeled (CALMIM Results) (CH_4 g/m^2/day)						
Daily Cover	3.81	0.51	3.95	0.004	4.10	8760
Intermediate (permitted min. depth)	313.99	154.99	305.04	16.15	595.72	8760
Intermediate (3 x permitted min. depth)	1.56	6.40	0.0	0.0	58.46	8760
Field Results (CH_4 g/m^2/day)						
June 2009 TDL (Green, 2011c)	4.637	2.385	4.110	0.0333	12.137	357
June 2009 Chamber (all) (Chanton, 2007-2009)	10.085	2.5154	10.085	8.3064	11.864	2
Oct. 2009 TDL (Green, 2011c)	19.234	19.997	13.247	0	138.97	814
Oct. 2009 Chamber (Chanton, 2007-2009)	0.414	n/a	n/a	n/a	n/a	1

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**CH4 kg/year**
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)	174,348	8,302,286
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)	53,999	2,571,381

CALMIM Results:	**Gas Recovery %**	**Permitted Minimum Cover CH_4 kg/year**	**3 x Permitted Minimum Cover CH_4 kg/year**	**Hectares (Acres)**
Daily Cover	100	51,175	n/a	4 (10)
Intermediate Cover	100	98,066,901	488,629	86 (213)
Total CH_4 emissions with oxidation (kg/year) (Sum of emissions for Permitted Daily Cover and selected Intermediate Cover)		**98,118,076**	**539,804**	**90 (223)**

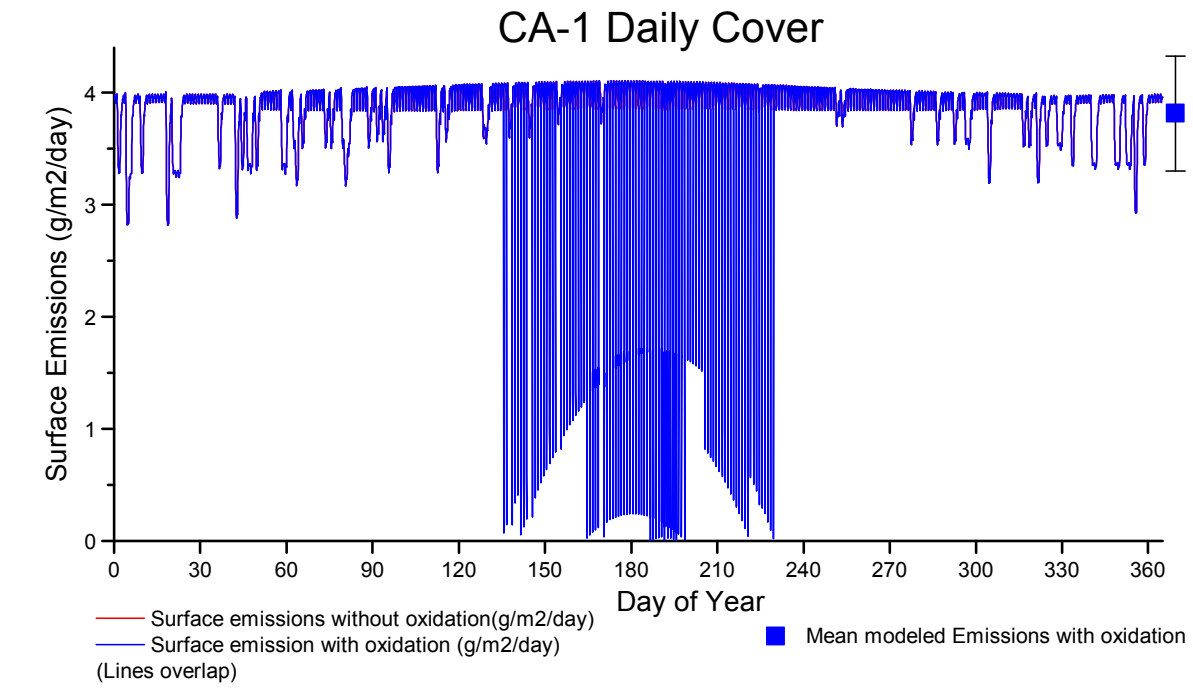
* www.ghgdata.epa.gov

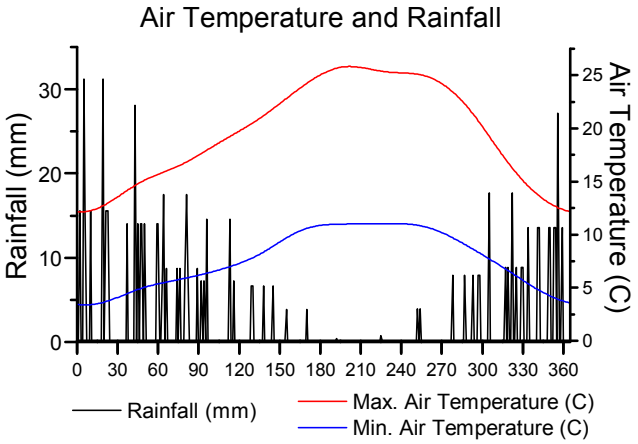
** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21

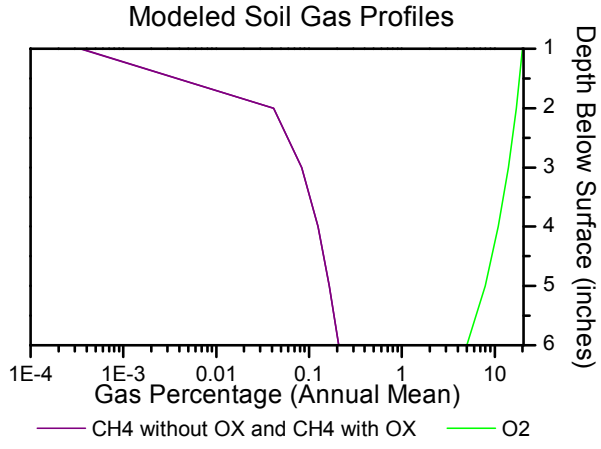
References:

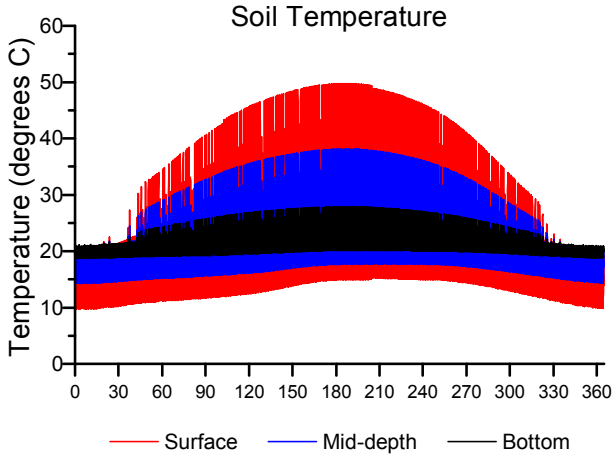
Chanton, J., 2007-2009. Waste Management static chamber and oxidation field measurements 2007 - 2009 at 17 sites by Jeff Chanton. data not published.

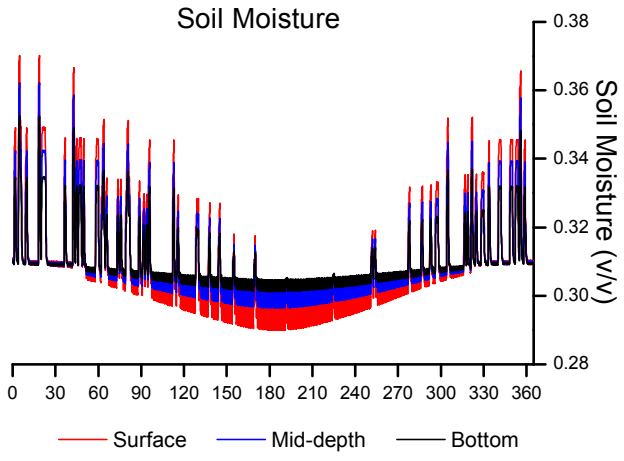
Green, R., 2011. TDL Measurements, June and October 2009 from Roger Green of Waste Management. Data not published.

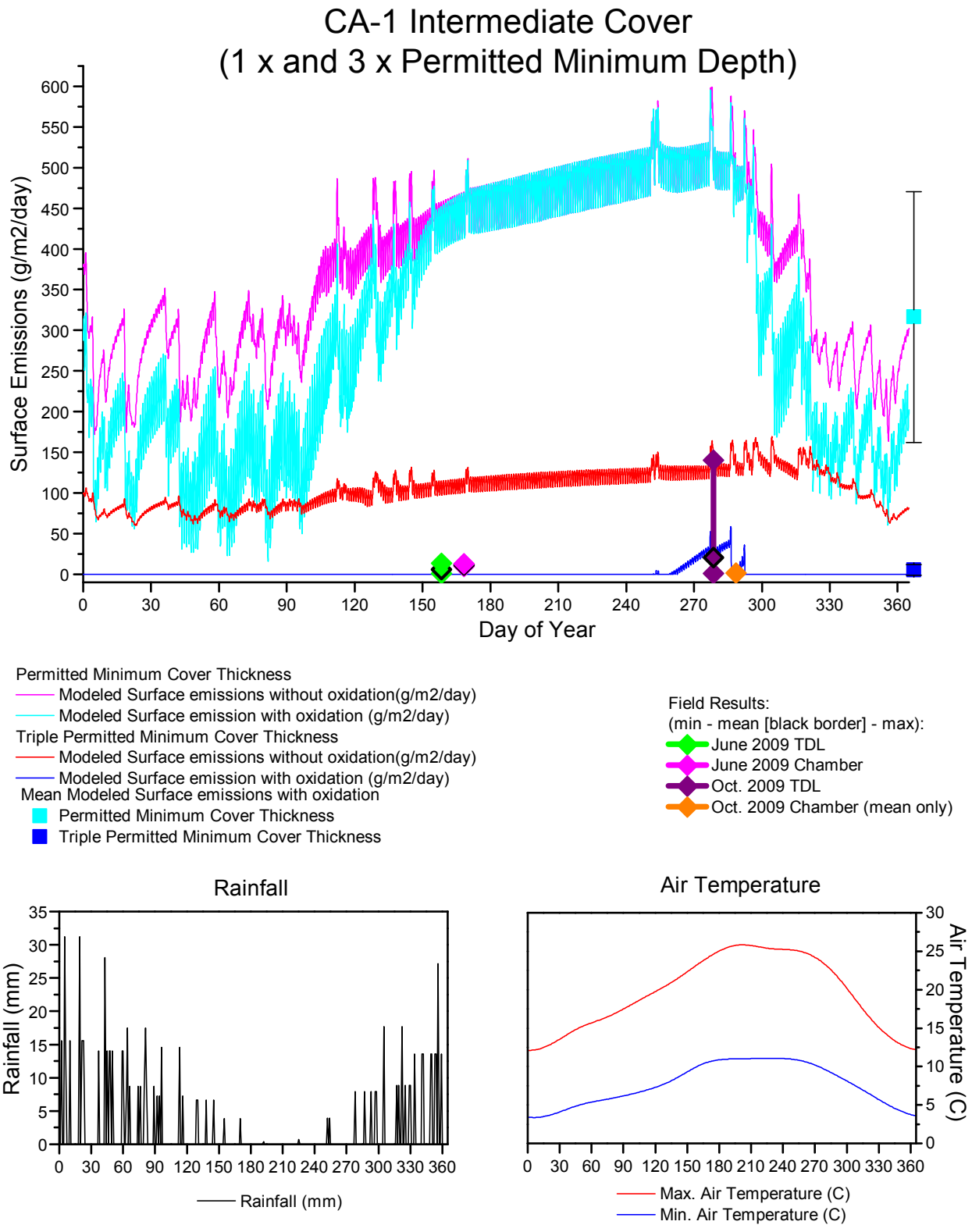

CA-1 Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2

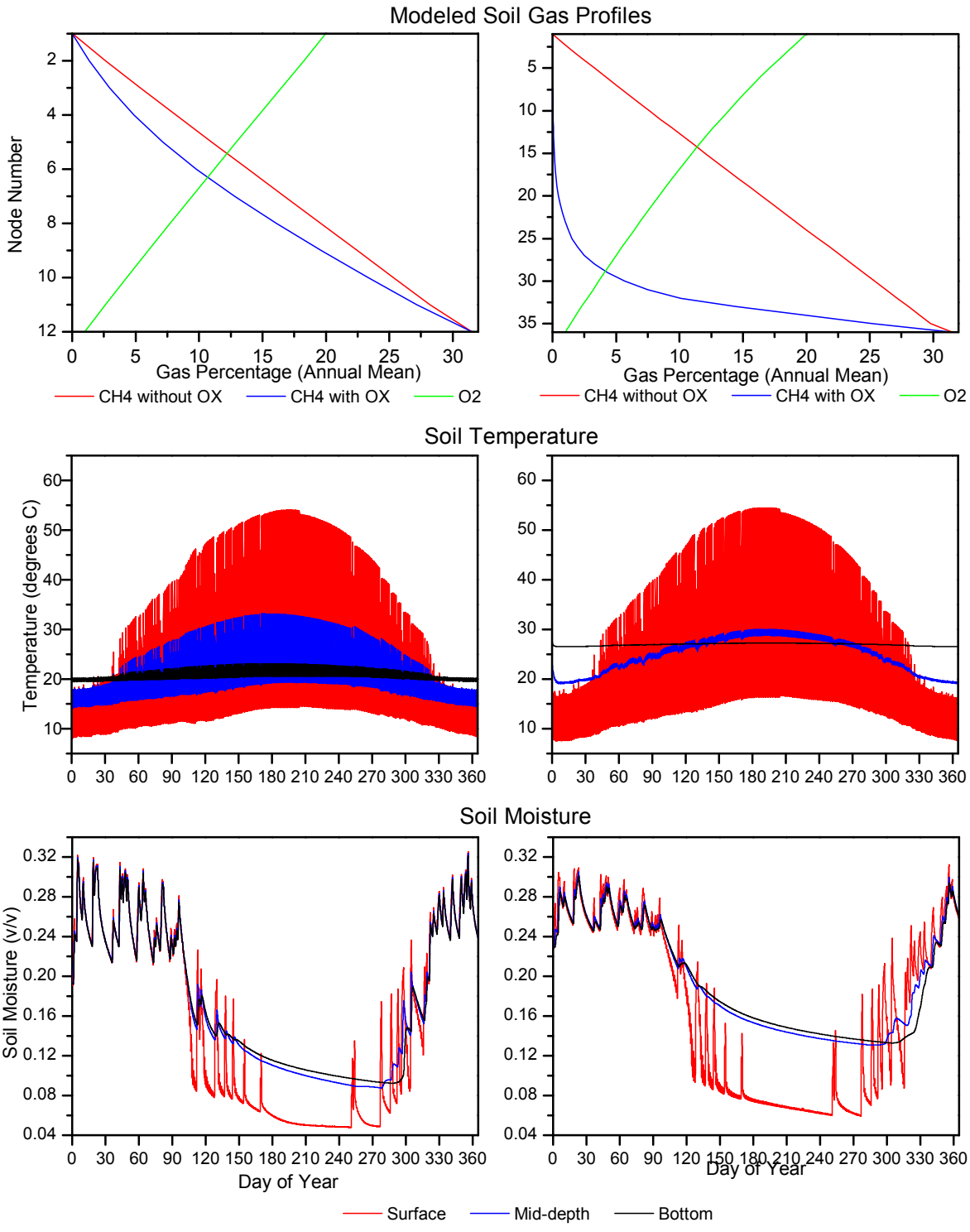

Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom

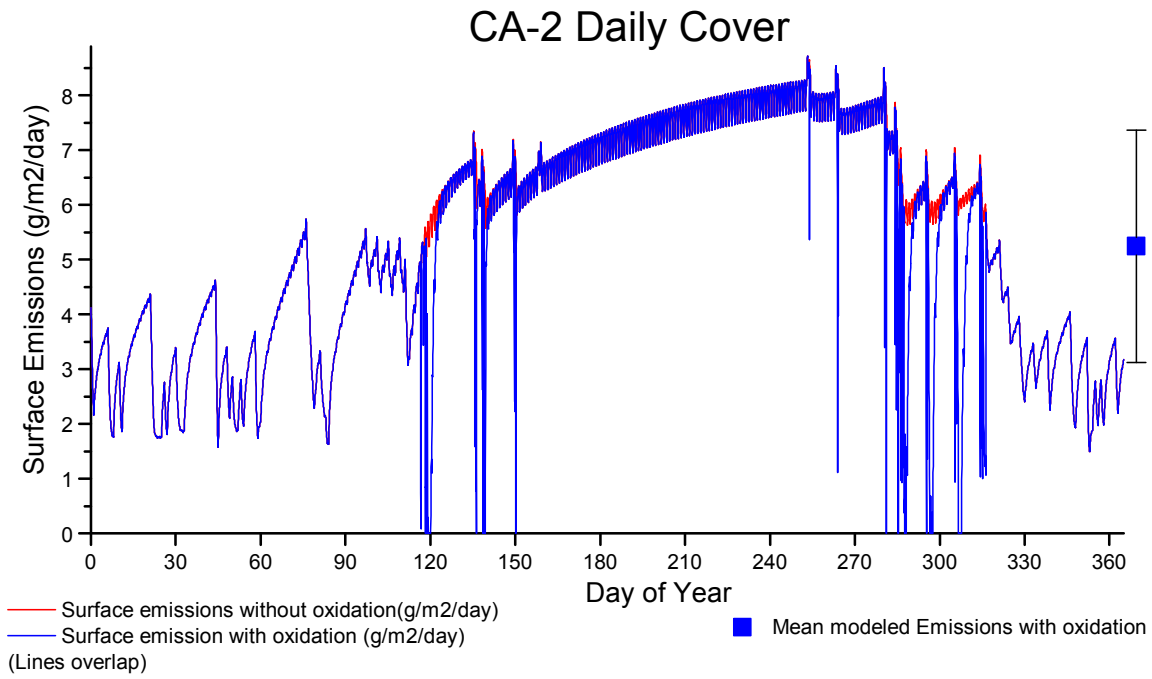

Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

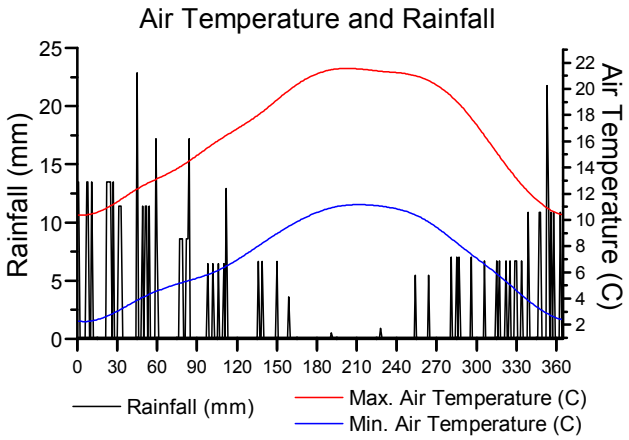

CA-1 Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results:
(min - mean [black border] - max):
June 2009 TDL
June 2009 Chamber
Oct. 2009 TDL
Oct. 2009 Chamber (mean only)
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)

