

A decision support tool for modifications in crop cultivation method based on life cycle assessment: a case study on greenhouse gas emission reduction in Taiwanese sugarcane cultivation

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Received: 13 December 2008 / Accepted: 3 May 2009 / Published online: 20 June 2009
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Abstract

Background, aim, and scope Nowadays, various crops are cultivated to supply emerging needs in sustainable fuels and materials. In addition to the development of crop processing technologies, cultivation processes in a cropping system could be modified to meet the emerging needs, along with the conventional needs in food supply. This study provides a decision tool for modifications in cultivation of crops based on life cycle assessment. Sugarcane cultivation in Taiwan is chosen as a case study to present such a decision tool, because it is an important potential indigenous resource for energy (for example, bio-ethanol) and materials (for example, bio-plastics). First, this study presents the amount of greenhouse gas (GHG) emissions associated with the production of 1 ton of sugarcane in Taiwan, which makes it possible to understand how it is consistent to develop this bio-resource in terms of both objectives: i.e., resource security and reduction of global warming impact. Next, sensitivity of the parameters in cropping systems, such as amount of irrigation, fertilization and tillage are assessed from a viewpoint of GHG emissions, using the LCI model constructed in the first step. Finally, equivalent impact level (EIL) lines are presented for some important parameters in

the cropping system to support considerations in modification of agricultural methods. Because the objective is to discuss parameters in cultivation processes, the scope of study is limited to cradle-to-gate of raw sugarcane transported to the cane processing plant.

Materials and methods In addition to GHG emissions from cultivation processes, such as soil preparation, growing, harvesting and transportation, auxiliary processes such as agrochemicals production, power generation and fossil diesel fuel refining was accounted for. To quantify the nitrous oxide emission from the soil ecosystem, a denitrification-decomposition (DNDC) model was used with the localized data obtained in this study. EIL lines were developed aiming at supporting decisions about modifying agricultural methods that should be made considering consequential changes in environmental impacts. For example, if the envisioned improvement in yield as a result of modification of parameters such as irrigation, tillage and fertilization is likely to achieve a value above the EIL line, GHG emission per ton of sugarcane would be decreased. An iterative procedure is applied to draw nonlinear EIL lines using Intergovernmental Panel on Climate Change (IPCC) Tier 3 method for nitrous oxide emission from soil.

Results A 3 year crop cycle was assumed, and the net GHG emissions associated with the sugarcane produced was -280 kg-CO₂-equiv. per ton of raw sugarcane. The emission of nitrous oxide from soil during cultivation accounted for 50.4% of the total emissions. One-at-a-time sensitivity analysis indicates that this result is most sensitive to yield and amount of nitrogen fertilizer applied, which are correlated to each other. The EIL lines were drawn for yield over five parameters in cultivation including amount of nitrogen fertilizer applied with respect to GHG emission.

Responsible editor: Mark Huijbregts • Joerg Schweinle

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For example, if an additional 5% of nitrogen fertilizer application realizes enhancement of yield by 5 tons per hectare, such modification simultaneously reduces total GHGs associated with sugarcane production.

Discussion The EIL lines drawn with respect to various environmental impacts aims to provide a simple-to-use guidance in reconsideration of agricultural options. The cradle-to-gate LCA of sugarcane provides information useful in development of bioethanol and bioplastics derived from sucrose in the cane juice. In doing so, it must be noted, if extension of farm area is among the options to be assessed, that release of the carbon stock from the original state of use should be accounted for in addition to the result presented in this study. Absorbed CO₂ should be quantified separately based on the content of the sugarcane, which could be varied for different cultivars.

Conclusions This study presents a decision tool to allow introduction of an environmental life cycle perspective in modification of cultivation methods, which has already been undergoing as driven by economic reasons. The data and inventory method presented in this study can be applied for varied end products derived from sugarcane. The algorithm to develop an EIL line for correlated parameters in the inventory model was presented.

