

ห้องสมุดงานวิจัย สำนักงานคณะกรรมการการวิจัยแห่งชาติ



E42133

**FULL CARBON ACCOUNTING IN BIOENERGY PRODUCTION
FROM SUGARCANE**

**MISS MONTHIRA YUTTITHAM
ID: 47022021**

**A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN ENVIRONMENTAL TECHNOLOGY**

**THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT
AT KING MONKUT'S UNIVERSITY OF TECHNOLOGY THONBURI**

2ND SEMESTER 2009

COPYRIGHT OF THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT

600256258

ห้องสมุดงานวิจัย สำนักงานคณะกรรมการการวิจัยแห่งชาติ



**FULL CARBON ACCOUNTING IN BIOENERGY PRODUCTION
FROM SUGARCANE**

**MISS MONTHIRA YUTTITHAM
ID: 47922021**



**A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN ENVIRONMENTAL TECHNOLOGY**

**THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT
AT KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI**

2ND SEMESTER 2009

COPYRIGHT OF THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT

Full Carbon Accounting in Bioenergy Production from Sugarcane



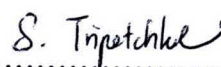
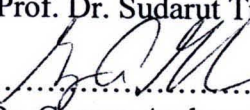
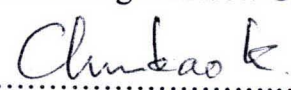
Miss Monthira Yuttitham
ID 47922021

A Thesis Submitted as a Part of the Requirements
for the Degree of Doctor of Philosophy in Environmental Technology

The Joint Graduate School of Energy and Environment
at King Mongkut's University of Technology Thonburi

2nd Semester 2009

Thesis Committee

 (Asst. Prof. Dr. Amnat Chidthaisong)	Chairman
 (Assoc. Prof. Dr. Shabbir H. Gheewala)	Member
 (Asst. Prof. Dr. Sudarut Tripetchkul)	Member
 (Dr. George Andrew Gale)	Member
 (Prof. Dr. Kasem Chunkao)	External Examiner

Thesis Title: Full Carbon Accounting in Bioenergy Production from Sugarcane

Student name

Miss Monthira Yuttitham,
The Joint Graduate School of Energy and Environment,
at King Mongkut's University of Technology Thonburi,
Telephone: 02-8704091, 085-4832009
E-mail: monthira_y@yahoo.com

Supervisor' name

Asst. Prof. Dr. Amnat Chidthaisong,
The Joint Graduate School of Energy and Environment,
at King Mongkut's University of Technology Thonburi,
Telephone: 02-4708309 ext. 4119 Fax. 02-8729805
E-mail: amnat_c@jgsee.kmutt.ac.th

Member

Assoc. Prof. Dr. Shabbir H. Gheewala,
The Joint Graduate School of Energy and Environment,
at King Mongkut's University of Technology Thonburi,
Telephone: 02-4708309 ext. 4139 Fax. 02-8729805,
E-mail: shabbir_g@jgsee.kmutt.ac.th

Member

Asst. Prof. Dr. Sudarut Tripetchkul,
Natural Resources Management, School of Bioresources and Technology,
at King Mongkut's University of Technology Thonburi,
Telephone: 02-4707556, Fax. 02-4523455,
E-mail: sudarut.tri@kmutt.ac.th

Member

Dr. George Andrew Gale,
Natural Resources Management, School of Bioresources and Technology,
at King Mongkut's University of Technology Thonburi,
Telephone: 02-4707555, Fax. 02-4523455,
E-mail: george.and@kmutt.ac.th

External Examiner

Prof. Dr. Kasem Chankaew
College of Environment, Kasetsart University,
Telephone: 02-5792116 ext. 105
E-mail: ecksc@ku.ac.th