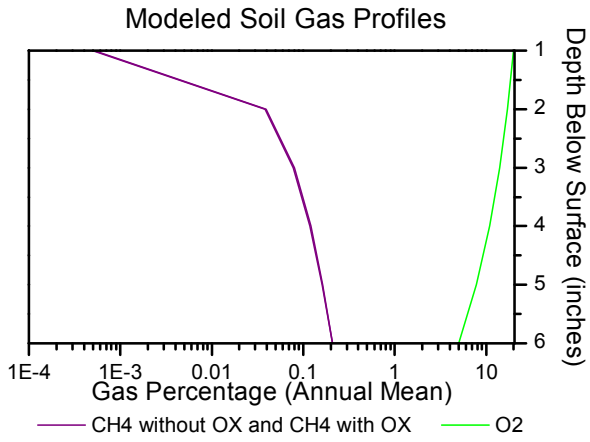
CA-1 Intermediate Cover

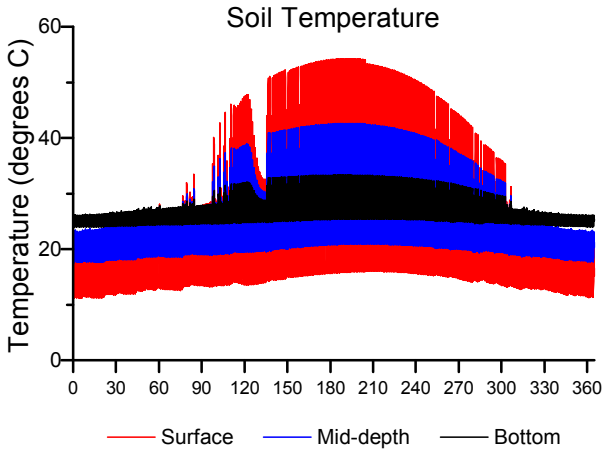
Permitted Minimum Cover Triple Permitted Min. Cover

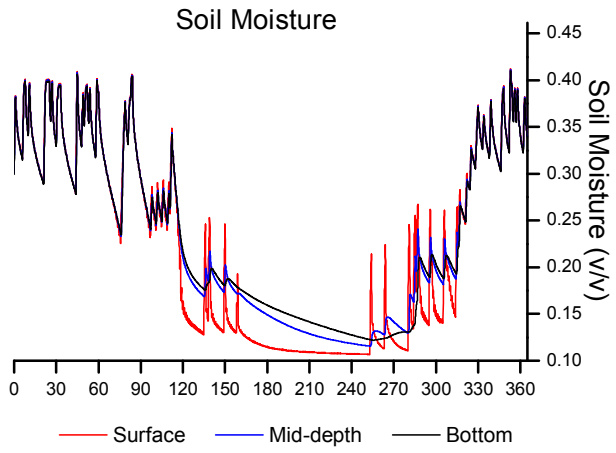


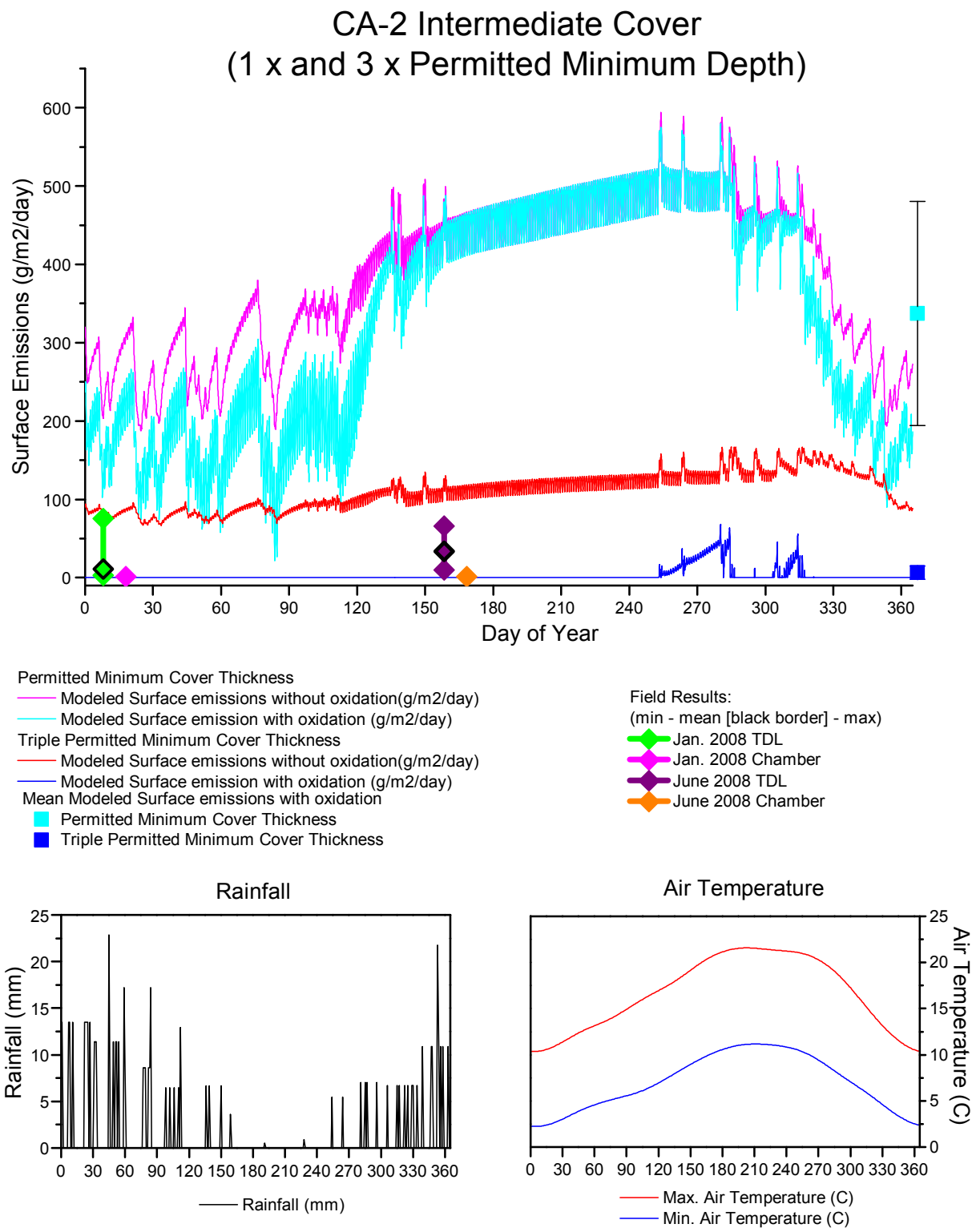

CA-2 Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2

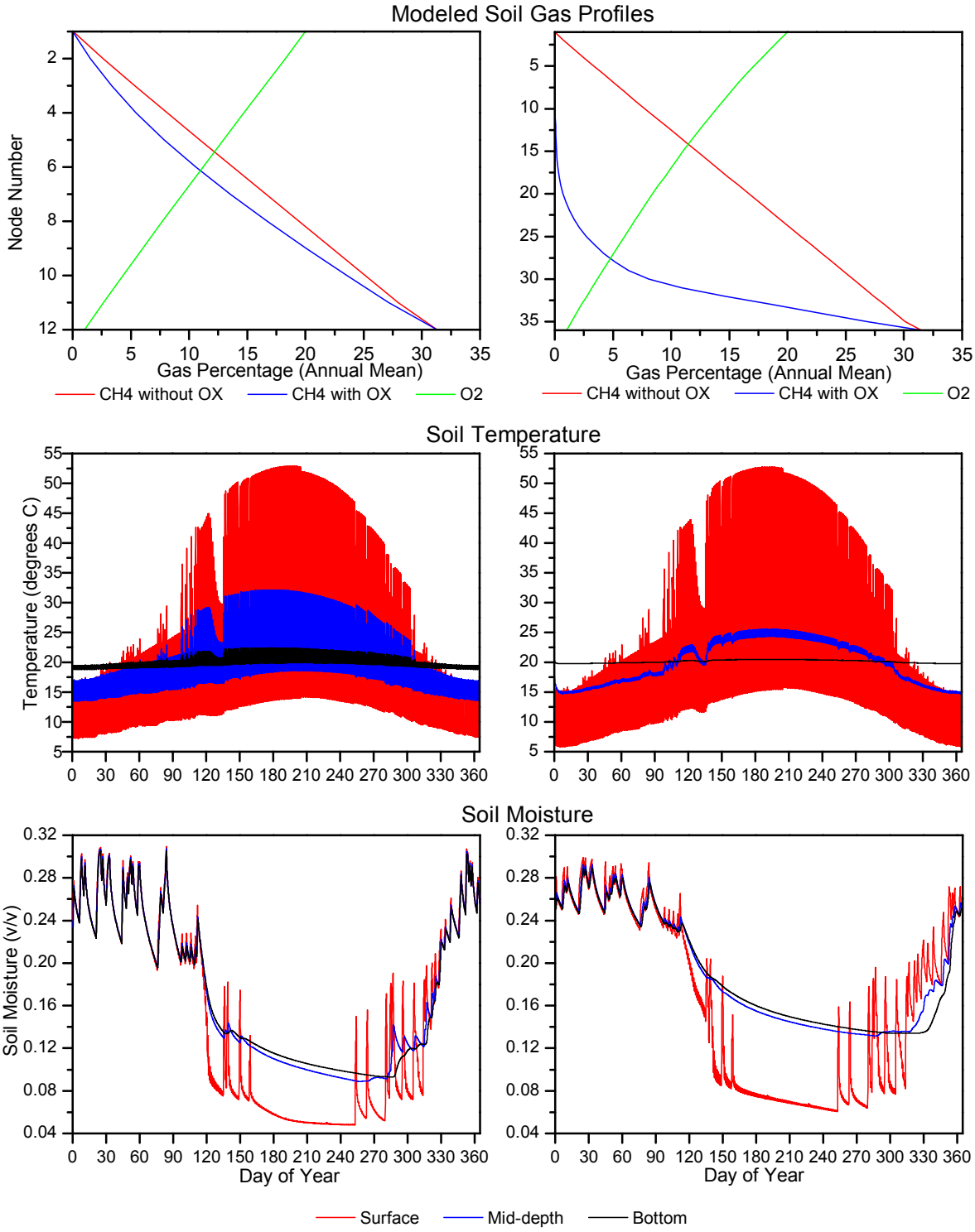

Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


CA-2 Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results:
(min - mean [black border] - max)
Jan. 2008 TDL
Jan. 2008 Chamber
June 2008 TDL
June 2008 Chamber
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)

CA-2 Intermediate Cover

Permitted Minimum Cover Triple Permitted Min. Cover



24. Site CA-3

Site Location: CA

Latitude: 37.494486

Longitude: -121.995375

Total Size: 46.5 Hectares (115 acres)

Site Description: This landfill is operated by Waste Management. TDL field measurements were performed by Waste Management in Feb. 2008 (three days on top of cover) and June 2008 (two days on top of cover, two days on slope of cover). Static chamber measurements were performed by Jeff Chanton during 2008. These are reported in two datafiles, one with results for Feb. 13 and 14, 2008, and the other with results for Feb. 2008 and August 2008. It is thought that all TDL and static chamber testing was done at the same time, so the August 2008 date is thought to be incorrect, and is reported here as June 2008.

Covers	**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**
Hectares (Acres)	4 (10)	42.5 (105)	42.5 (105)
Cover Type	Daily	Intermediate	**Intermediate**
Coverage % *	34%	33%	33%
Organic Matter %	2.5% (default)	2.5% (default)	2.5% (default)
Gas Recovery %	100%	100%	100%
Vegetation %	0%	0%	0%

* Coverage % is for use by CALMIM

Layers		**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**
1	**Material**	ADC Composted Organic Materials	Sandy Loam	Sandy Loam
	Thickness	6 in	12 in	36 in

Custom Boundaries

(No gas profile data available)

Additional Notes:

All covers were run in the same file so the simulated weather is the same for each cover.

The cover descriptions are the standard California covers used for CALMIM modeling.

In order to ensure all covers used the same generated weather the Daily, Intermediate 12, and Intermediate 36 covers were entered into one CALMIM file, with 34%, 33%, and 33% coverage in CALMIM respectively. To get correct total modeled emissions the totals for each cover must be adjusted from the 34% (Daily) or 33% (Intermediate) coverage to the appropriate actual percentages (9% daily and 91% for the selected intermediate cover).

Field Results:

There are two datafiles containing field measurement data from Jeff Chanton. One file (Chanton, 2008) contains results for this site for Feb. 13 and 14, 2008 (Feb. 14 is called "Feb 14 repeat"), but no data from summer 2008. The other file (Chanton, 2007-2009) contains static chamber and oxidation measurements for 17 sites, including results for Feb. 2008 and August 2008, with the Feb. 2008 data points a subset of the Feb.13, 2008 data points from the first file (it is not known what the subset selection criteria were). Note the statistics for the two Feb. 2008 data sets do not match since they are not for the same data points.

All field measurements were performed on intermediate cover. No field measurements were reported for the daily cover.

June 2008 TDL measurements were performed on the top of the cover as well as the slope and are listed separately.

The data in the Chanton, 2008 reference has been treated in two ways. In the "all" rows below, the non-significant flux values are replaced by zeroes, which are treated as a zero in Excel statistics (mean, standard

deviation, median). In the "non-zeroes" rows the non-significant values are replaced with a blank, so they are not used in the calculated statistics, thus the statistics are for all non-zero values. This different treatment does change the resulting statistics. To know how many zero values were included in the statistics for "all" rows, subtract the N for "non-zeroes" from the N for "all". Only the "non-zeroes" field results are included in the plots.

In the table below the reported CALMIM mean does not match the mean in the CALMIM Report due to rounding errors.

Field Results and Modeled Emissions

Source	Mean	Std Dev	Median	Minimum	Maximum	N=	Comments
Modeled Results (CALMIM 5.4) (CH_4 g/m^2/day)							
Daily cover (permitted)	5.37	2.19	5.34	0	8.96	8760	
Intermediate cover (permitted)	297.00	164.14	267.803	24.25	569.19	8760	
Intermediate cover (tripled)	0.01	0.301	0.0	0.0	12.34	8760	
Field Results (CH_4 g/m^2/day)							
Feb. 2008 TDL (Green, 2011d)	10.296	4.805	9.218	1.949	26.106	296	
Feb 13 2008 Chamber (all) (Chanton, 2008)	2.525	5.427	0.1534	-0.01209	20.187	24	(not plotted)
Feb 13 2008 Chamber (non-zeroes) (Chanton, 2008)	3.5065	6.159	0.5858	-0.01209	20.187	18	16 pos, 2 neg
Feb 14 2008 repeat Chamber (all) (Chanton, 2008)	0.266	0.4665	0.0270	-0.0196	1.788	24	(not plotted)
Feb 14 2008 repeat Chamber (non-zeroes) (Chanton, 2008)	0.3998	0.5261	0.1521	-0.0196	1.788	16	13 pos, 3 neg
Feb 13, 2008 Chamber (subset) Oxidation file (Chanton, 2007-2009)	5.2063	7.0120	2.2024	0.0000	20.19	12	All positive
June 2008 TDL (top) (Green, 2011d)	8.176	5.775	6.285	1.601	34.91	402	
June 2008 TDL (slope) (Green, 2011d)	6.041	2.786	5.331	2.005	26.15	341	
June 2008 Chamber (Reported as Aug 2008) Oxidation file (Chanton, 2007-2009)	8.067	14.94	0.4312	0.0062	65.36	46	All positive
Spokas Chamber "Published", Feb and June 2008 (Spokas et al., 2011a)	6.82	n/a	0.03	-0.02	9.2		

Reported to EPA under mandatory reporting rule (2010 data) *	MTCO2e **	CH4 kg/year	Acres
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)	58,880	2,803,810	
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)	24,519	1,167,571	

CALMIM Results:	Gas Recovery %	Permitted Minimum Cover CH4 kg/year	3 x Permitted Minimum Cover CH4 kg/year	Hectares (Acres)
Daily	100	83,787	n/a	4 (10)
Intermediate	100	45,446,799	1,480	42.5 (105)
Total CH4 emissions with oxidation (kg/year)		**45,530,586**	**85,267**	**46.5 (115)**