Recommendations and perspectives Results from this study require appropriate modification if they are to be used for studies for other regions. Such modifications would be straightforward, because all inventory data and assumptions are presented in this paper. Essentially, the functional unit used in this study is unit amount (by weight) of sugarcane. If some specific content (for example, sucrose or cellulose) is important in a study which attempts to use results from this study, variations in the content over cultivation methods and cultivar of sugarcane must be investigated further.

Keywords Carbon dioxide · Denitrification-decomposition model (DNDC model) · Equivalent impact level line (EIL line) · Fertilization · Greenhouse gases · Intergovernmental Panel on Climate Change (IPCC) · Irrigation · Nitrous oxide · Sensitivity analysis · Sugarcane · Tier 3 method

Nomenclature

Notations

| | |
|------|---|
| DNDC | denitrification-decomposition |
| EIL | equivalent impact level |
| E3 | alternative fuel for gasoline fuelled car, 97% gasoline, 3% anhydrous ethanol, by volume |
| E10 | alternative fuel for gasoline fuelled car, 90% gasoline, 10% anhydrous ethanol, by volume |
| GHG | greenhouse gas |
| GWP | global warming potential |

| | |
|------|---|
| IPCC | intergovernmental panel on climate change |
| LCA | life cycle assessment |
| LCI | life cycle inventory |
| OAT | one-at-a-time |

Symbols

| | |
|-----------------------|---|
| A_{CO_2} | atmospheric CO ₂ absorbed by sugarcane, kg |
| A_{C-stem} | carbon content in the stem of sugarcane, kg |
| E_{dc} | direct emissions of CO ₂ , CH ₄ and N ₂ O from soil in the cropping cycles, kg |
| E_{df} | direct emissions of CO ₂ , CH ₄ and N ₂ O from fossil fuel combustion, kg |
| E_{fallow} | emission from soil under the fallow land conditions, kg |
| E_{farm} | emission from soil under the sugarcane farm conditions, kg |
| E_c | GHG emissions in cradle-to-gate life cycle of chemicals and fossil diesel, kg-CO ₂ -equiv. |
| E_p | GHG emissions derived directly from power generation, kg-CO ₂ -equiv. |
| $EF_{fossil\ diesel}$ | emission factor of fossil diesel, kg/TJ |
| EF_p | GHG emission factor of electricity in Taiwan, kg-CO ₂ -equiv./kWh |
| ϕ_c | GHG emission inventory of chemicals and fossil diesel, kg-CO ₂ -equiv./kg or kL |
| $Q_{fossil\ diesel}$ | the quantity of fossil diesel consumed, TJ |
| Q_c | the quantity of chemicals and fossil diesel used, kWh |
| Q_p | the quantity of electricity generated, kWh |

1 Background, aim, and scope

Depletion of resources for energy and materials, food security and climate change caused by greenhouse gas (GHG) emissions are among the sustainability issues of greatest concern that must be tackled in the twenty first century (UNEP 2007). For example, in Taiwan where more than 98% of primary energy was imported in 2007 (Bureau of Energy 2007), the recent volatile price of fuel for daily transportation has been stimulating growing concerns about reliance on imported resources. On the other hand, adverse consequences induced by climate change as a result of global warming are another important issue. It has been pointed out that the rise in sea level will affect many of the most populated cities in Taiwan (Common Wealth Magazine 2007) and the increasing number of major typhoons is of great concern to the population. Inflation in the cost of foods such as oil, bread and starch products are making the lives of people difficult, and this is said to be a consequence of the competition between food and energy made from edible crops (New York Times 2008). In this way, in pursuit of

its own benefit and as a member in the global partnership towards sustainable development, Taiwan is searching for its way towards achieving two sustainability objectives: development of indigenous resources for materials and energy and reduction of GHG emission without affecting food security.