Topic: Full Carbon Accounting in Bioenergy Production from Sugarcane

Name of student: Ms. Monthira Yuttitham

Student ID: 47922021

Name of Supervisor: Asst. Prof. Dr. Amnat Chidthaisong

ABSTRACT

E 42133

This research study is focused on carbon dynamics and its life cycle inventory during sugarcane production and utilization in Eastern region. Field experiments were conducted to cover the whole sugarcane cropping season to measure soil carbon content, soil carbon fluxes, and sugarcane biomass decomposition. In addition, farm management and fossil fuel uses data were also obtained from the surveys of sugarcane farms and sugar mill factories. During the 2006/07 cropping year, soil surface emissions of CO₂ and CH₄ resulted in a carbon loss of 16.39 ton C/ha/yr. On the other hand, soil carbon gain was mainly through the incorporation of sugarcane biomass and organic fertilizer. In this study, inputs to soil of biomass were as followed 6.68 ton C/ha/yr from above ground biomass, 4.75 ton C/ha/yr from root system and 4.98 ton C/ha/yr from organic fertilizer. Decompositions of most of these biomass (80%) are completed within a year time. However, decomposability of each sugarcane parts did vary; with leaf sheath being the faster (2.67 months) and root the slowest (9.49 months). This left only a small fraction of incorporated biomass remained as part of soil organic carbon and may be one of the reasons why soil organic carbon content in sugar field is relatively low. For farm operations and managements, it was found that compared to surface soil emission, the GHG emissions was (0.56 ton C/ha/yr). Balancing between carbon loss and gain, it was estimated that sugarcane cultivation emitted 0.58 ton C/ha/yr. In the sugar mill factories, use of sugarcane biomass such as bagasse is an important GHG mitigation option. If it is assumed that all electricity consumed is generated from natural gas (baseline), the amount of CO₂ emission would be 5.80 kg CO₂-eq/ton cane. Utilization of bagasse, helps offset this emission to only 0.27 kg CO₂-eq/ton cane.

Keywords: Full carbon cycle inventory, Sugarcane, Soil carbon, Carbon budget, Sugar mill

ACKNOWLEDGEMENTS

I am deeply grateful to my advisor, Asst. Prof. Dr. Amnat Chidthaisong, for his supervision, helpful, advice and guidance during my work on my Ph.D. thesis. I would very much like to thank all those to my committee members, Dr. George Andrew Gale, Asst. Prof. Dr. Sudarut Tripetchkul and Assoc. Prof. Dr. Shabbir H. Gheewala, for their comments and suggestions in this study. In addition I would very much like to thank thesis external examiner: Prof. Dr. Kasem Chunkao for his suggestions and evaluation.

This research could not have been completed without the help and data supported by many people and office, especially, Mr. Nikom Saengong for providing access to research site and Mr. Chatri Yuttitham for his help on field experiments. In addition, Mr. Attapole Malai for his help for automatic chamber for flux measurement equipment, sugarcane farmers and sugar mill officers in Eastern Thailand for their answer to the question for farm management and sugar mill process. Thanks also to Mr. Sataporn Jaiarree and teams at Land development department for their help on soil profile and analyzing soil properties at the site, Office of the cane and sugar board for geographic information system data and Thai meteorological department for precipitation data.

This research project was supported by Royal Golden-Jubilee Ph.D. Programme, The Thailand Research Fund and The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi.

I would like to extend thanks to Prof. Dr. Christiane Schmullius at Department of Remote Sensing, Friedrich Schiller University Jena, Germany for remote sensing laboratory supported and helpful. She gave me a very good experience on remote sensing knowledge and cooperation. Thanks also to the whole Geography Department's Remote Sensing group at Friedrich Schiller University Jena, Germany and friends for the friendly and their great help for my living there for a year. A thank you also goes to all friends who gave some diversion and who were always considerate.

Last but not least, I really would like to be grateful to express my parents, my sister, my brother and my family who supported me throughout my study and who gave me willpower and warmth. They always gave me great care.