* www.ghgdata.epa.gov

** MTCO2e is metric tons of CO2 equivalent. CH4 kg/year = MTCO2e*1000/21

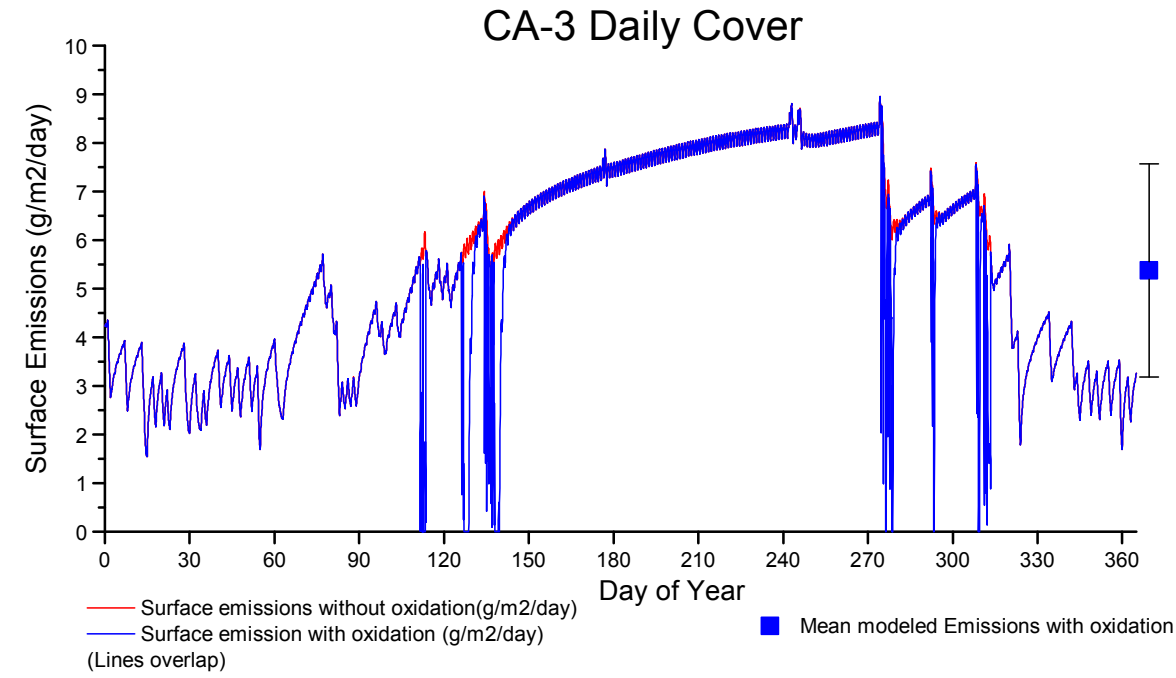
References:

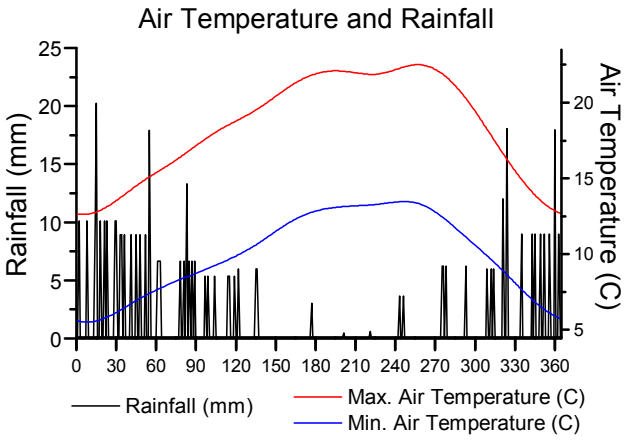
Chanton, J., 2007-2009. Waste Management static chamber and oxidation field measurements 2007 - 2009 at 17 sites by Jeff Chanton. data not published.

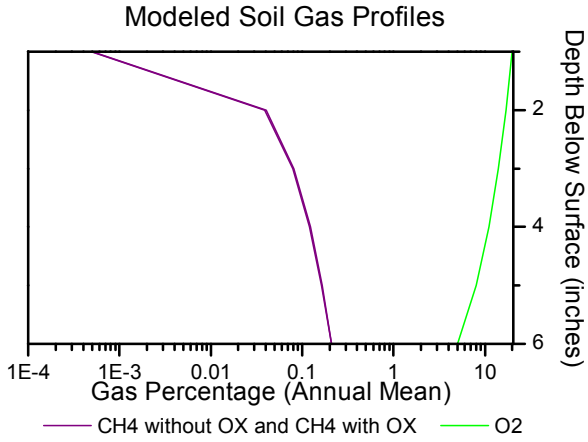
Chanton, J., 2008. Static Chamber field measurement results for 3 Waste Management sites. Data not published.

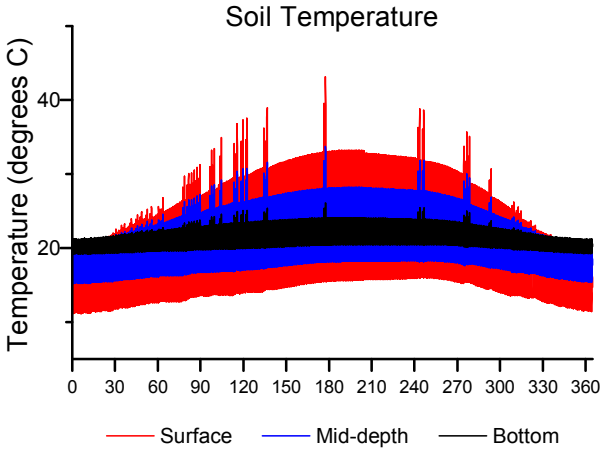
Green, R., 2011. TDL Measurements for Feb. and June, 2008. From Roger Green of Waste Management. Data not published.

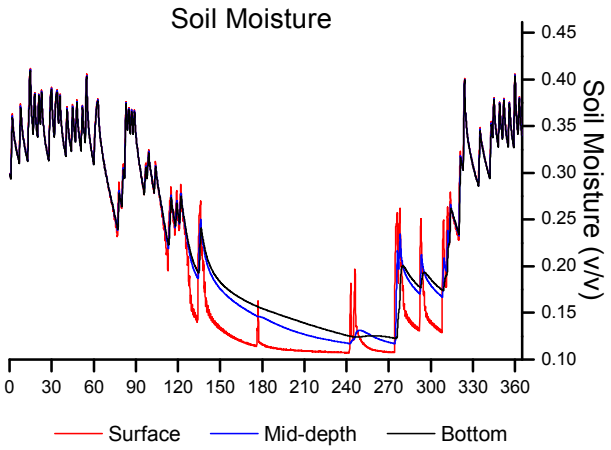
Spokas, K., Bogner, J., Chanton, J., 2011. A process-based inventory model for landfill CH4 emissions inclusive of seasonal soil microclimate and CH4 oxidation. Journal of Geophysical Research 116.

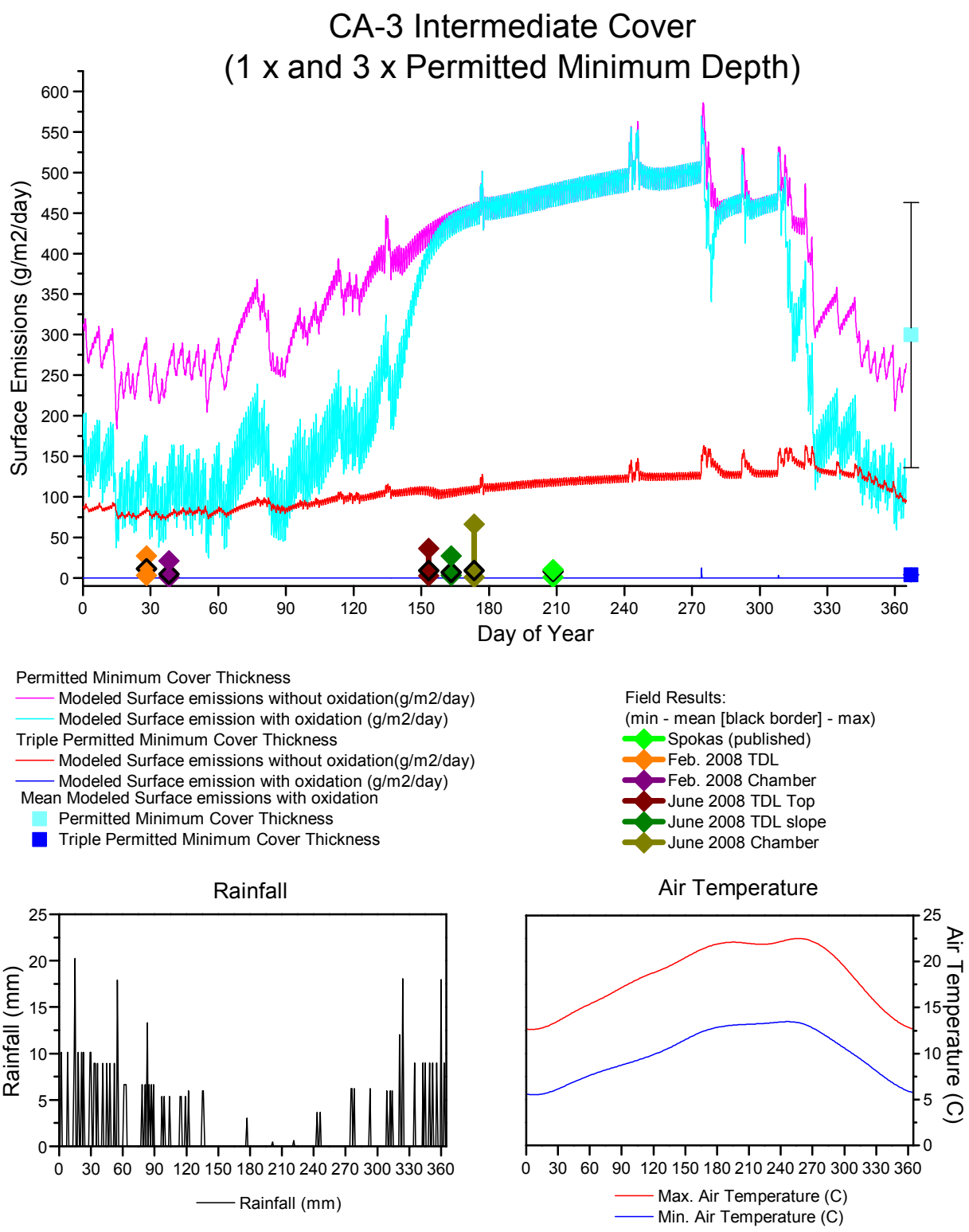

CA-3 Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Mean modeled Emissions with oxidation

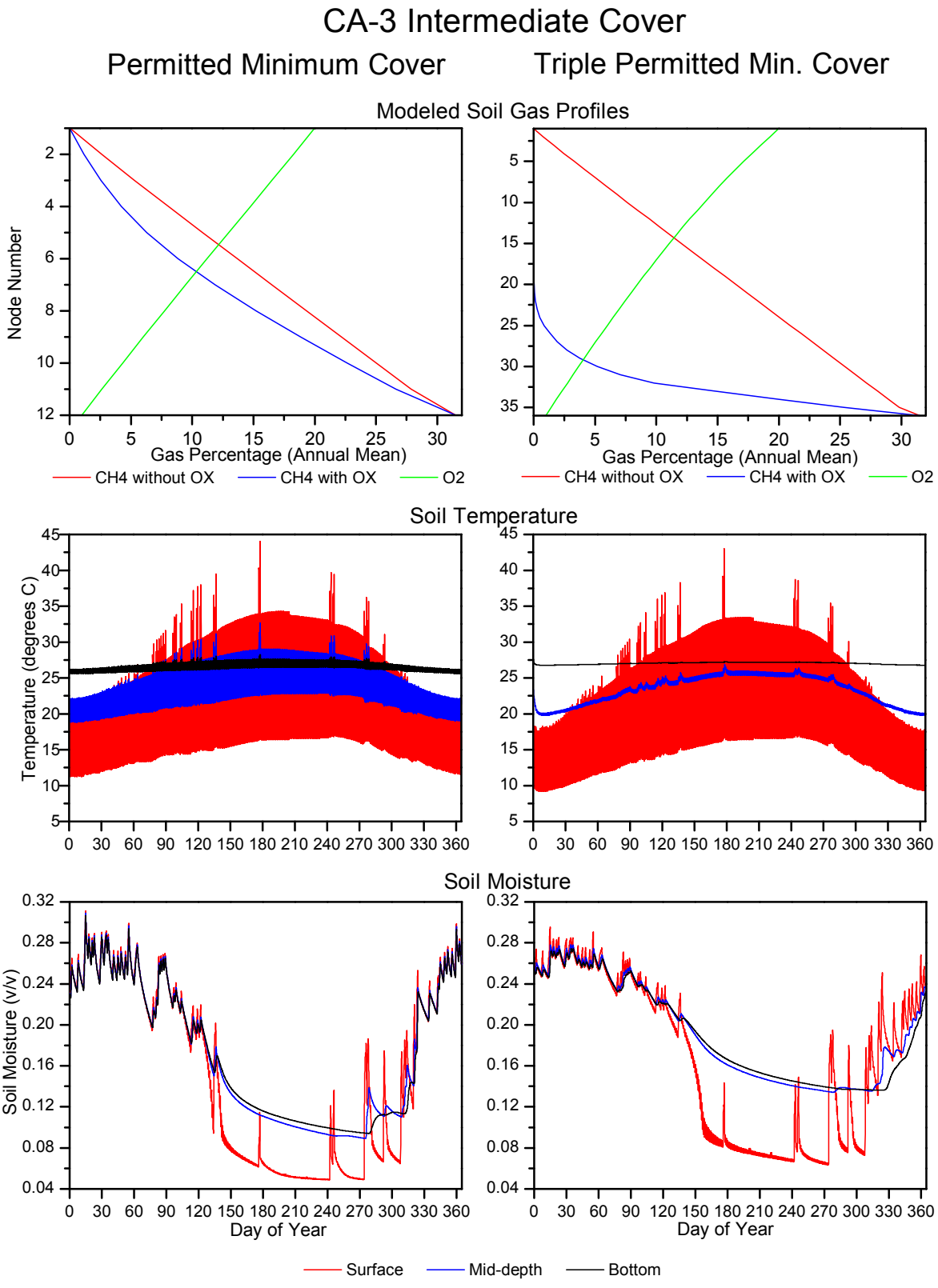

Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


CA-3 Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results:
(min - mean [black border] - max)
Spokas (published)
Feb. 2008 TDL
Feb. 2008 Chamber
June 2008 TDL Top
June 2008 TDL slope
June 2008 Chamber
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


CA-3 Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
Surface
Mid-depth
Bottom

25. Site CA-4

Site Location: CA

Latitude: 37°45'17.67"N (37.754915)

Longitude: 121°39'15.12"W (-121.654174)

Total Size: Hectares 95 (235 acres)

Site Description: This site is operated by Waste Management. TDL measurements were performed by Waste Management in June (June 30 to July 1) and October, 2009. Chamber measurements were also performed in October, 2009 in coordination with the Waste Management field study.

Covers

	Daily	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)	Final
Hectares (Acres)	4 (10)	76.5 (189)	76.5 (189)	14.5 (36)
Cover Type	Daily	Intermediate	Intermediate	Final
Coverage % *	25%	25%	25%	25%
Organic Matter %	2.5% (default)	2.5% (default)	2.5% (default)	2.5% (default)
Gas Recovery %	100%	100%	100%	100%
Vegetation %	0%	0%	0%	0%

* Coverage % is for use by CALMIM

Layers

		Daily	Intermediate 12 (permitted minimum depth)	Intermediate 36 (3 x permitted minimum)	Final
1	**Material**	ADC Composted Organic Materials	Sandy Loam	Sandy Loam	Loam
	Thickness	6 inches	12 in	36 in	12 inches
2	**Material**				Clay
	Thickness				12 inches
3	**Material**				Silty clay loam
	Thickness				24 inches

Custom Boundaries

(No gas profiles were available)

Additional Notes:

Daily cover is placed every 5 days at this facility.

The cover descriptions are the standard California covers used for CALMIM modeling.

In order to ensure all covers used the same generated weather the Daily, Intermediate 12, Intermediate 36, and Final covers were entered into one CALMIM file, each with 25% coverage in CALMIM. To get correct total modeled emissions the totals for each cover must be adjusted from the 25% coverage to the appropriate actual percentages (5% daily, 80% for the selected intermediate cover, and 15% for the Final cover).

Field Results:

All field testing was done on the intermediate cover only, on the top of the cover only (not on the slope). Results are in grams/m^2/day.

In the table below the reported CALMIM mean does not match the mean in the CALMIM Report due to rounding errors.