Biomass is a renewable resource and is considered a lower carbon-emitting energy source. The Taiwanese government announced a target for renewable energy introduction of 10% of the entire power generation capacity in 2010, in which biomass-derived energy accounts for 14.4% of the entire expected amount of energy for renewable source (Bureau of Energy 2005). One important feedstock for biomass derived fuels (for example, ethanol) production is sugarcane, a traditional agricultural product of Taiwan. Especially in the southern area, Taiwan has an advantageous climate and soil conditions for effective cultivation of sugarcane, with as much as 220,000 hectares of fallow land, in addition to the matured experience with sugarcane production as described below.

The history of sugarcane production in Taiwan starts in the sixteenth century (Taiwan Sugar Research Institute 2009). Sugar production reached its peak at more than 1.4 million tons during the period when Japan ruled this island. During this period, in the export of granulated sugar Taiwan ranked third in the world, only behind Cuba and Java. From 1952 to 1964, granulated sugar held the foremost place as an export and once accounted for 74% of the foreign exchange earnings. The area planted with sugarcane amounted to 109,718 hectares, which produced 1,069,547 tons of sugar in 1977 (Wang 2005). After that, because the international sugar price declined and because development of heavy and high-tech industries was emphasized more by the government, sugarcane production steeply diminished. For example in 2006, only 10,394 hectares of sugarcane farms remained in use (Agriculture and Food Agency 2006).

In June 2005, the Taiwanese government announced its ethanol fuel development strategies (Bureau of Energy 2005), which include (1) enforcing the official business vehicles in Taipei City (the capital of Taiwan) to use E3 (97% gasoline, 3% anhydrous ethanol, by volume) by 2008, (2) using E3 all over Taiwan by 2011 and then (3) completely utilizing E10 (90% gasoline, 10% anhydrous ethanol, by volume) for all vehicles by 2025. Consequently, recovery of large scale sugarcane production is foreseen.

To discuss how Taiwan should re-develop its sugarcane industry for satisfying the emerging needs, it is essential to understand the amount and structure of GHG emissions associated with sugarcane production. Materials and fuel derived from bio-resources such as bio-ethanol is often seen as “carbon neutral,” because raw material crops such as sugarcane absorb CO₂ during cultivation. However,

emissions from machines used for agricultural activities (for example, harvesting, tillage, etc.) and from ecological activities in soil affected by agricultural activities, as well as emissions occurring at the production of input substances to farms (including fertilizers, pesticides and water for irrigation) must be accounted for to correctly evaluate their role in establishing a lower GHG society to mitigate climate change issues.

Embodied environmental impacts of cultivated biomass are studied extensively. For sugarcane, cane-juice-derived ethanol production is analyzed for Brazil (Macedo et al. 2008), Cuba (Alonso-Pippo et al. 2008) and Thailand (Nguyen and Gheewala 2008) in detail. It can be seen from those papers that the cropping system (i.e., cycles of new planting, ratoon and fallow, schedules and methods for cultivation and harvesting activities, etc.) makes both the structure and intensity of impacts differ significantly. Those papers provide sensitivity and hot-spot analyses for emissions and impacts which are used in developing suggestions on reduction of the embodied impacts. For example, in a Brazilian study, elimination of the burning of leaves and cane tops in prior to harvesting was suggested. Thai study elucidates the significance of coal-based energy supply in sugarcane processing and suggests migration to other energy sources. Those useful suggestions stem from the results of typical patterns of interpretation in LCA. However, an analysis on options that could affect the yield of agricultural products seems absent or relatively weak in the preceding studies. Perhaps this is because correlations in the inventory data is disregarded or overlooked at the interpretation step, which tends to limit the scope of the analysis. For example, changes in application of fertilizer would at least affect yield, embodied impacts of the fertilizers and direct nitrous oxide emission from soil. To comprehensively evaluate overall impacts, consideration of relationships between yield and fertilization is required. This kind of analysis is of particular importance that could help agricultural sectors develop new (or re-optimize existing) cultivation methods reflecting the emerging (i.e., nonfood) needs and new environmental requirements. However, construction of a model for an analysis as described above is costly because agricultural experiments are needed for evaluating the relationships between yield and agricultural parameters, which take years of time with a considerable area of cultivated land.