CONTENTS

CHAPTER	TITLES	PAGE
	ABSTRACT	i
	ACKNOWLEDGEMENT	ii
	CONTENTS	Iii
	LIST OF TABLES	vi
	LIST OF FIGURES	x
	LIST OF ABBREVIATIONS	xiv
1	INTRODUCTION	1
	1.1 Background	1
	1.2 Rationales	2
	1.3 Objectives	4
	1.4 Scope of study	4
2	THEORIES AND LITERATURE REVIEW	5
	2.1 Introduction	5
	2.2 Greenhouse Gases, Greenhouse Effect, Climate Change and Global Warming	5
	2.3 Carbon cycle	8
	2.3.1 Carbon Cycle in general	8
	2.3.2 Global Carbon Budget	14
	2.3.3 Sugarcane plantation and carbon flow	15
	2.3.4 Sugarcane soil organic carbon	18
	2.4 Full carbon accounting in sugarcane production system	23
	2.4.1 Carbon flow in sugarcane agricultural part	24
	2.4.2 Carbon flow in sugar factory or sugarcane bioenergy system	37
	2.5 Sugarcane crop and its potential for bioenergy production	44
	2.5.1 Sugarcane crop and sugar production in the world	44
	2.5.2 Sugarcane Cropping in Thailand	50
3	METHODOLOGY	55
	3.1 Introduction	55
	3.2 Study site	56
	3.3 Field Experiments	58
	3.3.1 <i>In situ</i> gas flux measurements and instrumentation	58
	3.3.2 Soil property analysis	63
	3.3.3 Sugarcane biomass decomposition	66
	3.4 Full carbon accounting analysis	68
	3.4.1 Carbon flow in sugarcane plantation	68
	3.4.2 Carbon flow in sugar mill	76
	3.5 Geographic information (GIS) data and analysis for soil carbon mapping	80
	3.5.1 Study region and materials	80
	3.5.2 Data support, materials and equipments	81
	3.5.3 Sugarcane area and error evaluation	82

CONTENTS (Cont'd)

3.5.4 Soil sampling	84
4 SOIL CARBON BUDGETS	87
4.1 Introduction	87
4.2 Soil characteristics	87
4.2.1 Soil profile	87
4.2.2 Soil Characteristics before planting and after sugarcane harvest	89
4.3 Soil C stock	90
4.3.1 Field survey study	90
4.3.2 Soil Carbon budget in the sugarcane planting area of eastern Thailand	91
4.3.3 Soil C Stock in sugarcane plantation	103
4.3.4 Summary of the results	107
5 CARBON FLOWS AND BUDGETS IN SUGARCANE FARM	109
5.1 Introduction	109
5.2 Field measurements of CO ₂ and CH ₄ fluxes	109
5.3 Field measurements of sugarcane biomass decomposition	112
5.3.1 Lignin and Holo-cellulose contents	112
5.3.2 Dry mass losses, decomposition rate and sugarcane biomass nutrient recycling (Total C, Total N and C:N ratio)	114
5.4 Field measurements of biomass after harvest, sugarcane plant part, root density	121
5.5 Carbon inputs from organic fertilizer utilization	125
5.6 Soil carbon budget	126
5.7 Surveys of energy consumption and greenhouse gas emissions from sugarcane farm operation and management	128
5.7.1 Greenhouse gases emissions from fossil fuel utilization (Diesel and Gasoline) from farm operations and managements	128
5.7.2 Carbon and greenhouse gas emissions from chemical utilization (fertilizer, herbicide and insecticide)	133
5.7.3 Total greenhouse gases emission from farm operations and managements	138
5.8 Full carbon accounting from sugarcane plantation	141
5.9 GHG emission and full carbon accounting comparison from the previous studies	142
5.10 Summary of the results	148
6 CARBON FLOW AND BUDGETS IN SUGAR MILLS	150
6.1 Introduction	150
6.2 Carbon budget in sugar mill products	150
6.2.1 Sugar production in Eastern Thailand	151
6.2.2 Carbon budget in products and waste materials	154
6.3 GHG emissions from wastewater treatment in sugar mill	155

CONTENTS (Cont'd)