Source	Mean	Std Dev	Median	Minimum	Maximum	N=
Modeled (CALMIM 5.4 Results) (CH_4 g/m^2/day)						
Daily Cover	5.28	2.36	5.41	0.0	8.98	8760
Intermediate (permitted min. depth)	326.01	154.44	320.42	0.85	583.83	8760
Intermediate (3 x permitted min. depth)	1.67	6.22	0.0	0.0	52.67	8760
Final Cover	7.24E-5	0.005	0.0	0.0	0.35	8760
Field Results (CH_4 g/m^2/day)						
June 2009 TDL (Green, 2011a)	14.451	11.350	10.316	1.019	59.075	635
Oct. 2009 TDL (Green, 2011a)	9.479	6.643	7.933	0	46.289	598
Oct. 2009 Chamber (Chanton, 2007-2009)	0.749	1.029	0.312	0.035	2.663	7

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**CH4 kg/year**
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)	176,436	8,401,714
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)	337,146	16,054,571

CALMIM Results:

	Gas Recovery %	Permitted Minimum Cover CH_4 kg/year	3 x Permitted Minimum Cover CH_4 kg/year	Hectares (Acres)
Daily Cover	100%	91,526	n/a	4 (10)
Intermediate Cover	100%	90,521,790	463,342	76.5 (189)
Final Cover	100%	6	n/a	14.5 (36)
Total CH_4 emissions with oxidation (kg/year) (Sum of emissions for Permitted Daily Cover, selected Intermediate Cover, and Final Cover)		**90,613,322**	**554,874**	**95 (235)**

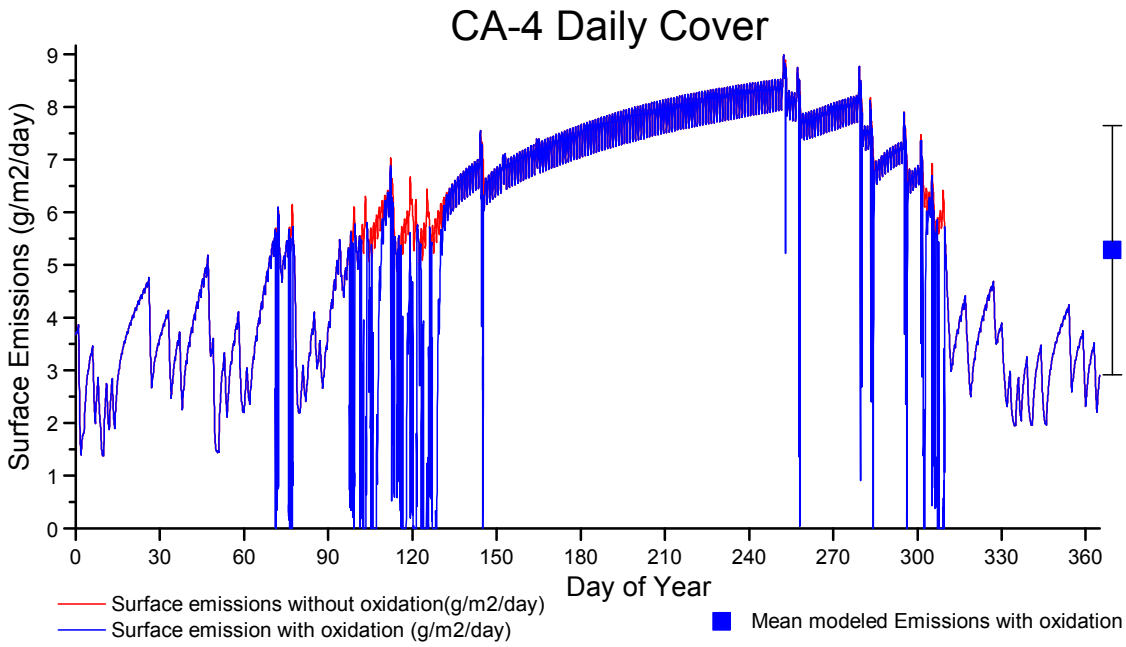
* www.ghgdata.epa.gov

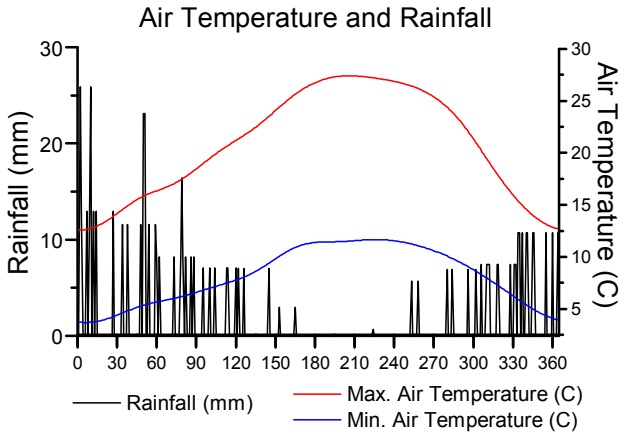
** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21

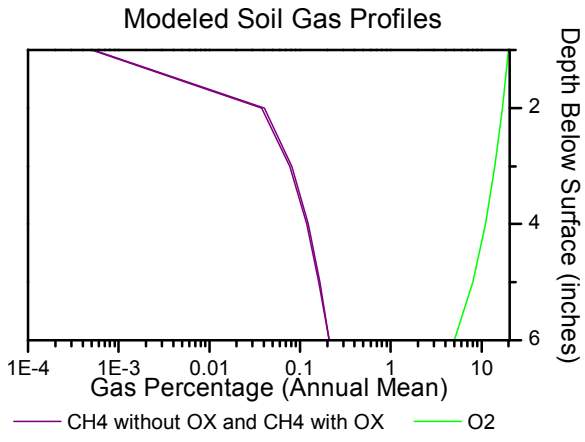
References:

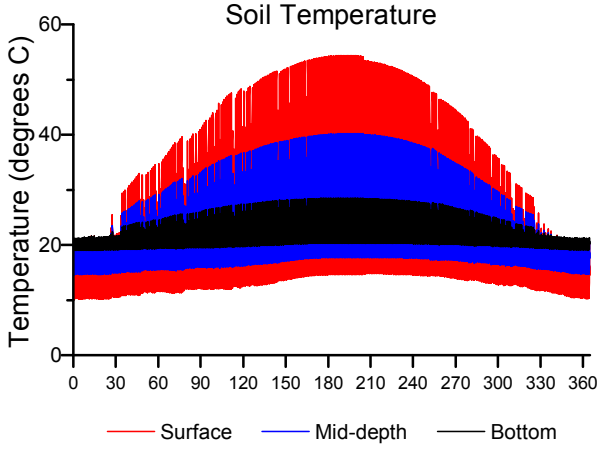
Chanton, J., 2007-2009. Waste Management static chamber and oxidation field measurements 2007 - 2009 at 17 sites by Jeff Chanton. data not published.

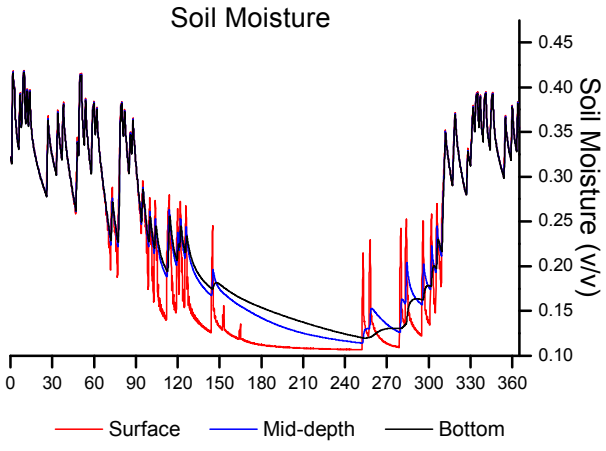
Green, R., 2011. TDL Measurements for June and October, 2009. From Roger Green of Waste Management

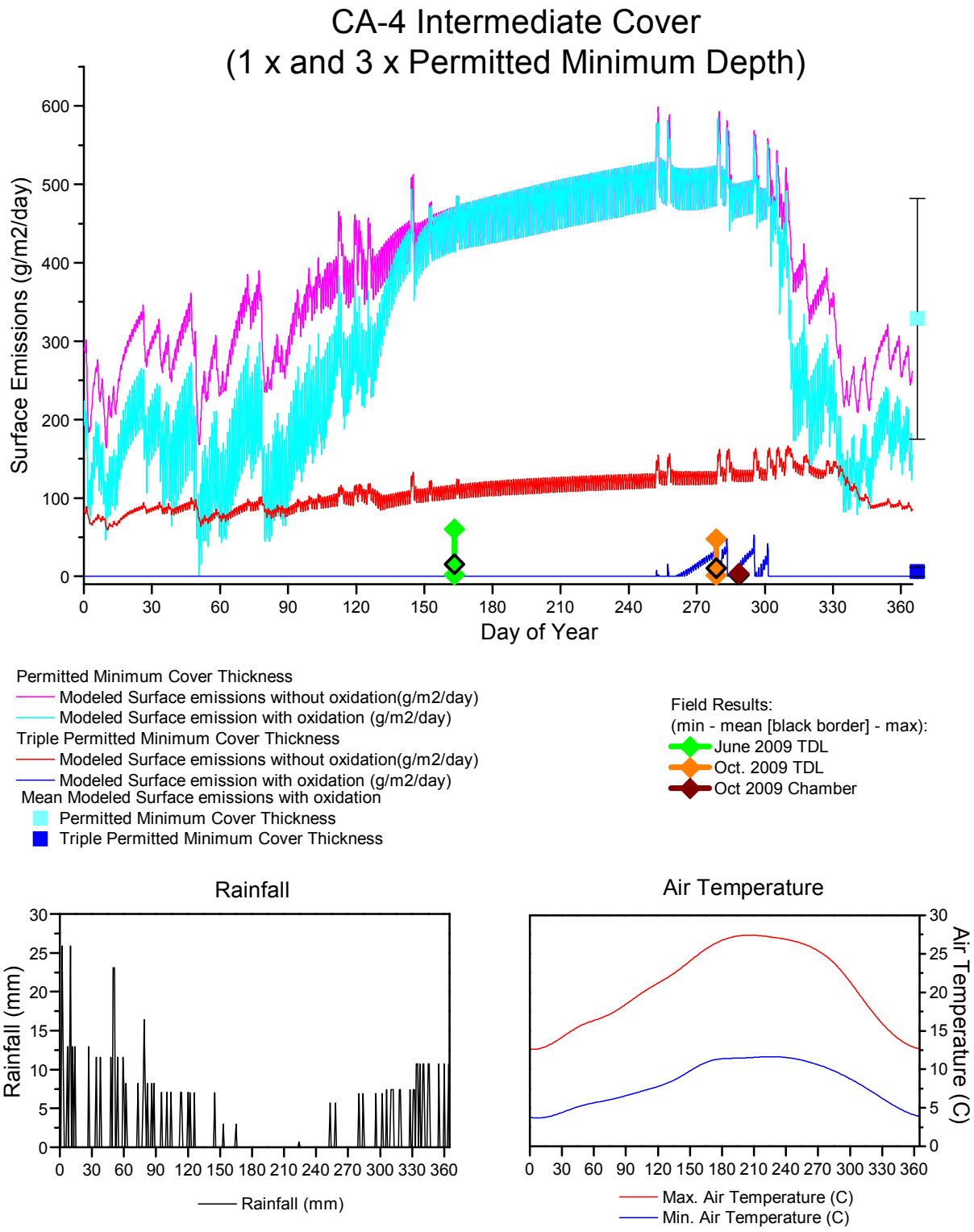

CA-4 Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2

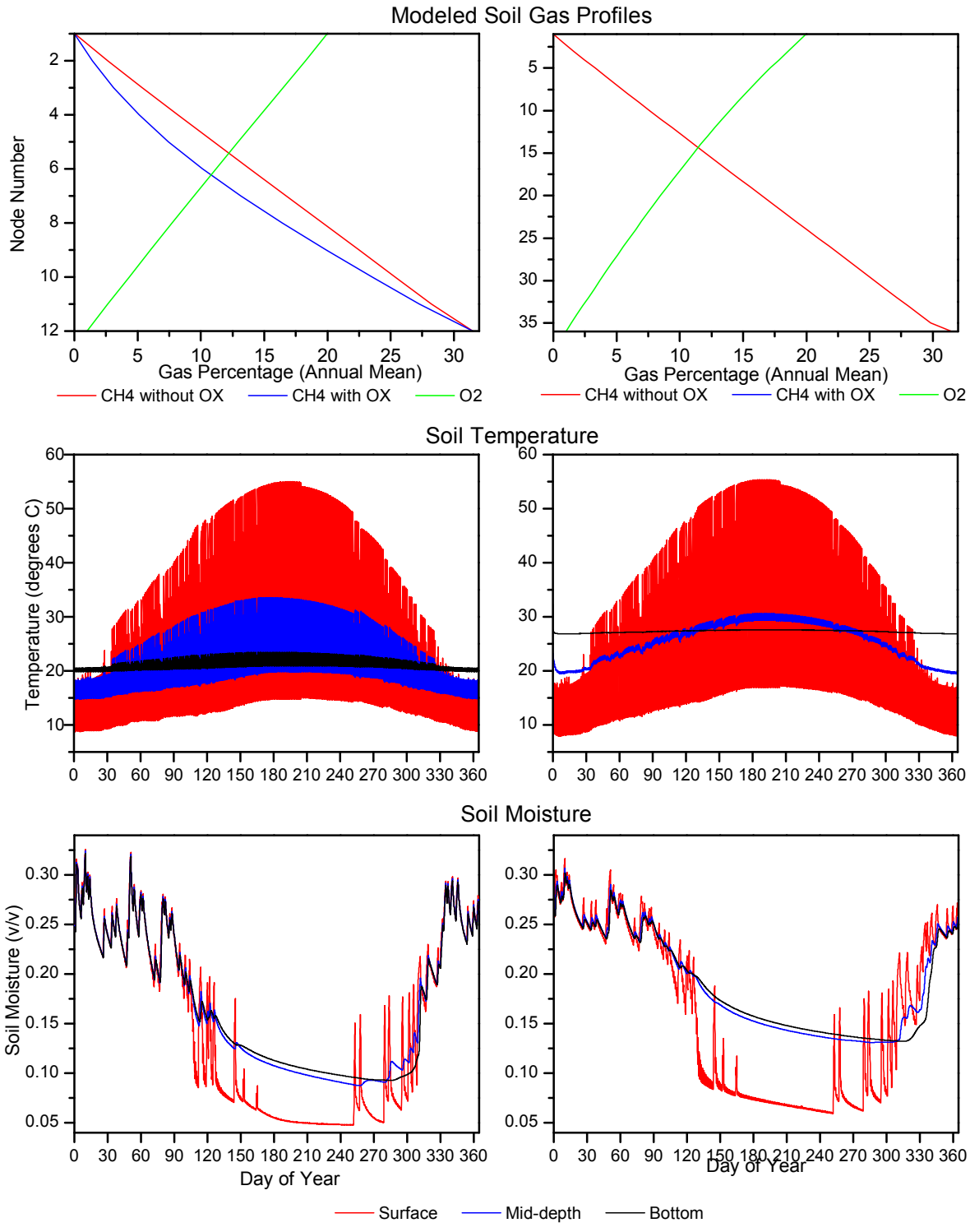

Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom

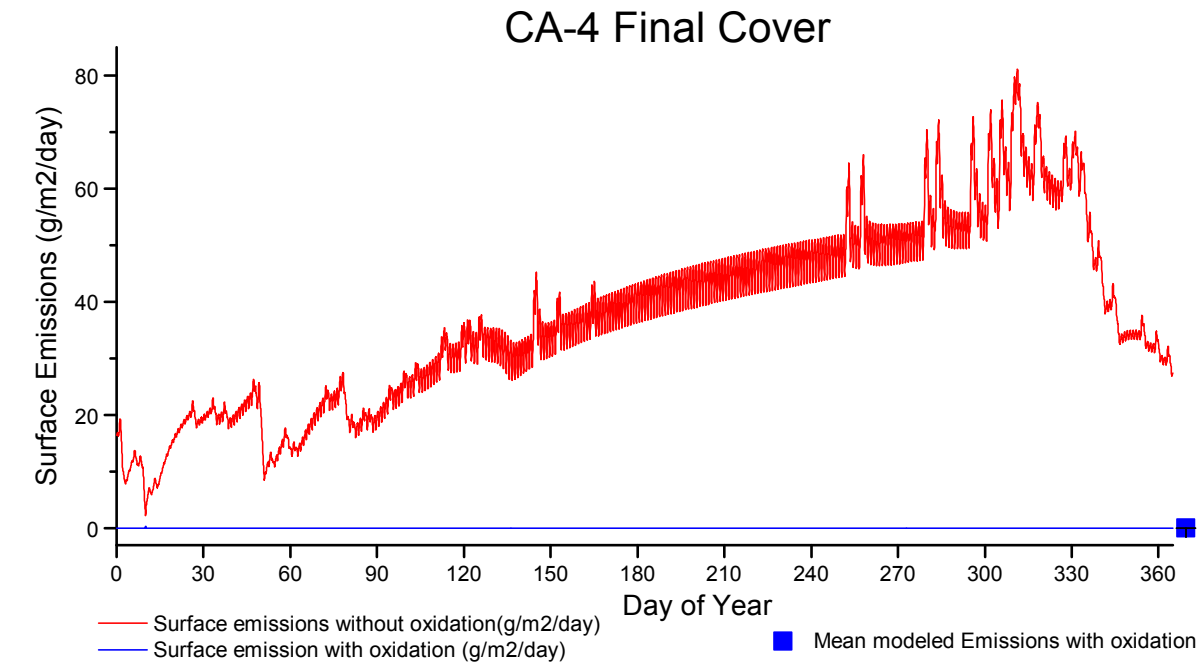

Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

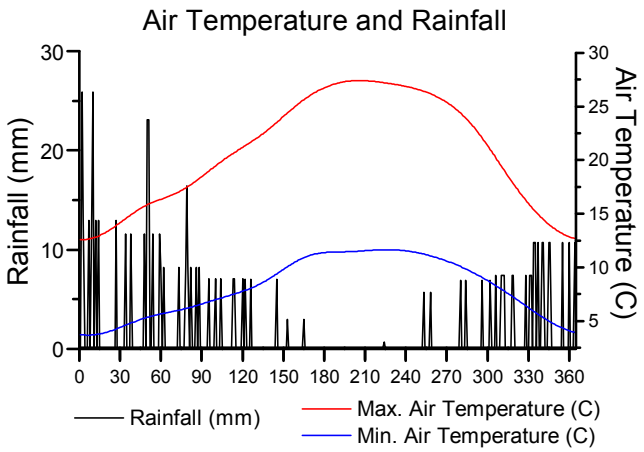

CA-4 Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results:
(min - mean [black border] - max):
June 2009 TDL
Oct. 2009 TDL
Oct 2009 Chamber
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)

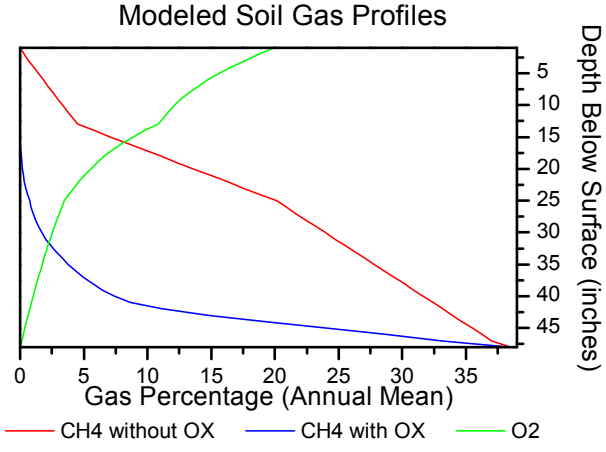
CA-4 Intermediate Cover

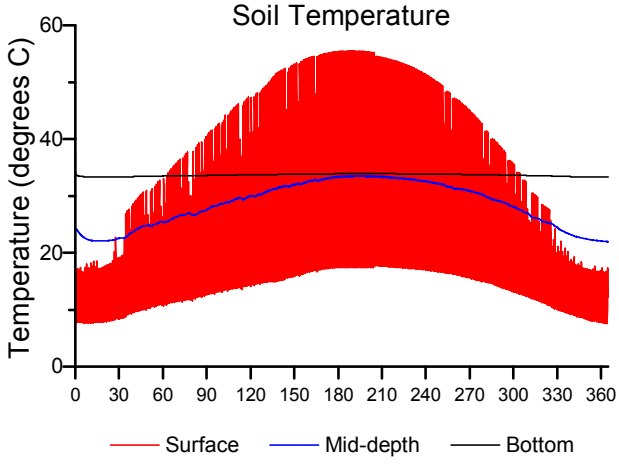
Permitted Minimum Cover Triple Permitted Min. Cover

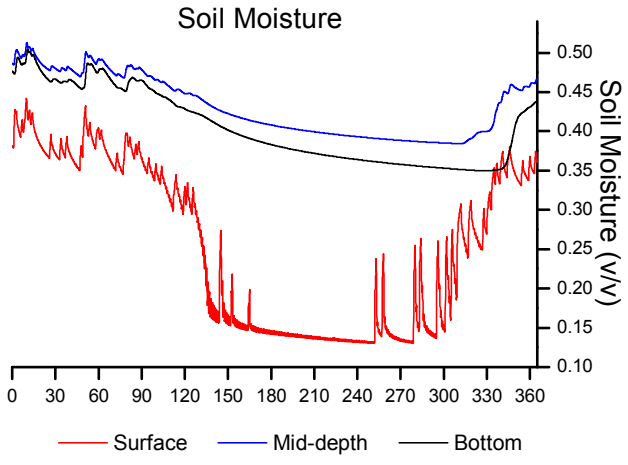



CA-4 Final Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

26. Site CA-5

Site Location: CA

Latitude: 34°44'39.01"N (34.74169)

Longitude: 118° 7'3.28"W (-118.117578)

Total Size: 38 hectares (95 acres)

Site Description: This is a site operated by Waste Management. TDL testing was performed in Sept. 2007 and Jan. 2008 by Waste Management.