In this study, an LCA-based decision tool for development of cultivated biomass is presented. As a case study, GHGs associated with Taiwanese sugarcane production are analyzed based on the context in Taiwan described above. First, an LCA was conducted for unit area of land used for cultivation of sugarcane aiming at understanding the structure of GHG emissions. Next, sensitivity of the net GHG emission to the parameters in the sugarcane cropping

system is analyzed to better understand the presented result and, at the same time, to identify improvement opportunities. Finally, a decision support tool termed equivalent impact level (EIL) line is used to further evaluate the identified opportunities. Modification of parameters (for example, fertilization, irrigation, number of times of tillage) is analyzed in relation to consequential yield of sugarcane using the LCI model developed in the previous steps of the case study. By using EIL line, it becomes possible to make an aware decision considering consequential changes in environmental impacts of interest when modification of parameters in cropping systems are discussed aiming at an enhancement of renewable resource. This approach does not use the relationship between yield and the parameter of focus which need a simulation based on costly experiences. Rather, the EIL line suggests the yield that has to be achieved when analyzed parameters are modified. Construction of EIL line is possible with or without nonlinear inventory models, as demonstrated in this paper.

Furthermore, carbon stock changes associated with changes in cultivation methods and enhancement of cultivated area needs attention. How this aspect should be assessed using the results from our calculations is also discussed.

The case study only covers global warming impact, although other impact categories (for example, emissions of acidifying and eutrophication pollutants, water scarcity and toxicity) are identified as crucial factors that must be considered in particular cases of decision making in general. Especially for the region where sugarcane is burnt before harvesting, NO_x and particulates emission take place, which is identified as an important factor for the regional environment. In Taiwanese sugarcane cultivation, this is not the case, and other impacts are considered minimal. Even so, the EIL lines can be developed for other impacts, or even for an indicator aggregating those impacts, in the same way as those for GHG emission.

2 Methods

2.1 Calculation of GHG emissions and absorption

The GHGs emission and absorption associated with sugarcane in Taiwan were quantified on the basis of the cultivation of a sugarcane cropping system, which consists of one year new planting, one year ratoon and one year fallow using 1 ha of arable land. The agricultural processes involved in one term of sugarcane cultivation are listed in Table 1. Based on this information, the scope of the study is defined as in Fig. 1. The foreground processes considered in this study include soil preparing (P1), sugarcane growing (P2), sugarcane harvesting (P3) and sugarcane transporta-

tion (P4). In addition to the emissions from the combustion of fossil fuels in each of those processes, emission of nitrous oxide generated by the activities on microorganisms in the soil was also calculated. The background processes, such as chemical (i.e., fertilizer, pesticide, herbicide and raticide) manufacturing, power generation and fossil diesel refining were also accounted for. Data on amount of resources used and GHG emissions for all activities were collected by interviews with producers and by searching the literature. The primary data sources for each process are summarized in Table 2. The inventory data for sugarcane cropping system are presented in Table 3.

The relevant GHGs in this study are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emitted from production of agricultural inputs (i.e., chemicals, water), operation of farm equipments (i.e., diesel trucks and machines, and electric water pumps) and soil during sugarcane cultivation. Absorption of atmospheric CO_2 by sugarcane is also considered in this study.