6.4 Potential of sugarcane biomass (bagasse) for bioenergy generation	157
6.4.1 Sugarcane biomass resources and power generation potential in sugar mill	157
6.4.2 Power supply and GHG emission in sugar mill process	158
6.4.3 Scaling up the greenhouse gases mitigation potential of bagasse	160
6.5 Potential of molasses for bioethanol as a fuel transport: <i>Conclusion from others publication</i>	162
6.5.1 Well to Tank fossil fuel use and GHG emissions	163
6.5.2 Tank to Wheel fossil fuel use and GHG emissions	165
6.5.3 Conclusion of GHG emissions from the whole process	166
6.5.4 The potential of molasses for producing ethanol in sugar mill in Eastern Thailand and the whole area of Thailand	166
6.6 Summary of carbon budget and greenhouse emissions and reduction from sugar mills	167
6.6.1 Carbon budget in product and waste material	167
6.6.2 Greenhouse gas emissions and reduction potential in sugar mills	168
7 SUMMARY AND RECOMMENDATIONS	171
7.1 Carbon budget and GHGs emission reduction potential	172
7.1.1 Soil carbon budget	172
7.1.2 Net carbon budget in sugarcane cultivation	173
7.1.3 Net carbon budget in sugar mill factory	174
7.1.4 Summary of net carbon in sugarcane plantation and sugar mill factory	175
7.2 Recommendations for further research	175
REFERENCES	176
APPENDIXES A	195
APPENDIXES B	200
APPENDIXES C	202

LIST OF TABLES

TABLES	TITLE	PAGE
2.1	Global, U.S. and Indian emissions of CO ₂ by fossil fuel combustion	11
2.2	Estimates of the associated sources (+) and sink (-) of carbon (Pg C/yr for the 1990s) from different types of land-use change and management	12
2.3	Average annual budget of CO ₂ perturbations for 1980 to 1989. Fluxes and reservoir changes of carbon are expressed in Gt C/yr, error limits correspond to an estimated 90% confidence interval	14
2.4	Annual global budgets of carbon dioxide	15
2.5	Global carbon budget for the 1980s and 1990s (Pg C/yr)	15
2.6	The chemical compound components of sugarcane parts	18
2.7	Carbon sequestration potentials limited only by availability of land, biological resources and land-suitability, and the potential estimated to be realistically achievable by 2012 adapted from figures in (Freibauer <i>et al.</i> , 2004; Smith, 2004)	26
2.8	Calculation of annual C budgets in sugarcane production affected by different crop residue application rates (1997)	28
2.9	Soil respiration rate in different vegetation types from different country	35
2.10	Total annual carbon uptakes for 1 ha of sugarcane plantation	41
2.11	Use of sugarcane in the world	45
2.12	World sugarcane producers	46
2.13	Sugar production in the world in 2007/08 production year	47
2.14	Regional potential bioethanol production from wasted sugarcane and sugarcane bagasse	50
2.15	National production of sugarcane and harvested area in Thailand	52
2.16	Lists of industrial firms that produce ethanol in Thailand	54
3.1	Crop calendar for sugarcane plantation in 2006-2007	58
3.2	Carbon emissions for different fuel sources and the energy conversion units	70
3.3	Emission factors for production, transportation, storage and transfer of organic chemicals	74
3.4	Materials and data required in the GIS part	82
4.1	Characteristics of the soil underlying the sugarcane crop at the experimental site	88
4.2	Soil profile at the experimental site	88
4.3	Soil bulk density of the soil samples in study sites of Ban Bueng-Sattahip (Bbg-Sh) soil series at 0-10, 10-20 and 20-30 cm depth	90
4.4	Soil C stock of the soil samples at soil profile	90
4.5	General characteristics and soil C stock of the soil samples in study sites Ban Bueng-Sattahip (Bbg-Sh) soil series 0-10, 10-20 and 20-30 cm depth (\pm of 4 replications)	91
4.6	Soil bulk density of the soil samples at the study sites of Ban Bueng-Sattahip (Bbg-Sh) soil series at 0-30 cm depth	91