Covers	**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**
Hectares (acres)	4 (10)	34 (85)	34 (85)
Cover Type	Daily	Intermediate	**Intermediate**
Coverage % *	34%	33%	33%
Organic Matter %	2.5% (default)	2.5% (default)	2.5% (default)
Gas Recovery %	100%	100%	100%
Vegetation %	0%	0%	0%

* Coverage % is for use in CALMIM

Layers		**Daily**	**Intermediate 12 (permitted minimum depth)**	**Intermediate 36 (3 x permitted minimum)**
1	**Material**	ADC Composted Organic Materials	Sandy Loam	Sandy Loam
	Thickness	6 in	12 in	36 in

Custom Boundaries

(No gas profile data available)

Additional Notes:

The cover descriptions are the standard California covers used for CALMIM modeling.
In order to ensure all covers used the same generated weather the Daily, Intermediate 12, and Intermediate 36 covers were entered into one CALMIM file, with 34%, 33%, and 33% coverage in CALMIM respectively. To get correct total modeled emissions the totals for each cover must be adjusted from the 34% or 33% coverage to the appropriate actual percentages (10.5% daily and 89.5% for the selected intermediate cover).

Field Results:

All field results are from intermediate covers, at the top of the cover (no slope). There are three sections of intermediate cover at this landfill but the particular intermediate cover area (1, 2, or 3) was not specified. Field results are TDL measurements from Waste Management.

Lancaster Recycling and Disposal (Lancaster, CA) Field Results and Modeled Emissions

Source	Mean	Std Dev	Median	Minimum	Maximum	N=
Modeled (CALMIM 5.4) Results (CH_4 g/m^2/day)						
Daily Cover	6.55	2.16	7.42	0.0	9.22	8760
Intermediate (permitted min. depth)	398.01	135.76	456.70	75.01	599.83	8760
Intermediate (3 x permitted min. depth)	28.55	44.01	0.0	0.0	154.96	8760
Field Results (CH_4 g/m^2/day)						
Sept. 2007 (top) (Green, 2011b)	0.904	1.640	0.146	0	8.918	138
Jan. 2008 (top) (Green, 2011b)	3.963	4.103	3.200	0.672	30.268	296

Reported to EPA under mandatory reporting rule (2010 data) *	**MTCO2e ****	**Hectares (Acres) ***
Landfill emissions estimated from methane recovery, destruction and other factors (MTCo2e)		
Landfill emissions estimated from modeled methane generation and other factors (MTCO2e)		

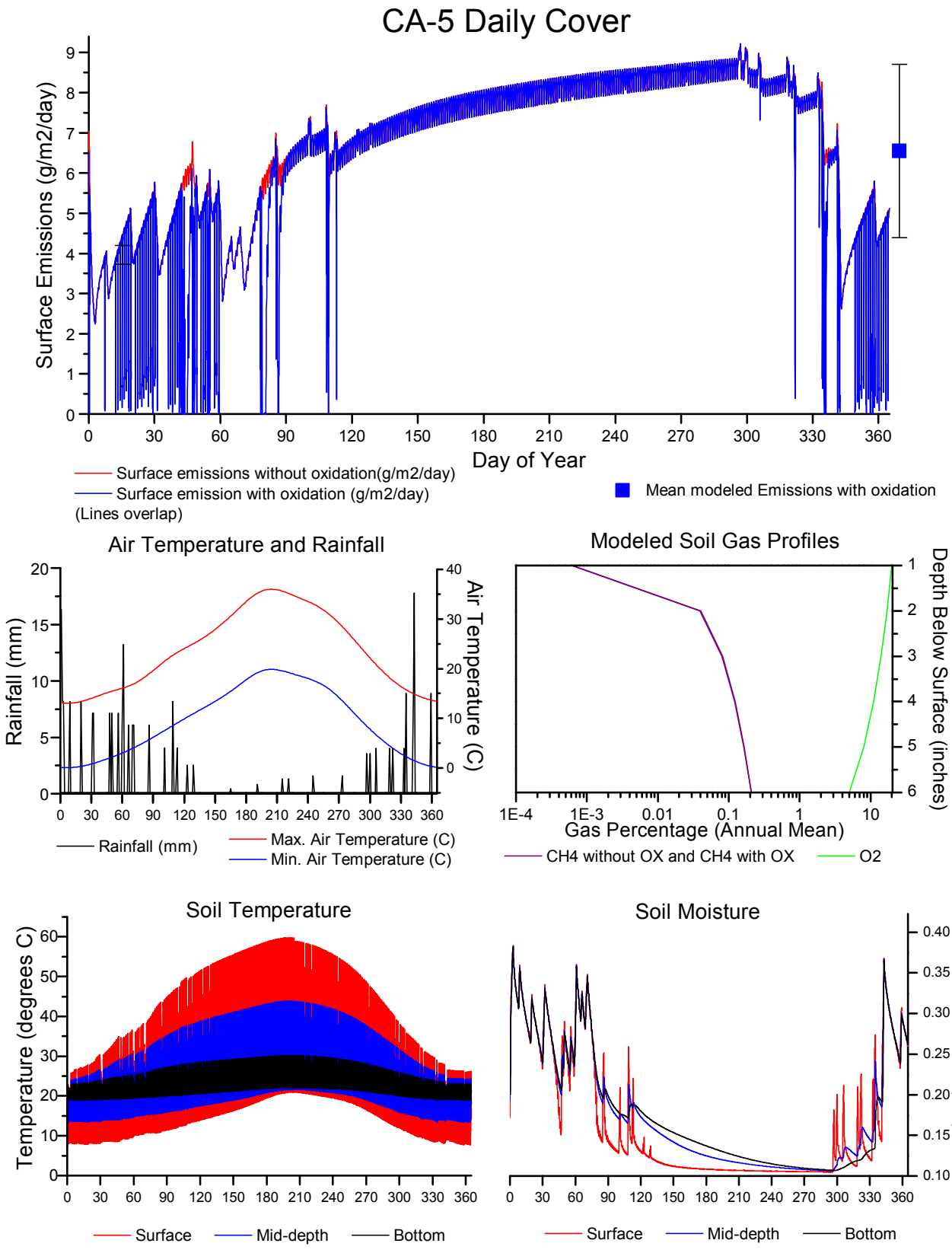
CALMIM Results:	**Gas Recovery %**	**Permitted Minimum Cover CH4 kg/year**	**3 x Permitted Minimum Cover CH4 kg/year**	**Hectares (Acres)**
Daily	100%	98,439	n/a	4 (10)
Intermediate	100%	49,483,017	3,549,420	34 (85)
Total CH4 emissions with oxidation (kg/year) (Sum of emissions for Permitted Daily Cover and selected Intermediate Cover		**49,581,456**	**3,647,859**	**38 (95)**

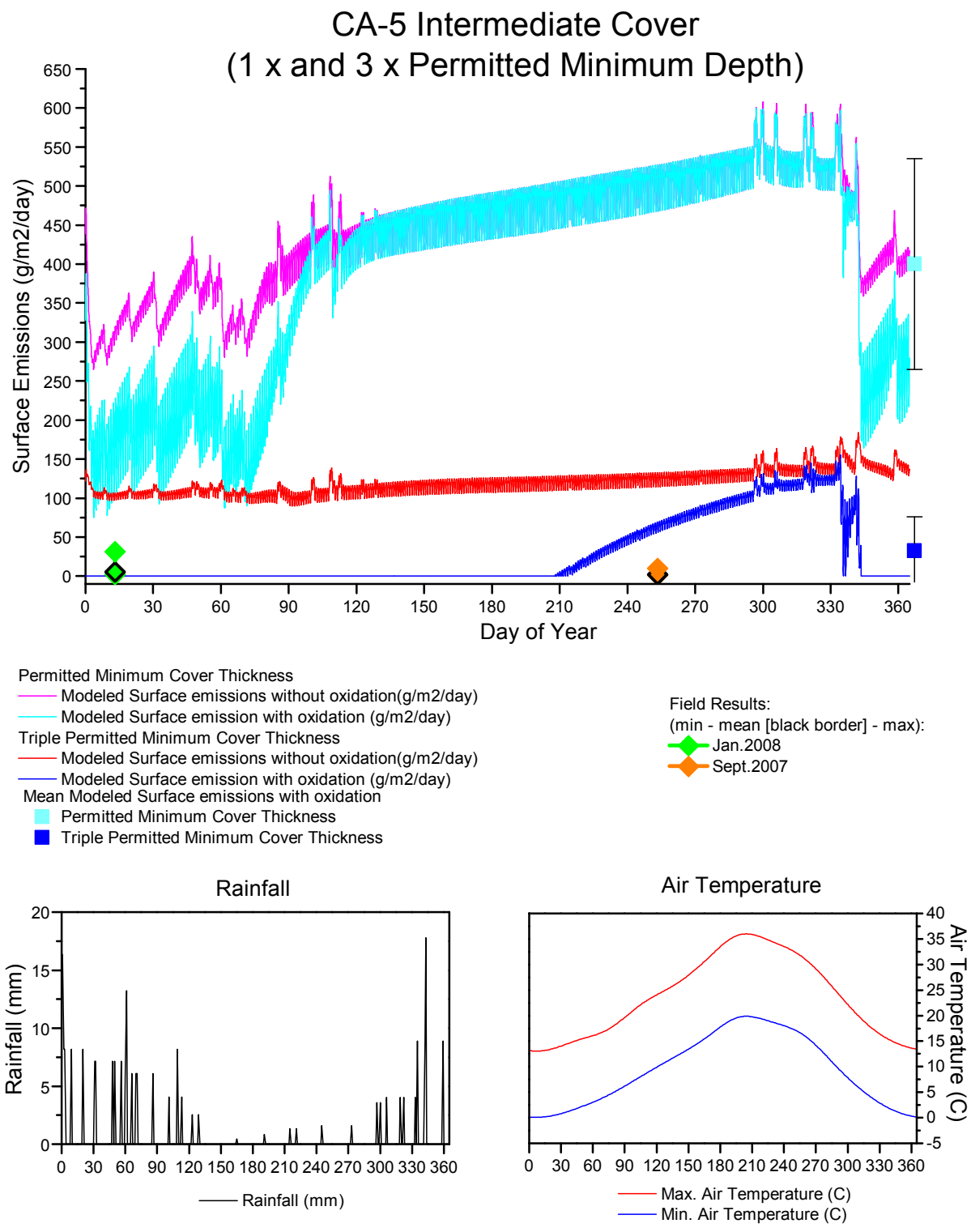
* www.ghgdata.epa.gov. "Surface area containing waste" is given in m^2, converted to hectares and acres here.

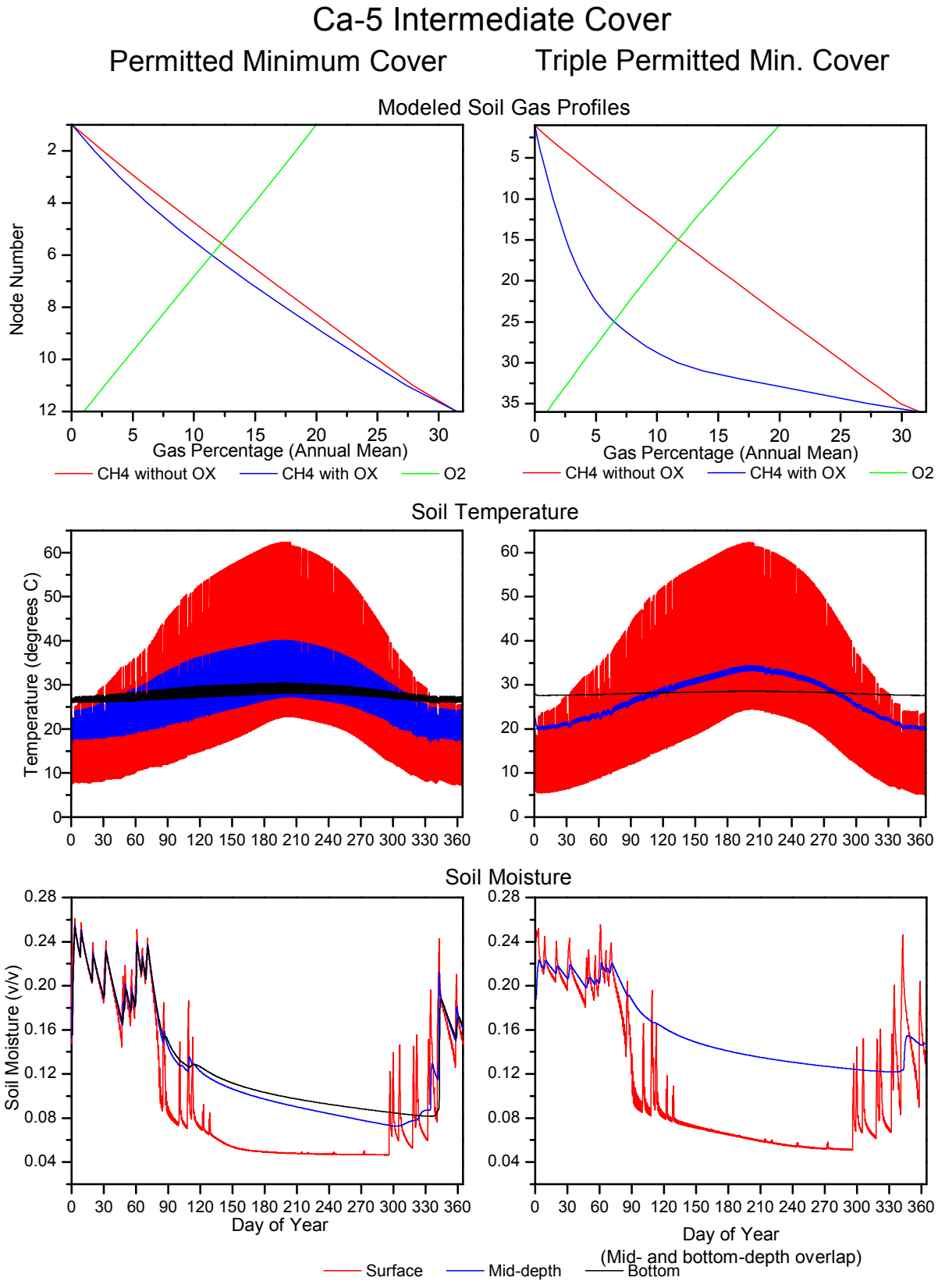
** MTCO2e is metric tons of CO^2 equivalent. CH4 kg/year = MTCO2e*1000/21

References:

Green, R., 2011. TDL Measurements, Sept. 2007 and Jan. 2008. From Roger Green of Waste Management. Data not published.


CA-5 Daily Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX and CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom


CA-5 Intermediate Cover
(1 x and 3 x Permitted Minimum Depth)
Surface Emissions (g/m2/day)
Day of Year
Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Triple Permitted Minimum Cover Thickness
Modeled Surface emissions without oxidation(g/m2/day)
Modeled Surface emission with oxidation (g/m2/day)
Mean Modeled Surface emissions with oxidation
Permitted Minimum Cover Thickness
Triple Permitted Minimum Cover Thickness
Field Results:
(min - mean [black border] - max):
Jan.2008
Sept.2007
Rainfall
Rainfall (mm)
Rainfall (mm)
Air Temperature
Air Temperature (C)
Max. Air Temperature (C)
Min. Air Temperature (C)


Ca-5 Intermediate Cover
Permitted Minimum Cover
Triple Permitted Min. Cover
Modeled Soil Gas Profiles
Node Number
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Soil Moisture
Soil Moisture (v/v)
Day of Year
(Mid- and bottom-depth overlap)
Surface
Mid-depth
Bottom

27. Leon County Landfill

Site Location: Tallahassee, FL

Latitude: 30.42

Longitude: -84.14

Total Size: Unknown

Site Description: This study examined the ability of bio-covers to reduce landfill emissions over existing waste and covers. Two bio-cover test cells were constructed over a thin interim cover, and a third cell with only the thin interim cover was used the control cell. Emissions were tested using static chambers. The bio-covers were made using "chipped wood/mulch," a mixture of ground garden waste and wood chips, and a gas distribution layer made of clean recycled glass chips.