2.2 Direct emissions from the sugarcane industry

Fossil diesel is used as the fuel to drive trucks (road transportation) and agricultural machinery (off-road transportation). The emissions from road and off-road transportation, and from soil in the sugarcane cropping cycles are accounted for as the direct emissions from the sugarcane industry. Calculation of emissions in this category is carried out by following the guidelines issued by the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al. 2006) described in Eqs. 1 and 2.

$$E_{df} = Q_{fossil\ diesel} \times EF_{fossil\ diesel} \quad (1)$$

$$E_{dc} = E_{farm} - E_{fallow} \quad (2)$$

where

E_{dc} : direct emissions of CO_2 , CH_4 and N_2O from soil in the cropping cycles, kg

E_{df} : direct emissions of CO_2 , CH_4 and N_2O from fossil fuel combustion, kg

E_{fallow} : emission from soil under the fallow land conditions, kg

E_{farm} : emission from soil under the sugarcane farm conditions, kg

$EF_{fossil\ diesel}$: emission factor of fossil diesel, kg/TJ

$Q_{fossil\ diesel}$: the quantity of fossil diesel consumed, TJ

Emissions from soil in the IPCC guidelines (Eggleston et al. 2006) are further categorized in the calculation method into 3 types (i.e., Tier 1–3 methods). In this study two of the three methods, Tier 1 and 3, were applied and

Table 1 Schedule of sugarcane cultivation (Wang 2005; Zeng and Wu 1996)

| Date | New planting | Ratoon | Fallow |
|---------|--|--|--|
| 2/20 | Soil preparing (deep plowing and harrowing) | | |
| 2/21 | Soil preparing (ridge making) and basic fertilizer (60 kg-N/ha, 50 kg-P/ha and 50 kg-K/ha) | | |
| 2/25 | 1st herbicide (glyphosate 7.50 L/ha and atrazine 3.00 kg/ha) | | |
| 3/1 | Sugarcane planting (picking seedlings and transporting seedlings) | | |
| 3/10 | Intertillage (using a rotary tiller) and 2nd herbicide (2,4-D 1.75 kg/ha and ametryn 2.00 kg/ha) | 1st herbicide (glyphosate 7.50 L/ha and atrazine 3.00 kg/ha) | |
| 3/15 | | Exposing root and basic fertilizer (60 kg-N/ha, 50 kg-P/ha and 50 kg-K/ha) | |
| 3/25 | | 2nd herbicide (2,4-D 1.75 kg/ha and ametryn 2.00 kg/ha) | |
| 4/10 | 1st pesticide (demeton-s-methyl 1.50 L/ha) | 1st pesticide (demeton-s-methyl 1.50 L/ha) | |
| 4/10–20 | Additional planting | | |
| 4/15 | Intertillage and additional fertilizer (140 kg-N/ha and 50 kg-K/ha) | Intertillage and additional fertilizer (140 kg-N/ha and 50 kg-K/ha) | |
| 5/1 | | | Weeding (glyphosate 7.50 L/ha and atrazine 3.00 kg/ha) |
| 5/10 | Intertillage | Intertillage | |
| 5/15 | | | Deep plowing |
| 5/20 | Earthing up | Earthing up | |
| 6/1 | 2nd pesticide (oxydemeton methyl 1.25 L/ha) | 2nd pesticide (oxydemeton methyl 1.25 L/ha) | |
| 6/10 | Final earthing up | Final earthing up | |
| 7/15 | 1st raticide (brodifacoum 2.00 kg/ha) | 1st raticide (brodifacoum 2.00 kg/ha) | |
| 10/1 | 2nd raticide (brodifacoum 2.00 kg/ha) | 2nd raticide (brodifacoum 2.00 kg/ha) | |
| 3/1 | Harvesting | Harvesting | |

the results were compared. The Tier 1 method enables the calculation of emissions from soil associated with land use in a simple way by choosing the parameters and equations from tables prepared in the guideline. On the other hand, the Tier 3 method is tailored to address local circumstances, repeated over time, driven by high-resolution activity data and disaggregated at a sub-national level. Estimates based on a Tier 3 method are considered to have a greater certainty than results from Tier 1.