LIST OF TABLES (Cont')

TABLES	TITLE	PAGE
4.7	Error matrix analysis in sugarcane and non-sugarcane area map evaluation	93
4.8	Ten-major soil series that were planted to sugarcane in the study region (Chonburi and Rayong provinces)	95
4.9	Characteristics and properties of the soils used in the present study (\pm the standard deviations from composite sample/3 replications)	97
4.10	Estimation of carbon stock in different soil organic carbon techniques (\pm standard deviation from composite sample/3 replications)	99
4.11	Soil carbon stock changes at 30 cm depth, compare between LDD data sheet and our field by Walkley's method, LDD and Flash combustion	101
4.12	Organic carbon in sugarcane soil of Thailand at depth 0-25 cm, 0-50 cm and 0-100 cm	106
5.1	Biomass composition (% by dry weight)	113
5.2	Changes in lignin content for four sugarcane components varied at two different depth levels	114
5.3	Changes in Holo-cellulose fraction on four sugarcane components and two different depth levels	114
5.4	Weight losses, rate constant and turn over time for sugarcane biomass decomposition	118
5.5	The sugarcane components properties before decomposition study: leaf, leaf sheath, shoot and root (<i>mean \pm standard deviation</i> from 3 replications)	121
5.6	The amount of sugarcane biomass after harvested (top and leaves, shoot, root), (Error bars represent standard deviation of ten replications (<i>mean \pm S.D.</i>) for sugarcane biomass and 15 replications for root density)	123
5.7	The amount of sugarcane plant part (Stalk, Leaf, Leaf sheath, shoot and root), (Error bars represent standard deviation of ten replications (<i>mean \pm S.D.</i>)	123
5.8	Calculation of annual soil carbon budget and Global Warming Potential (2006-2007) cropping years	128
5.9	The amount of diesel fuel use and equivalent to CO ₂ emissions from different management practices based on 59 questionnaires	131
5.10	Quantity of fuel (Benzene 91) used in different sugarcane management base on 59 questionnaires and equivalent to CO ₂ emission	132
5.11	Fertilizer use and equivalent to CO ₂ emission from chemical fertilizer base on the information from 59 questionnaires, the emission from chemical production	134

LIST OF TABLES (Cont')

TABLES	TITLE	PAGE
5.12	Direct and indirect N ₂ O emission from agriculture soil, the emission from chemical fertilizer and organic fertilizer utilization	136
5.13	N ₂ O emissions from Nitrogen Fertilizer and CO ₂ emissions from Urea application and equivalent to CO ₂ emission	137
5.14	CO ₂ equivalent from herbicide, insecticide application	136
5.15	The percentage of sugarcane biomass burning and un-burnt data from 59 questionnaires	137
5.16	Greenhouse gases emissions (CH ₄ and N ₂ O emissions) from biomass burning, represented to CO ₂ equivalent	138
5.17	GHG emissions equivalent to CO ₂ emission from farm operation and management (Include sugarcane biomass burning)	140
5.18	GHG emissions equivalent to CO ₂ emission from farm operation and management (Exclude sugarcane biomass burning)	140
5.19	Summary of net carbon flux for agriculture from previous studied and sugarcane plantation in this study	143
5.20	Direct materials, energy-related and chemical utilization for sugarcane production	144
5.21	Carbon footprint in agriculture and food product	145
5.22	Calculation of annual carbon budget in sugarcane plantation (Include sugarcane biomass burning)	146
5.23	Calculation of annual carbon budget in sugarcane plantation in term of carbon equivalent (Include sugarcane biomass burning)	147
6.1	Sugarcane area, yield, and productivity in Chonburi and Rayong provinces, Eastern region and the whole area in Thailand	152
6.2	Sugar and by-product of sugar; molasses, filter cake, bagasse from sugar mill in Eastern Thailand from 2003/04 to 2007/08 production years	153
6.3	Background information of 4 sugar mills factory in Eastern Thailand	154
6.4	Total carbon stock in sugar products and waste materials	155
6.5	Background information of wastewater and treated wastewater properties	156
6.6	Average wastewater, treated wastewater properties and greenhouse gases emission from wastewater treatment from sugar mill process	156
6.7	Average electricity utilization (MWh) and CO ₂ emission estimated from 4 sugar mills in Eastern region from 2003/04 to 2007/08 production years	160
6.8	Average electricity utilization (kWh) and equivalent to CO ₂ emission for the whole area of Eastern Thailand from 2003/04 to 2007/08 production years	162
6.9	Sugarcane yield and it potential for power generation in Eastern Thailand and the whole area in Thailand from 2003/04 to 2007/08 production years	161