Covers	**No Bio-cover "N" (Control)**	**Deep Bio-cover "D"**
Hectares (Acres)	0.06 (0.14)	0.06 (0.14)
Cover Type	Final	Final
Coverage % *	50%	50%
Organic Matter %	High (5%)	High (5%)
Gas Recovery %	0%	0%
Vegetation %	0%	0%

* Coverage % is for use by CALMIM

Layers		**No Bio-cover "N"**	**Deep Bio-cover "D"**
1	**Material**	Sandy-clay	Chipped-wood mulch Modeled as "ADC Wood Chips" in CALMIM
	Thickness	15cm	60cm
2	**Material**		Glass chips from fluorescent tubes Modeled as "Rocks - Pebbles" in CALMIM
	Thickness		25cm
3	**Material**		Sandy-clay
	Thickness		15cm

Custom Boundaries

None

Additional Notes:

The Shallow Bio-Cover was not modeled in CALMIM.

Field Results:

Field Results (CH_4 g/m^2/day) Median Value, Positive fluxes only (Bogner et al., 2010)			
Date	**No Bio-Cover (N)**	**Shallow Bio-Cover (S)**	**Deep Bio-Cover (D)**
7/6/2004	154.475	3.322	6.214
8/3/2004	247.269	5.754	1.578
9/22/2004	84.612	0.639	6.018
10/29/2004	62.687	36.846	0.956
12/3/2004	89.371	8.764	11.451
1/19/2005	52.202	6.367	5.353
2/16/2005	58.986	92.267	3.060
3/30/2005	70.000	15.689	7.973
4/29/2005	15.980	494.438	11.223
5/24/2005	35.505	13.666	3.734
7/14/2005	110.310	7.271	40.460
8/10/2005	67.208	7.182	24.176
9/14/2005	51.322	135.067	18.671
11/8/2005	33.193	1.137	3.093
1/24/2006	37.545	0.038	0.370
4/18/2006	5.541	1.352	7.353
6/19/2006	32.926	0.579	2.189
7/21/2006	122.537	17.331	4.860

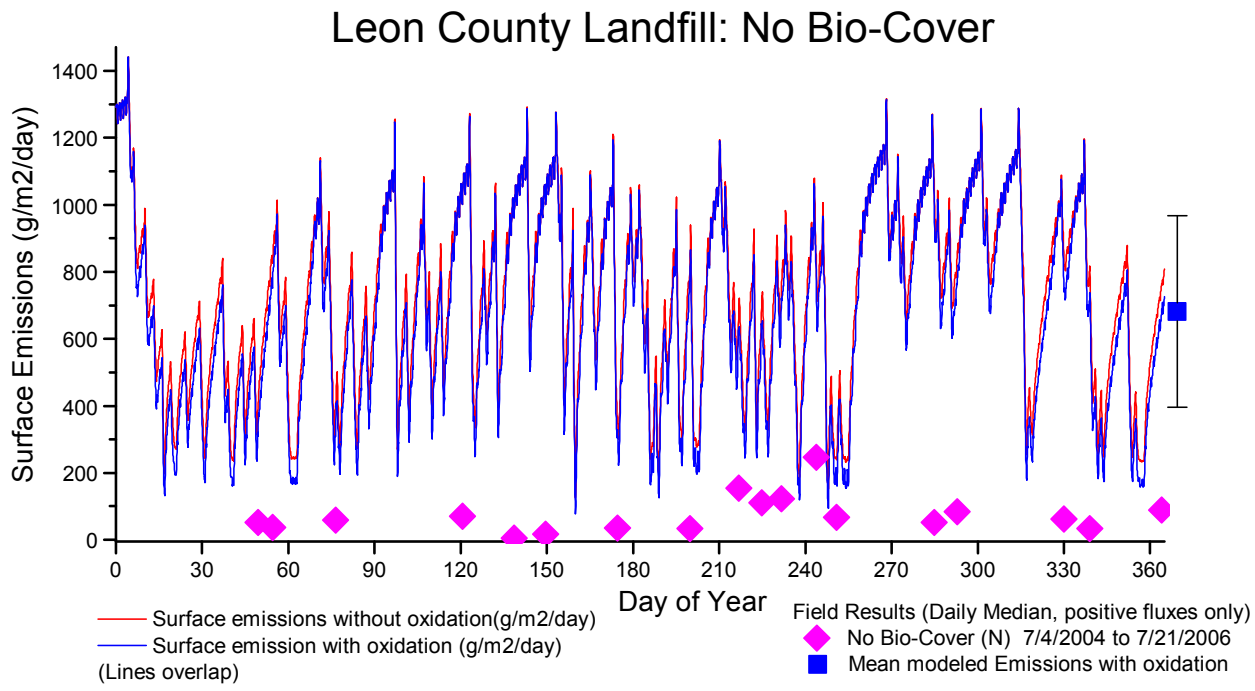
Modeled (CALMIM 5.4) Results. Surface emissions with oxidation. (CH_4 g/m^2/day

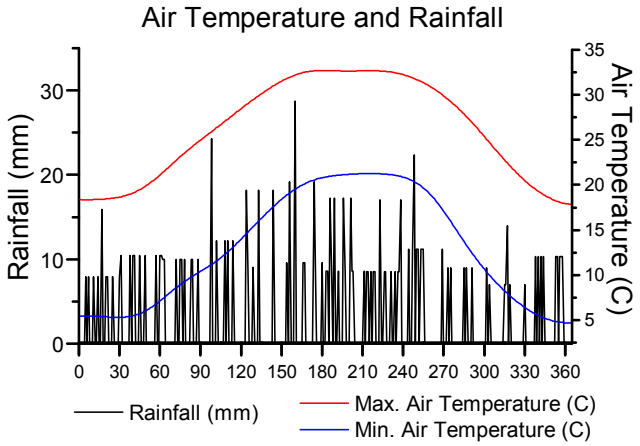
	Mean	SD	Median	Minimum	Maximum	N
Leon County: No Bio-Cover	681.63	285.73	676.23	76.46	1441.98	8760
Leon County:Deep Bio-Cover	0.00	0.00	0.00	0.00	0.00	8760

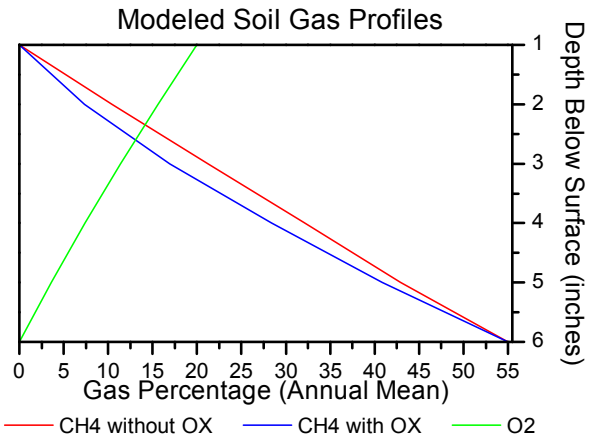
Discussion:

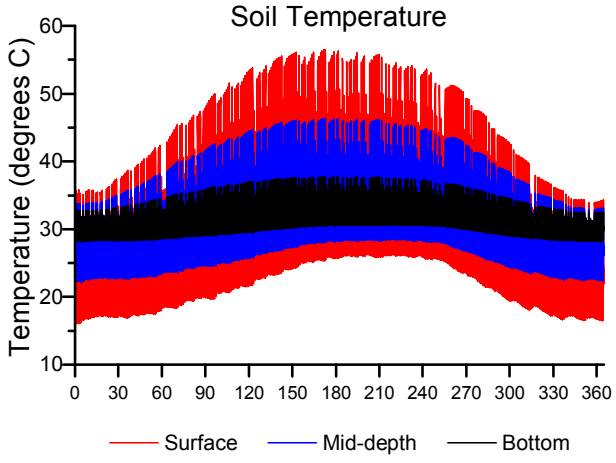
References:

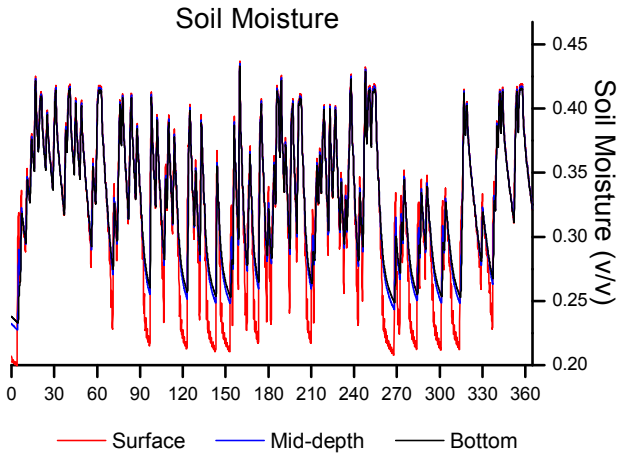
Bogner, J., Chanton, J., Blake, D., Abichou, T., Powelson, D., 2010. Effectiveness of a Florida Landfill Biocover for Reduction of CH_4 and NMHC Emissions. Environmental Science and Technology 44, 1197-1203.


Leon County Landfill: No Bio-Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
(Lines overlap)
Field Results (Daily Median, positive fluxes only)
No Bio-Cover (N) 7/4/2004 to 7/21/2006
Mean modeled Emissions with oxidation


Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)


Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2


Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom


Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

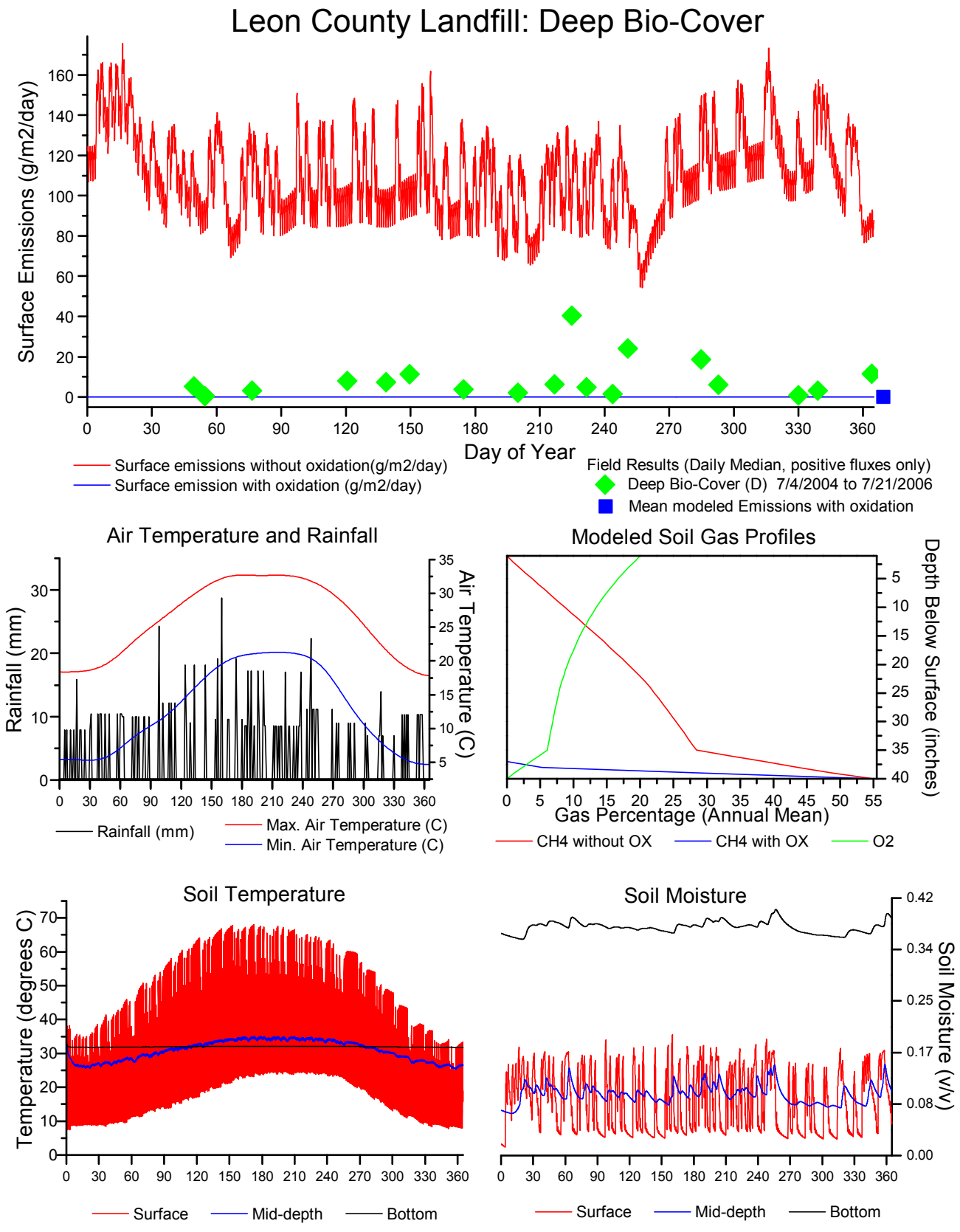

Leon County Landfill: Deep Bio-Cover
Surface Emissions (g/m2/day)
Day of Year
Surface emissions without oxidation(g/m2/day)
Surface emission with oxidation (g/m2/day)
Field Results (Daily Median, positive fluxes only)
Deep Bio-Cover (D) 7/4/2004 to 7/21/2006
Mean modeled Emissions with oxidation
Air Temperature and Rainfall
Rainfall (mm)
Air Temperature (C)
Rainfall (mm)
Max. Air Temperature (C)
Min. Air Temperature (C)
Modeled Soil Gas Profiles
Depth Below Surface (inches)
Gas Percentage (Annual Mean)
CH4 without OX
CH4 with OX
O2
Soil Temperature
Temperature (degrees C)
Surface
Mid-depth
Bottom
Soil Moisture
Soil Moisture (v/v)
Surface
Mid-depth
Bottom

Table D-2 CALMIM modeling results

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
01-AA-0001	37.5923	-122.081	Turk Island Landfill	183.6867	1200000	0
01-AA-0006	37.7144	-122.195	Davis Street	538.9502	4800000	0
01-AA-0008	37.49277	-121.992	Tri-Cities LF	2723.48	10103797	311.8252
01-AA-0009	37.75389	-121.652	Altamont LF	12627.01	44281078	1496.207
01-AA-0010	37.75333	-121.723	Vasco Road LF	2601.021	13093577	1029.612
01-AA-0011	37.8898	-122.311	Albany LF/East Shore Park	152.2134	1000000	0
01-AC-0001	37.87	-122.316	Berkeley LF/Waterfront Park	140.9352	1000000	0
03-AA-0001	38.30315	-120.911	Amador Co. LF	143.0884	750430	0.016986
04-AA-0002	39.67425	-121.729	Neal RD LF	1099.515	3708103	213.1383
05-AA-0014	38.07333	-120.492	Red Hill SLF	80.11954	100000	0.024055
05-AA-0023	38.03398	-120.842	Rock Creek LF	574.1817	779435.7	376.5368
06-AA-0001	39.07096	-122.172	Evans Rd LF-P1	149.5675	200000	4.863602
06-AA-0002	39.36037	-122.545	Stonyford LF	23.63483	23475	29.44771
07-AA-0001	37.972	-122.376	W Contra Costa LF	3185.899	8763337	1256.381
07-AA-0002	38.02532	-122.087	Acme Sanitary LF	1048.868	7103899	726.976
07-AA-0003	37.9875	-121.845	Contra Costa SLF (aka GBF LF)	237.3284	1200000	0
07-AA-0032	38.00472	-121.936	Keller Canyon LF	3269.738	11113595	933.244
08-AA-0006	41.79083	-124.219	Crescent City LF	557.5668	505757	0.154767
09-AA-0003	38.648	-120.83	Union Mine DS	351.0939	1507869	345.6621
09-CR-0015	38.87491	-119.987	Meyers LF	36.55348	100000	66.1545
10-AA-0002	36.6856	-119.94	Chateau Fresno LF	677.1089	3800000	0
10-AA-0004	36.943	-119.685	Clovis LF	237.4769	1289192	91.13836
10-AA-0005	36.6999	-119.829	City of Fresno LF	902.1558	4700000	0
10-AA-0006	36.10972	-120.359	Coalinga DS	408.206	561983.4	2072.628
10-AA-0009	36.66306	-120.145	American Ave.	1649.656	11034902	11207.53
10-AA-0011	36.5943	-119.562	Southeast Regional	142.4703	1300000	0
10-AA-0013	36.68694	-119.761	Orange Ave.	279.3949	1159242	1607.411
10-AA-0018	36.88917	-119.779	Rice Road Disposal Site	2.624453	350000	0
10-AA-0025	36.5513	-119.739	Chestnut Ave DS	246.6424	1000000	0
11-AA-0001	39.63435	-122.283	Glenn County LF	635.0769	875573.7	820.3583
12-AA-0005	40.76167	-124.088	Cummings Road LF	227.1277	1600000	0
12-AA-0022	40.68945	-124.238	Table Bluff LF	57.48621	200000	0.108467
13-AA-0001	32.84552	-115.681	Imperial SWS	16.49321	158998.7	276.9083