LIST OF TABLES (Cont')

TABLES	TITLE	PAGE
6.10	Well to Tank (WtT) and GHG emissions for fossil fuel	163
6.11	Well to Tank (WtT) and GHG emissions for bioethanol	165
6.13	Conclusion of WtT, TtW, WtW and avoided CO ₂ emission	166
6.14	Summarized of carbon budget from sugar milling, the case study in Eastern region of Thailand	168
6.15	Summary of carbon budget from sugar milling, the case study in Eastern region of Thailand	168
6.16	Summarized of greenhouse gases emission in sugar milling, the case study in Eastern region of Thailand	169
6.17	Calculation of GHGs emission in sugar milling based on bioenergy scenario (the current situation in Eastern Thailand) in term of carbon equivalent by % of product and waste material	169

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	The Origin of global warming and the greenhouse effect	6
2.2	Atmospheric CO ₂ concentrations during the past 1000 years	7
2.3	Variations of the globally averaged Earth's surface temperature over the last 150 years, the red bars are representing the global temperature value for each year, the blue line is the 10-year running average and the green bar is the 2006 value	7
2.4	The global carbon cycle, including the amount of carbon in every reservoir(unit Gt; gigatons)	9
2.5	Carbon dioxide concentrations (in ppmv) of the air at the Mauna Loa, Hawaii, from 1958 to 2008. In the graph above, the dashed red line represents the monthly mean values, centered on the middle of each month. The black line represents the same, after correction for the average seasonal cycle	10
2.6	Sugarcane plant part	17
2.7	Sugarcane root system	17
2.8	Changes with time of soil organic matter, total nitrogen and organic carbon content under sugarcane monoculture from 30 years	19
2.9	Soil carbon stocks in the 0–10, 0–20, 0–50 and 0–100 cm depths in sugarcane areas with 2, 6 and 8 years after replanting, compared to the same soil mass. The star indicates statistical difference at 5% of significance between burned and unburned treatments	21
2.10	Total organic carbon (TOC) associated with minerals (MOM) as function of the time of sugarcane cultivation in the layers of 0–0.2 and 0.2–0.4 m	22
2.11	(C) C3 plant (forest)-derived carbon content and (D) C4 plant (sugarcane)-derived carbon content in the 0–30 cm soil layer of forests (0 year) and sugarcane fields cultivated for 1 to 30 years in the Northeastern Region of Thailand. Sampling sites were as follows: d Khon Kaen; c, Namphoy. Data correspond to three replicates	23
2.12	(C) C3 plant (forest) derived carbon content and (D) C4 plant (sugarcane)-derived carbon content in the 0–30 cm soil layer of forests (0 year) and sugarcane fields cultivated for 8 to 40 years in the Central Plain Region of Thailand. Sampling sites were as follows: c, d, Kanchanaburi forests	23
2.13	C flow in the sugarcane production, solid line indicates carbon uptake while dot line indicates carbon release or emission	24

LIST OF FIGURES (Cont')

FIGURE	TITLE	PAGE
2.14	Example of annual carbon fluxes in agriculture ecosystems for the early years following a change from conventional tillage to no-till based on average US crop inputs. Values embedded in arrows measure rates of flow; other values measure changes in stocks. Rates of flow between the atmospheres and biosphere (crop/soil pool) are inherent in the change in soil carbon stock. Units in $\text{kg C ha}^{-1} \text{ year}^{-1}$ based on data in West and Marland, (2001), West and Marland (2002).	25
2.15	Total US average carbon dioxide emissions for three crop types using three different tillage practices. CT, RT, and NT are conventional tillage, reduced tillage, and no-till, respectively. The graph is for non-irrigated areas, which comprise 85% (by area) of US corn crops, 95% of soybean crops, and 93% of wheat crops (West and Marland, 2002)	30
2.16	Five main sources of biogenic CO_2 efflux from soil, ordered according the turnover rates and mean residence times of C in soil. The sources and compartments of the CO_2 efflux consider C pools with different turnover rates and MRT, the localization of C pools and the agents of CO_2 production (Kuzyakov, 2006).	33
2.17	The respiratory pathways in living tissues include glycolysis, the pentose phosphate pathways, and the TCA cycle	34
2.18	Relationship between soil respiration (R_s) and soil surface temperature (T_s). Regression equation for the thinned section was $\ln(R_s) = 0.071(T_s) - 2.10$ ($r^2=0.89$) and for the intact section was $\ln(R_s) = 0.090(T_s) - 3.15$ ($r^2=0.79$) (Mizue <i>et al.</i> , 1999)	36
2.19	Sugar production processes from sugarcane	39
2.20	World sugarcane production trend	46
2.21	Sugar producers 2007/08 (left) and sugar exporters 2007/08 (right) in the world sugar trend	48
3.1	Schematic diagram of research framework	56
3.2	Map of Chonburi and Rayong provinces, Thailand, showing the study area, red circle showing the experimental site for flux measurements	57
3.3	Some important climatological data for the study areas in 2006 and 2007 at Chonburi and Rayong provinces	58
3.4	Illustration of closed-automatic chamber and a flux measurement setting	60
3.5	The suitcase-sized box for determining of CO_2	61
3.6	Example of calibration curve used to calculate CO_2 and CH_4 concentration, left for CH_4 and right for CO_2	62
3.7	Textural triangle used to determine soil texture	64
3.8	Litter bag placements at 0 and 15 depths	67
3.9	Flow diagram of carbon flow in sugarcane plantation system	69
3.10	Flow diagram of carbon flow in sugar mill process	77

LIST OF FIGURES (Cont')

FIGURE	TITLE	PAGE
3.11	Schematic diagram of research framework in part of GIS and remote sensing	81
3.12	Method of soil sampling and preparation for soil carbon analysis.	86
4.1	Soil profiles of Ban Bueng-Sattahip (Bbg-Sh) soil series	89
4.2	Sugarcane area and non-sugarcane area with all points sampled from the 2005 accuracy assessment	93
4.3	Map of the ten soil series that are included in this study and their soil organic carbon levels	98
4.4	Soil bulk density in the study area	99
4.5	Comparison between SOC analysis methods by t-Test: Paired Two Sample for Means at 99% confidence level	100
4.6	Soil bulk density of the soil samples at the study sites of Ban Bueng-Sattahip (Bbg-Sh) soil series at 0-30 cm depth	101
4.7	Map of distribution of organic carbon at 0-25 cm depth in Thailand (modified from Moncharoen, <i>et al.</i> , 2001) and sugarcane area (Office of the cane and Sugar Board, 2006)	104
4.8	Map of distribution of organic carbon at 0-50 cm depth in Thailand (Modified from Moncharoen, <i>et al.</i> , 2001) and sugarcane area (Office of the cane and Sugar Board, 2006)	105
4.9	Map of distribution of organic carbon at 0-100 cm depth in Thailand (Modified from Moncharoen, <i>et al.</i> , 2001) and sugarcane area (Office of the cane and Sugar Board, 2006)	105
5.1	Average of soils CO ₂ flux from sugarcane field during March 2006 to February 2007 and soil temperature at 5 cm depth and soil moisture at 6 cm depth, Error bars represent standard deviation of four replications (<i>mean ± S.D</i>)	110
5.2	Average of soils CH ₄ flux on sugarcane field from March to December 2006 and soil temperature at 5 cm depth and soil moisture at 6 cm depth, Error bars represent standard deviation of four replications (<i>mean ± S.D.</i>).	111
5.3	Relationship between soil CO ₂ flux and soil moisture and soil temperature	112
5.4	Sugarcane components sampled before planting (0 days; 9 March, 2006 and at the 10 th month (296 days, 1 January, 2007), (M0=sampled before planting), (M10=sampled at 10 months)	116
5.5	Example of time course of sugarcane biomass decomposition during the planting period	117
5.6	The dry weight remained at 0 and 15 cm depth during the planting period (0-296 days)	119
5.7	Total C, Total N and C:N ratio during decompose (0 to 296 days) of sugarcane components (leaf, leaf sheath, shoot and root) at 0 and 15 depth level (\pm standard deviation from 3 replications)	121
5.8	Sugarcane biomass components, processing pathways and their final products destinations	124