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
13-AA-0004	32.6764	-115.546	Calexico DS	357.5729	511965	8287.989
13-AA-0005	32.77389	-116	Ocotillo C&F	15.15158	25000	0
13-AA-0006	32.90472	-115.288	Holtville DS	112.5413	150014	0
13-AA-0007	33.39222	-114.753	Palo Verde C& F	29.1306	50779	0
13-AA-0008	32.99833	-115.53	Brawley LF	332.8062	430333	11526.6
13-AA-0009	33.27111	-115.492	Niland C&F	31.94322	54338	222.802
13-AA-0010	33.41528	-115.676	Hot Spa C&F	30.57699	52071	101.78
13-AA-0011	33.22944	-115.986	Salton City C&F	29.88867	51451	1548.743
13-AA-0012	32.8131	-114.62	Pichacho C&F	69.63298	104223	0
13-AA-0019	32.85792	-115.532	Republic-Imperial	638.128	2499739	4444.701
13-AA-0026	33.05694	-114.994	Mesquite Regional Landfill	78.21749	0	0
14-AA-0003	36.59421	-118.035	Lone Pine DS	64.12681	119072	2151.249
14-AA-0004	36.7884	-118.176	Independence DS	253.5318	109326	192.2166
14-AA-0005	37.32961	-118.4	Bishop Sunland	17.42352	354052	2956.053
14-AA-0006	35.9708	-116.244	Shoshone DS	34.84704	25000	1695.538
14-AA-0007	35.85071	-116.182	Tecopa DS	34.58768	50000	3042.599
14-AA-0016	36.47	-116.86	Furnace Creek	35.7738	50000	0
15-AA-0044	35.41418	-118.949	Bakersfield	160.9287	2000000	0
15-AA-0045	34.99028	-117.648	Boron SLF	70.49006	219751.7	0
15-AA-0047	35.4121	-119.467	Buttonwillow SLF	210.6124	100000	0
15-AA-0048	35.42499	-118.929	China Grade SLF	117.9004	2000000	0
15-AA-0050	35.19009	-118.908	Arvin SLF	27.44022	3500115	8065.369
15-AA-0052	35.6311	-119.757	Lost Hills SLF	73.01658	100000	0
15-AA-0055	35.70974	-118.409	Kern Valley LF	52.77651	250000	0
15-AA-0056	34.82787	-118.888	Lebec LF	60.16811	75000	0
15-AA-0057	35.51042	-119.411	Shafter-Wasco SLF	230.1958	3587442	3961.259
15-AA-0058	34.99336	-118.139	Mojave-Rosamond SLF	420.475	557013	1354.808
15-AA-0059	35.60254	-117.738	Ridgecrest SLF	21.55801	1851819	1466.733
15-AA-0061	35.20377	-119.453	Taft SLF	224.2496	1205498	10174.97
15-AA-0062	35.12362	-118.34	Tehachapi SLF	976.9663	1372266	1575.714
15-AA-0063	35.73526	-119.259	McFarland-Delano LF	24.79483	1000000	0
15-AA-0150	34.95605	-117.956	Edwards AFB Main LF	260.6297	351010	4048.33
15-AA-0273	35.34387	-118.758	Bakersfield SLF (Bena)	930.7061	6605299	10416.71
16-AA-0004	36.01195	-120.115	Avenal LF	1926.781	3001875	8987.608
16-AA-0009	36.30907	-119.596	Hanford LF	331.7666	1750000	0
16-AA-0011	36.13639	-119.576	Corcoran LF	178.0708	300000	0
16-AA-0027	35.96561	-120.012	Kettleman Hills SLF	399.4912	2126109	117.9498

SWIS	Latitude	Longitude	Site Name	CARB 2010	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
17-AA-0001	38.95333	-122.601	Eastlake SLF	1421.719	1284303	279.1396
18-AA-0003	41.13123	-121.147	Bieber LF	31.28781	50000	29.47884
18-AA-0004	41.05	-120.453	Madeline DF	6.462016	10000	1.229025
18-AA-0005	40.79222	-120.371	Ravendale DF	6.462016	10000	1.500571
18-AA-0009	40.35281	-120.555	Bass Hill LF	319.9503	428786	844.7924
18-AA-0010	40.318	-121.023	Westwood DF	41.93621	54482	80.62154
18-AA-0011	40.13669	-120.17	Herlong DF	30.11938	50000	26.72349
18-AA-0013	40.16278	-120.159	Sierra Army Depot	72.40439	100000	114.6211
19-AA-0011	33.8875	-118.26	Compton Disposal Site	95.15403	200000	0
19-AA-0012	34.1575	-118.196	Scholl Canyon LF	6669.748	29409357	4974.116
19-AA-0013	34.117	-117.925	Azusa LF (Zone I)	2340.45	5644688	960.4412
19-AA-0015	34.04111	-117.824	Spadra LF	3592.952	16400000	0
19-AA-0040	34.21018	-118.312	Burbank LF #3	492.9754	2585415	586.1942
19-AA-0050	34.7474	-118.117	Lancaster Waste Mgt.	605.5608	6225912	3612.262
19-AA-0052	34.4295	-118.647	Chiquita Canyon	5915.518	26805620	5915.62
19-AA-0053	34.02033	-118.006	Puente Hills LF	29536.66	1.25E+08	3012.091
19-AA-0056	34.15125	-118.72	Calabasas LF	5264.928	23441895	6804.69
19-AA-0057	34.49884	-118.396	Pitchess Detention Cntr	56.03263	75000	0
19-AA-0061	33.333	-118.31	Pebbly Beach	51.07354	69863.66	71.33773
19-AA-0062	33.43654	-118.506	Two Harbors LF	13.49547	25000	0
19-AA-0063	32.96474	-118.537	US Navy LF (San Clemente Island)	38.81784	53296.33	168.0621
19-AA-0580	34.04825	-118.17	Blanchard Street Dump	82.13428	250000	0
19-AA-0581	34.18178	-118.462	Cogen	289.3175	750000	0
19-AA-0587	34.1	-118.094	Longden Ave Disposal Site	538.5066	1000000	0
19-AA-0778	34.28889	-118.401	Russell Moe Landfill	92.84143	250000	0
19-AA-0819	34.1444	-118.301	Toyon	1038.096	16000000	0
19-AA-0820	34.29371	-118.392	Lopez Canyon LF	3224.328	19200000	6601.762
19-AA-0821	34.12742	-118.491	Mission Canyon #1-3	209.1798	5300000	0
19-AA-0822	34.1066	-118.488	Mission Canyon #4-8	0	21200000	0
19-AA-0835	34.2263	-118.404	Sheldon-Arleta	219.8917	5500000	0
19-AA-0836	34.055	-118.108	Operating Industries (OII) (NPL Site)	2499.479	22000000	0
19-AA-2000	34.32731	-118.515	Sunshine Canyon City/County Landfill	0	23919659	8342.549
19-AA-5100	34.14056	-117.944	City of Duarte LF	25.50548	200000	0

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
19-AA-5321	33.83333	-118.333	Torrance Municipal Dump	57.9948	150000	0
19-AA-5350	34.0269	-118.469	City Of Santa Monica LF #2	98.62556	200000	0
19-AA-5560	34.02778	-117.928	Industry Hills Sheraton Resort	421.1888	3500000	0.269015
19-AA-5624	34.57033	-118.15	Antelope Valley	2367.451	5373691	3558.938
19-AE-0001	33.79444	-118.333	Palos Verdes	7040.034	23600000	0
19-AF-0001	34.03354	-117.905	BKK West Covina (Class I and III LFs)	843.5743	45800000	0.201616
19-AH-0001	33.9799	-118.017	Whittier-Savage Canyon	346.5055	6484566	1163.95
19-AI-0001	33.91111	-118.044	Norwalk Dump	73.08538	563841.7	0.00575
19-AK-0084	33.85606	-118.158	Paramount Dump	94.13874	250000	0
19-AK-5003	33.76848	-118.112	City Dump & Salvage 1 & 3 (includes land Whaler's Cove, Bixby Ranch, The Gas Lamp, and Best Western, The Marina)	28.40017	1000000	0.293041
19-AK-5004	33.765	-118.104	City Dump & Salvage 4	30.29351	75000	0.014662
19-AK-5017	33.75433	-118.106	City Dump & Salvage 2 (The Market Place development)	1129.019	80000	0.003815
19-AQ-0009	33.8504	-118.28	Southwest Conservation District LF	55.47204	534000	0
19-AQ-0010	33.8487	-118.28	Gardena Valley 1 and 2	67.09457	200000	0
19-AQ-0012	33.84413	-118.273	Cal Compact/Metro LF	342.5909	3000000	0.077284
19-AQ-0014	33.85056	-118.278	BKK Carson/Victoria Golf Course	19.57761	3000000	0
19-AQ-0016	33.839	-118.257	Gardena Valley #6 (Don Kott Ford)	3129.731	200000	0
19-AR-0003	33.79922	-118.241	Ascon Sanitary LF	275.3487	2000000	0
19-AR-0006	34.2186	-118.382	Penrose Pit	862.4641	9000000	0
19-AR-0008	34.23993	-118.385	Bradley Ave East & West	6777.651	34498710	0
19-AR-1199	34.23333	-118.411	Branford LF	180.9173	435000	0
19-AR-5036	34.23494	-118.386	Gregg Pit/Pick-Your-Part	48.94404	500000	0

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
19-AR-5068	34.07778	-118.233	Bishop Canyon LF	1013.014	1900000	0
19-CR-5517	34.05	-118.25	Gaffey St.	17.7208	900000	0
20-AA-0002	37.06806	-120.201	Fairmead LF	247.1985	2788245	577.8566
21-AA-0001	38.16564	-122.568	Redwood SLF	4333.472	14143215	1928.069
21-AA-0002	38.09595	-122.789	West Marin SLF	266.7452	240000	0.008847
21-AA-0003	37.95361	-122.49	San Quentin Disposal Site	331.0971	500000	0.02907
21-AA-0047	37.94889	-122.491	Horst Hanf Landfill/Bayview Park	17.14478	50000	0
21-AA-0049	38.05667	-122.517	Hamilton AFB Landfill #26	42.51051	100000	0.038859
22-AA-0001	37.50432	-120.006	Mariposa Co. SLF	400.9106	379461.1	183.4985
23-AA-0003	39.36118	-123.782	Casper Refuse DF	114.4783	150000	0.026817
23-AA-0008	39.64619	-123.455	Laytonville LF	25.51824	50000	0.037775
23-AA-0018	38.83389	-123.544	South Coast Rd LF	48.57366	50000	2.268357
23-AA-0019	39.16944	-123.164	City of Ukiah SWDS	736.9037	750000	29.87925
23-AA-0021	39.44265	-123.353	City of Willits DS	250.2097	250000	0.257854
24-AA-0001	37.39389	-120.498	Hwy 59 DS	888.6548	4743590	3784.09
24-AA-0002	37.03949	-120.972	Billy Wright LF	955.9947	1303009	1240.105
25-AA-0001	41.45861	-120.566	Alturas	65.86781	100000	1317.923
25-AA-0002	41.31667	-120.042	Eagleville	6.257927	10000	1.501054
25-AA-0003	41.87567	-120.156	Fort Bidwell	6.257927	10000	2.888528
25-AA-0004	41.37	-120.083	Lake City	6.257927	10000	4.680581
25-AA-0021	41.54217	-120.006	Cedarville	6.264543	10000	3.777917
26-AA-0001	38.5545	-119.455	Walker SLF	29.7137	51061.94	100.1773
26-AA-0002	38.26979	-119.216	Bridgeport SLF	58.20991	100298.7	36.62885
26-AA-0003	37.90694	-119.065	Pumice Valley	92.60093	154017	1016.533
26-AA-0004	37.68748	-118.781	Benton Crossing	331.3457	490568.6	4100.901
26-AA-0005	37.53077	-118.357	Chalfant SLF	27.87908	50000	5.53553
26-AA-0006	37.81825	-118.469	Benton SLF	76.4275	100000	12.79753
27-AA-0003	36.88083	-121.699	Lewis Rd. LF	116.3841	500000	0
27-AA-0005	36.53167	-121.407	Johnson Cnyn LF	252.9571	1535681	2648.096
27-AA-0006	36.12722	-121.135	Jolon Rd LF	149.4967	200000	0.492084
27-AA-0007	36.803	-121.618	Crazy Horse LF	892.8559	4600000	1224.748
27-AA-0010	36.70961	-121.762	Monterey Peninsula LF	2024.966	8388784	5242.73
27-AA-0012	35.83333	-120.972	Lake San Antonio South Shore LF	15.40843	25000	0
28-AA-0001	38.18056	-122.276	American Canyon LF	614.8521	2500000	0.056859
28-AA-0002	38.584	-122.534	Clover Flat LF	1122.103	971147.6	136.0649

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
28-AA-0003	38.452	-122.183	Berryessa Garbage	28.67505	50000	1.530558
29-AA-0001	39.21667	-121.067	McCourtney Rd LF	185.1116	1000000	0.182817
30-AB-0014	33.7074	-117.999	Gothard Street Landfill	81.02982	300000	0
30-AB-0017	33.63041	-117.844	Coyote Canyon SLF	4856.907	27000000	0
30-AB-0018	33.77639	-117.741	Santiago Canyon SLF	1458.54	11000000	0
30-AB-0019	33.48654	-117.625	Prima Descha SLF	2954.884	23761947	5010.161
30-AB-0026	33.7074	-117.998	City Of Huntington Beach Landfill	226.2527	400000	0
30-AB-0035	33.934	-117.841	Olinda Alpha SLF	13104.52	52017040	6259.49
30-AB-0166	33.832	-117.989	Sparks-Rains LF	22.57449	250000	0
30-AB-0168	33.645	-117.945	Newport Terrace LF	64.1063	150000	0
30-AB-0356	33.78333	-117.933	Longsdon Pit	164.6091	400000	0.00026
30-AB-0360	33.71809	-117.703	Frank R. Bowerman	9692.325	42803585	5403.076
30-AB-0366	33.71809	-117.703	Forster Canyon Landfill	371.9922	750000	0
30-CR-0063	33.50135	-117.648	Lane Road Disposal Station 21	260.2438	584000	0
30-CR-0096	33.66795	-117.832	Cannery Street Disposal Station #16	181.7358	400000	0
31-AA-0110	33.65408	-117.975	Roseville LF	152.219	300000	0
31-AA-0120	38.76318	-121.26	Berry Street Mall LF	68.94768	100000	0
31-AA-0140	38.76531	-121.268	Loomis Landfill	15.27015	500000	0
31-AA-0210	38.83583	-121.345	Western Regional LF	2158.925	5796347	800.2643
31-AA-0220	38.83583	-121.345	Lincoln Disposal Site	20.32204	50000	0
31-AA-0310	38.90083	-121.266	Auburn Sanitary Landfill	175.6373	375000	0
31-AA-0520	38.95526	-121.091	Meadow Vista LF	1.377012	100000	0.114415
31-AA-0530	39.02389	-121.024	Clipper Creek LF	5.764949	10000	0.015306
31-AA-0540	38.97525	-120.846	Foresthill Sanitary Landfill	19.87806	50000	0.012802
31-AA-0550	38.99965	-120.846	Colfax LF	18.2039	25000	0.020334
31-AA-0560	39.0924	-120.941	Eastern Regional LF	80.36817	500000	0.051503
31-AA-0624	39.28563	-120.219	Rocklin Pit	3.556134	10000	23.77682
32-AA-0007	38.7872	-121.227	Portola LF	48.75443	75000	0.006071
32-AA-0008	39.95306	-121.034	Gopher Hill LF	84.05212	75000	23.20318
32-AA-0009	39.95681	-121.041	Chester LF	54.56577	50221.1	31.30223
33-AA-0001	40.32667	-121.138	Tequesquite/City of Riverside	343.8697	2400000	761.3323

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
33-AA-0002	33.9703	-117.411	West Riverside	62.23204	1000000	0
33-AA-0003	34.00638	-117.392	Highgrove LF	432.4162	3000000	0.025
33-AA-0004	34.00667	-117.287	Corona Disposal Site	166.3044	4000000	0
33-AA-0005	33.86823	-117.538	Elsinore	49.16632	250000	0.036893
33-AA-0006	33.95349	-117.118	Badlands DS	1392.579	8753350	80.96672
33-AA-0007	33.88389	-116.997	Lamb Canyon DS	1109.497	7388148	254.1969
33-AA-0008	33.72	-117.108	Double Butte DS	171.4986	3000000	0
33-AA-0009	33.79667	-117.287	Mead Valley DS	284.915	2500000	0.774573
33-AA-0011	33.87858	-116.436	Edom Hill DS	1182.612	6983228	72.28234
33-AA-0012	33.71833	-116.135	Coachella Valley DS	420.0853	2500000	0
33-AA-0013	33.53556	-116.631	Anza DS	78.49276	100000	0
33-AA-0015	33.43923	-116.082	Oasis DS	77.91114	103566.9	5060.253
33-AA-0016	33.77754	-115.409	Desert Center DS	85.56236	150160	117.9162
33-AA-0017	33.7075	-114.631	Blythe DS	21.96574	865611.5	3529.637
33-AA-0071	33.57194	-116.003	Mecca Landfill II	173.2468	220027.9	321.5821
33-AA-0217	33.79923	-117.468	El Sobrante SWLF	3678.868	27821992	1348.287
34-AA-0001	38.51667	-121.187	Kiefer LF	9309.961	19821930	3404.479
34-AA-0004	38.41991	-121.355	Elk Grove LF	58.45832	450000	0
34-AA-0007	38.43333	-121.369	Dixon Pit LF	20.60152	100000	0
34-AA-0016	38.54055	-121.411	14th Avenue Landfill (East/West Pits)	119.7247	250000	0
34-AA-0018	38.58736	-121.456	Sacramento City LF	889.6897	4000000	0
34-AA-0020	38.528	-121.378	L & D LF	3292.487	4166226	5369.435
34-AA-0023	38.48533	-121.305	Gerber Road LF	238.4102	560000	0
34-CR-5047	38.55861	-121.43	Elvas Avenue DS	28.41912	75000	0
35-AA-0001	36.82476	-121.323	John Smith Road SWDS	224.3908	1565464	352.6614
36-AA-0005	34.11667	-117.64	Upland LF	64.22116	550000	0.013396
36-AA-0017	34.08861	-117.221	California St. LF	343.6419	1888217	1138.625
36-AA-0026	34.64206	-117.295	Oro Grande	62.57927	100000	0
36-AA-0039	34.81	-116.645	Newberry	15.40843	25000	0
36-AA-0041	35.67519	-117.352	Trona Angus LF	120.4333	200000	0
36-AA-0042	34.23428	-117.147	Heaps Peak SWDS	53.22846	100000	0.032778
36-AA-0044	34.425	-117.612	Phelan RDS	240.5367	300000	0
36-AA-0045	34.59333	-117.27	Victorville RDS	294.1543	5397557	2526.177
36-AA-0046	34.83617	-117.018	Barstow RDS	112.5491	1900773	861.5023
36-AA-0047	34.86867	-116.684	Yermo DS	70.93669	100000	0
36-AA-0048	34.53724	-117.112	Apple Valley DS	250.2757	300000	0

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
36-AA-0049	35.49591	-116.142	Baker RDS	42.8264	75000	0
36-AA-0050	34.38647	-117.317	Hesperia RDS	100.4416	750000	0
36-AA-0051	34.04538	-117.346	Colton LF	1231.393	6728365	637.5747
36-AA-0052	34.0437	-117.064	Yucaipa SWDS	67.99674	500000	10.11498
36-AA-0053	34.14833	-117.337	Cajon SWDS	988.2303	1950000	0.089993
36-AA-0054	34.03525	-117.591	Milliken	1625.93	12000000	0.050579
36-AA-0055	34.14328	-117.428	Fontana RDS (Mid-Valley)	3080.996	12434442	1123.433
36-AA-0056	34.30603	-116.82	Big Bear RDS	520.9504	450000	2749.225
36-AA-0057	34.23776	-116.37	Landers DS	876.133	1185509	735.3631
36-AA-0058	34.0914	-116.603	Morongo DS	80.18382	100000	6.125275
36-AA-0059	34.83213	-114.7	Needles Sanitary LF	71.19016	100000	0
36-AA-0060	34.45648	-116.136	Twentynine Palms DS	239.1866	300000	0
36-AA-0061	35.17807	-117.249	Lenwood-Hinkley	178.644	250000	0
36-AA-0062	34.4307	-116.854	Lucerne Vlly	35.16564	50000	0
36-AA-0067	34.24833	-116.064	USMC- 29 Palms	128.2241	197663.1	2864.281
36-AA-0068	35.26589	-116.662	Fort Irwin	211.3844	298868.6	15882.35
36-AA-0084	35.3054	-116.799	Goldstone Echo (Military)	16.34206	25000	0
36-AA-0087	34.01283	-117.215	San Timoteo SWDS	280.1448	3772065	540.7351
36-AA-0312	34.10517	-117.216	Norton AFB LF	32.47685	250000	0.324055
36-AA-0318	35.31313	-115.384	Mountain Pass Mine and Mill	12.32675	20000	0
36-CR-0059	34.07082	-117.273	Waterman LF	26.54795	300000	1.500756
37-AA-0001	32.73333	-116.943	Jamacha	20.31327	1800000	0
37-AA-0002	33.23667	-117.07	Valley Center	14.37825	130000	0
37-AA-0004	33.2412	-117.18	Bonsall	106.8152	200000	0
37-AA-0005	33.0863	-116.862	Ramona LF	219.6144	1809103	1580.119
37-AA-0006	33.24667	-116.293	Borrego Springs LF	182.288	293349.9	817.0866
37-AA-0008	33.07833	-117.165	San Marcos LF	2219.282	6000000	0
37-AA-0010	32.60333	-117.005	Otay SWLF	8322.516	26355216	2832.482
37-AA-0016	33.04	-117.243	Encinitas	89.58759	585000	0
37-AA-0017	32.65667	-117.098	Duck Pond	7.521495	80000	0
37-AA-0018	32.96833	-117.018	Poway	24.59488	165000	0
37-AA-0019	32.82	-116.988	Gillespie	43.09727	165000	0
37-AA-0020	32.856	-117.162	Miramar SWLF	6732.816	32115735	15657.18
37-AA-0022	32.73333	-117.06	South Chollas	627.0912	3000000	0
37-AA-0023	32.86232	-117.025	Sycamore SW LF	3444.657	17757893	3315.669
37-AA-0026	32.76333	-117.217	Mission Bay Landfill #1	291.8179	750000	0

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
37-AA-0027	32.69333	-117.03	Hillsborough	6.62362	350000	0
37-AA-0033	32.83667	-117.153	South Miramar Sanitary Landfill	47.90877	3000000	0
37-AA-0429	32.73667	-117.137	Arizona St.	332.3423	2000000	0
37-AA-0434	32.68667	-117.05	Paradise Park/Sweetwater III	91.74471	200000	0
37-AA-0901	33.3	-117.345	Box Canyon LF	271.078	500000	0
37-AA-0902	33.39667	-117.54	San Onofre LF	95.56099	153560.4	1076.975
37-AA-0903	33.36444	-117.419	Las Pulgas LF	701.4567	958357.1	3280.438
37-AH-0002	33.12667	-117.282	Palomar Airport	114.4449	1000000	0
37-AK-0001	33.20833	-117.36	Mission Ave. SLF	21.17719	200000	0
37-AK-0006	33.2	-117.367	Maxon St.	13.99708	150000	0
37-AO-0009	33.13904	-117.203	Old San Marcos	160.8468	400000	0
37-CR-0088	32.68708	-117.038	Bell Jr. High/Sweetwater II	15.15434	250000	0
39-AA-0002	37.91431	-121.29	French Camp LF	383.6913	400000	0.052801
39-AA-0003	38.0994	-121.136	Harney Lane LF	328.0567	2000000	0
39-AA-0004	38.03778	-120.937	Foothill LF	976.0747	5085567	1790.517
39-AA-0005	37.67	-121.457	Corral Hollow	93.73047	750000	0
39-AA-0015	37.87417	-121.188	Forward LF (+ Austin Rd LF - 0001)	1987.695	19330965	2287.064
39-AA-0022	38.097	-121.102	North County LF	549.8854	2751741	652.8362
40-AA-0001	35.66314	-120.532	Paso Robles LF	290.5645	1740941	718.0066
40-AA-0002	35.77509	-120.734	Camp Roberts SWDS	127.4735	200000	660.8322
40-AA-0004	35.1873	-120.596	Cold Canyon	620.9456	4428005	564.5447
40-AA-0008	35.52333	-120.63	Chicago Grade	215.5801	1172273	313.1916
40-AA-0009	35.28578	-120.832	Camp San Luis Obispo	33.19503	50000	0
40-AA-0014	35.30778	-120.025	California Valley LF	16.15504	25000	0
41-AA-0002	37.50057	-122.411	Corinda Los Trancos LF (Ox Mtn)	6226.25	19019665	848.0619
41-AA-0003	37.6735	-122.387	Sierra Point	191.0259	500000	0
41-AA-0007	37.6766	-122.468	Junipero Serra Solid Waste DS	60.68001	450000	0
41-AA-0008	37.683	-122.444	Hillside LF	458.5569	1794183	311.2951
41-AA-0009	37.56867	-122.363	Burlingham LF	167.494	1000000	0
41-AA-0010	37.5708	-122.277	San Mateo Composting (3rd Ave.)	303.6394	500000	0
41-AA-0011	37.4929	-122.176	Marsh Road	506.8632	3524629	0
42-AA-0010	34.59167	-120.027	New Cuyama	32.31008	50000	0

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
42-AA-0011	34.69417	-120.132	Foxen LF	51.83295	750000	0
42-AA-0012	34.7197	-120.524	Vandenburg AFB	251.3251	328390.6	1291.476
42-AA-0015	34.48151	-120.126	Tajiguas LF	1967.215	9377430	2522.637
42-AA-0016	34.95152	-120.38	City of Santa Maria LF	148.1323	3695790	1562.13
42-AA-0017	34.62555	-120.483	Lompoc LF	215.9584	1246858	1257.465
42-CR-0014	34.60749	-120.075	Santa Ynez Airport LF	5.396519	50000	0
42-CR-0015	34.61517	-120.15	Ballard Canyon	20.49405	50000	0
43-AA-0004	36.99577	-121.479	Pacheco Pass LF	290.6844	2070983	582.35
43-AA-0006	37.42621	-122.084	Shoreline-Mtn. View (Vista)	325.6957	2000000	0
43-AA-0007	37.4184	-122.008	Sunnyvale LF	411.9359	2300000	0
43-AM-0001	37.44932	-122.107	Palo Alto RDS	318.2587	2589128	94.65744
43-AN-0003	37.45897	-121.941	Newby Island	4106.24	18678727	256.1485
43-AN-0007	37.43325	-121.957	Zanker Rd. LF	180.238	1045969	201.9781
43-AN-0008	37.18507	-121.671	Kirby Canyon LF	2402.703	7312751	1001.822
43-AN-0011	37.28667	-121.815	Hellyer Park LF	53.96519	500000	0
43-AN-0015	37.21481	-121.898	Guadalupe SLF	2762.783	5273156	415.927
43-AO-0001	37.41639	-121.971	All Purpose LF	363.3166	2000000	0
44-AA-0001	36.97602	-122.106	City of Santa Cruz LF	831.0469	2059131	206.2836
44-AA-0002	36.914	-121.824	City of Watsonville	295.0902	1182946	182.1558
44-AA-0003	37.09375	-122.075	Ben Lomond WDS	111.4455	750000	0
44-AA-0004	36.91738	-121.811	Buena Vista DS	1561.034	3545628	400.814
45-AA-0019	40.57	-122.407	Redding SLF (Benton)	138.4949	750000	18.27756
45-AA-0020	40.41639	-122.36	Anderson LF	849.9717	2662141	74.97389
45-AA-0021	40.47833	-122.217	Simpson Paper Company	295.8492	400000	5.574347
45-AA-0022	40.93584	-121.669	Intermountain LF	27.85942	25000	1.78527
45-AA-0043	40.48156	-122.535	West Central	3175.595	2639174	136.4196
45-AA-0058	40.49722	-122.197	Twin Bridges	214.1894	200000	27.20439
46-AA-0001	39.67	-120.22	Loyalton LF	67.32864	93344.29	55.97813
47-AA-0001	41.24667	-122.123	McCloud	27.24343	50000	5.444804
47-AA-0002	41.70031	-122.598	Yreka LF	187.1603	240190	526.03
47-AA-0003	41.35278	-122.345	Black Butte SWDS	153.4982	150000	103.4778
47-AA-0019	41.43167	-122.348	Weed SWDS	28.50477	25000	23.00358
47-AA-0026	41.78	-123.4	Happy Camp SWDS	6.415783	10000	7.566055
47-AA-0027	41.99167	-121.6	Tulelake SWDS	47.69379	75000	32.40136
47-AA-0029	41.32667	-123.153	Kelly Gulch LF	6.180074	10000	2.626728

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
47-AA-0030	41.15278	-123.133	Cecilville LF	7.079328	10000	0.086402
47-AA-0031	41.7	-121.467	Lava Beds LF	6.357369	10000	6.605442
47-AA-0035	41.59167	-121.905	New Tenant SWDS	35.88188	50000	44.28364
47-AA-0044	41.43833	-123.48	Rogers Creek LF	6.180074	10000	2.54247
47-AA-0045	41.23833	-123.274	Hotelling Gulch LF	7.079328	10000	0.257196
48-AA-0001	38.22694	-121.978	Solano Garbage Company	458.4422	750000	0
48-AA-0002	38.312	-121.837	Hay Road Landfill	357.0231	4627309	1352.931
48-AA-0004	38.1775	-121.689	Rio Vista	60.72647	100000	0
48-AA-0075	38.21188	-121.981	Potrero Hills	2941.45	11798655	1875.526
49-AA-0001	38.29964	-122.75	Central LF	2726.385	11186958	410.8724
49-AA-0002	38.70667	-123.339	Annapolis LF	52.67139	75000	0.004698
49-AA-0004	38.65028	-122.865	Healdsburg	140.5957	500000	0.176639
50-AA-0001	37.38816	-121.136	Fink Rd LF	268.819	3263170	1038.331
50-AA-0002	37.62609	-120.85	Geer Road LF	82.16574	500000	0
50-AA-0003	37.60566	-121.037	Bonzi LF	134.3935	826830.7	3050.235
52-AA-0001	40.19565	-122.297	Red Bluff LF	273.3805	1287514	66.44498
53-AA-0013	40.74389	-122.925	Weaverville LF	156.1712	150000	8.995766
54-AA-0001	35.91989	-119.267	Earlimart DS	34.4098	200000	1584.862
54-AA-0002	36.22956	-119.152	Exeter DS	303.6394	500000	3126.889
54-AA-0004	36.02111	-119.106	Teapot Dome DS	141.7205	1890725	2070.832
54-AA-0008	36.15056	-119.231	Woodville DS	543.3984	2933226	5566.207
54-AA-0009	36.39222	-119.392	Visalia DS	645.0803	3241649	11076.34
54-AA-0010	35.81067	-118.654	Balance Rock DS	74.91643	100000	0
54-AA-0011	35.991	-118.105	Kennedy Meadows DS	16.8941	25000	21.3845
54-AA-0012	36.56111	-119.194	Orosi Disposal Site	31.881	50000	439.5781
55-AA-0001	37.8075	-120.225	Big Oak Flat LF	28.51479	25000	0.191063
55-AA-0002	37.94833	-120.402	Tuolumne Central (Jamestown)	537.4251	750000	0.008403
55-AA-0005	37.88958	-120.534	Sierra Conservation Center	23.41831	50000	0.059768
56-AA-0004	34.229	-119.203	Coastal LF (including Santa Clara LF)	627.5215	4000000	0
56-AA-0005	34.4025	-118.998	Toland Rd. LF	2422.933	6054447	3333.698
56-AA-0007	34.29454	-118.795	Simi Valley LF	4155.177	16641305	5309.809
56-AA-0008	33.24778	-119.505	Pacific Missile TC LF	30.81687	50000	0
56-AA-0011	34.22501	-119.17	Bailard LF	967.5609	4000000	0
56-AA-0125	34.27855	-118.811	Tierra Rejada	173.528	400000	1.507651

SWIS	Latitude	Longitude	Site Name	CARB 2010 estimated emissions MT CH4/year (after removing CO2E multiplier)	2010 Waste-In-Place WIP (tons)	CALMIM (Mg/yr)
57-AA-0001	38.59028	-121.692	Yolo Co. Central LF	1667.84	6455584	1353.729
57-AA-0004	38.52972	-121.806	UC Davis LF	14.93466	367258.8	50.37376
58-AA-0001	39.1	-121.38	Beale AFB LF	144.5353	200000	0
58-AA-0002	39.46667	-121.29	Ponderosa SLF	36.06821	75000	0
58-AA-0005	39.1671	-121.557	Yuba Sutter Disposal Inc. LF (YSDI)	116.3289	2500000	0
58-AA-0006	39.16333	-121.558	Yuba Sutter Disposal Area LF (YSDA)	94.06463	150000	0
58-AA-0011	39.07306	-121.394	Ostrom Road SLF	791.0121	3340557	670.7947

Table D-3. Comparison of the top ten CALMIM emitting California sites

SWIS	Latitude	Longitude	Site Name	ARB 2010 estimated emissions MT CH4/year	CALMIM	% Final Cover	% Intermediate Area	Recovery?
36-AA-0068	35.26589	-116.662	Fort Irwin		15882.35	0.00	**84**	**False**
37-AA-0020	32.856	-117.162	Miramar SWLF	6733	15657.18	0.00	**98**	True
13-AA-0008	32.99833	-115.53	Brawley LF	333	11526.60	0.00	**100**	**False**
10-AA-0009	36.66306	-120.145	American Ave.	1650	11207.53	0.00	**96**	True
54-AA-0009	36.39222	-119.392	Visalia DS	645	11076.34	0.00	**94**	**False**
15-AA-0273	35.34387	-118.758	Bakersfield SLF (Bena)	931	10416.71	0.00	**93**	True
15-AA-0061	35.20377	-119.453	Taft SLF	224	10174.97	0.00	**88**	**False**
16-AA-0004	36.01195	-120.115	Avenal LF	1927	8987.61	0.00	**92**	**False**
19-AA-2000	34.32731	-118.515	Sunshine Canyon City/County Landfill	0	8342.55	0.00	**97**	True
13-AA-0004	32.6764	-115.546	Calexico DS	358	8287.99	0.00	**74**	**False**
15-AA-0050	35.19009	-118.908	Arvin SLF	27	8065.37	0.00	**100**	True

Notes: Percent cover area was calculated from the given intermediate/final as well as waste footprint areas in the database.

Table D-4. Comparison of the top ten CARB emitting California sites.

SWIS	Latitude	Longitude	Site Name	ARB 2010 estimated emissions (Mg CH4/yr)	CALMIM (Mg CH_4/yr)	% Final Cover	% Intermediate Area	Recovery?
19-AA-0053	34.02	-118	Puente Hills LF	29537	3012.09	**81.00**	**17**	True
30-AB-0035	33.934	-117.8	Olinda Alpha SLF	13105	6259.49	**0.00**	**98**	True
01-AA-0009	37.754	-121.7	Altamont LF	12627	1496.21	**15.32**	**80**	True
30-AB-0360	33.718	-117.7	Frank R. Bowerman	9692	5403.08	**0.00**	**96**	True
34-AA-0001	38.517	-121.2	Kiefer LF	9310	3404.48	**13.60**	**82**	True
37-AA-0010	32.603	-117	Otay SWLF	8323	2832.48	**9.57**	**86**	True
19-AE-0001	33.794	-118.3	Palos Verdes	7040	0.00	**100.00**	**-**	True
19-AR-0008	34.24	-118.4	Bradley Ave East & West	6778	0.00	**100.00**	**-**	True
37-AA-0020	32.856	-117.2	Miramar SWLF	6733	15657.18	**0.00**	**98**	True
19-AA-0012	34.158	-118.2	Scholl Canyon LF	6670	4974.12	**28.64**	**69**	True

Notes: Percent cover area was calculated from the given intermediate/final as well as waste footprint areas in the database.