LIST OF FIGURES (Cont')

FIGURE	TITLE	PAGE
5.9	The carbon uptake in each sugarcane plant part, (Units in ton C)	124
5.10	Total CO ₂ emission equivalents from sugarcane farm management combining between diesel and gasoline fuel consumption	133
5.11	Annual C budget in sugarcane plantation activities	142
5.12	Annual carbon fluxes in sugarcane plantation system. Values embedded in arrows measure rates of flow; other values measure changes in stocks. Rates of flow between the atmospheres and biosphere (crop/soil pool) are inherent in the change in soil carbon stock. Units in ton CE/ha/year	148
6.1	Map showing the sugar mill factories in Thailand and sugarcane area in 2006/07 cropping years	151
6.2	Life cycle framework for transportation fuels (Yan <i>et al.</i> , 2009)	162
6.3	WtT fossil fuel use and GHG emissions for fossil fuels in developed countries (results from studies which considered only fossil fuel use or GHG emissions are shown on the axis), Yan <i>et al.</i> , 2009.	164
6.4	A linear correlation of the WtT fossil fuel use and GHG emissions for the data points from various studies, Yan <i>et al.</i> , 2009	165
6.5	Carbon contents, CO ₂ emission and reduction equivalent in sugar mill	170
7.1	Greenhouse gas emissions from activities involved sugarcane farm managements	173
7.2	Carbon budget in sugarcane plantation (% of total budget)	174

List of Abbreviations

- Brix: Degree Brix (symbol °Bx)
- Bbg: Ban Bueng soil series
- Bbg-Sh: Ban Bueng and Sattahip soil series
- BOD: Biological Oxygen Demand
- Cb: Chon Buri soil series
- CDM: Clean Development Mechanism
- CFC₃: Chlorofluoro carbons
- CH₄: Methane
- CO₂: Carbon dioxide
- COD: Chemical Oxygen Demand
- GHG: Greenhouse gases
- GIS: Geographic Information System
- ha: hectare
- Hg: Hup Kraphong soil series
- IPCC: Intergovernmental Panel on Climate Change
- Knk: Khlong Nok Krathung soil series
- KP: Kyoto protocol
- LDD: Land Development Department
- Nm: Nong Mot soil series
- N₂O: Nitrous oxide
- OC: Organic Carbon
- Pg: petagram = 10¹⁵ g
- Pga: Phang Nga soil series
- Pp: Phon Phisai soil series
- ppmv: Parts per million on a volume basis
- Ra: Aboveground plant respiration
- Rb: Belowground plant respiration
- Re: Ecosystem respiration
- Rp: Plant respiration
- Rm: Microbial respiration

Rs: Root respiration

SF₆: Sulfur hexafluoride

Sh: Sattahip soil series

SOC: Soil Organic Carbon

Suk: Satuek soil series

Tg: Thung Wa soil series

Tg = 10¹² g C

UNFCCC: United Nations Framework Convention on Climate Change

Walkley's method: Walkley and Black method