When applying the Tier 1 method to a consideration of the nature of sugarcane fields and cultivation patterns, it was assumed that:

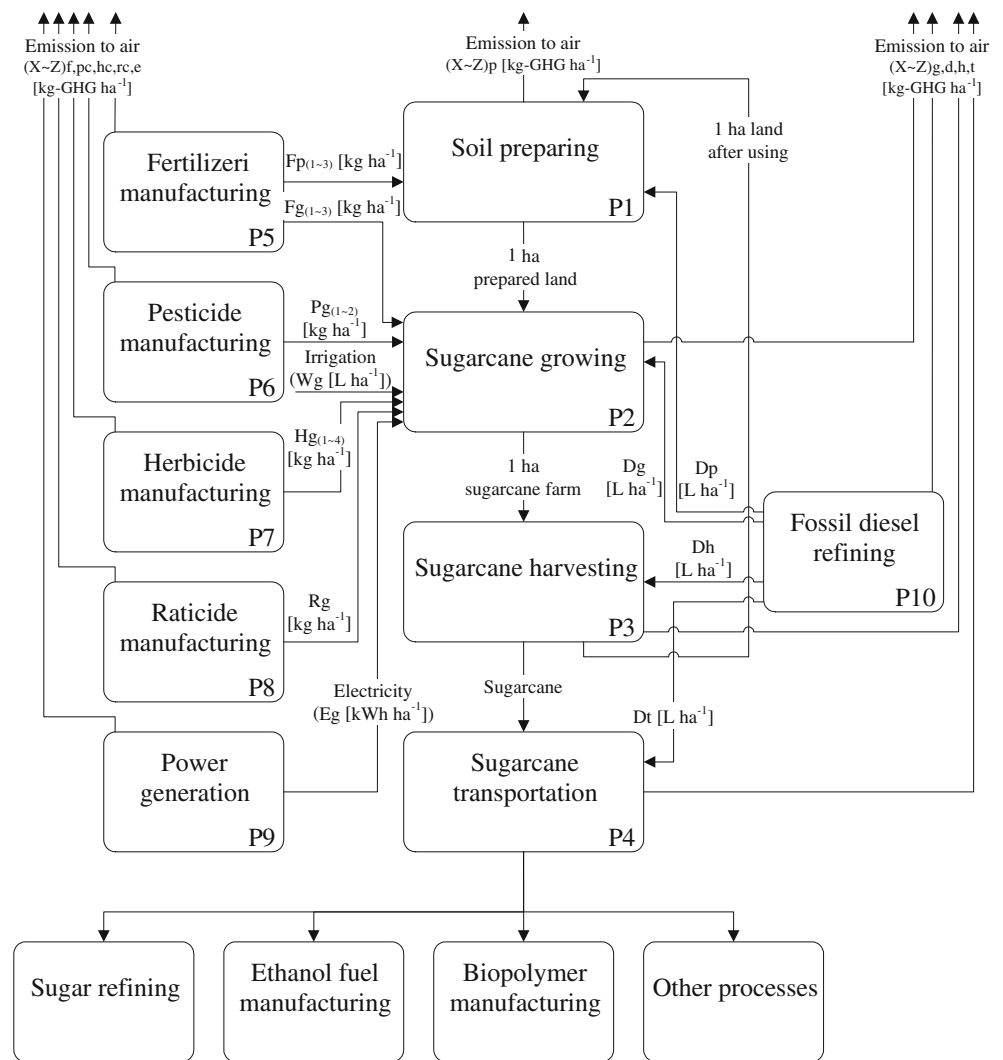
- 1) the net CO₂ emission from soil is zero. This is because there is no carbon input into soil from agricultural activities except for leaves and cane top removed from the cane at harvesting, and the

carbon absorption from the atmosphere into soil is negligible;

- 2) in general, CH₄ is primarily emitted from rice paddies and enteric fermentation in domestic livestock. CH₄ emission from sugarcane fields is negligible; and therefore
- 3) the primary GHG from soil during sugarcane cultivation is N₂O. Nitrogen sources are the nitrogen fertilizer and crop residues (i.e., cane top and leaves), as well as the nitrogen gas in the atmosphere fixed by the microorganisms.

The calculation of N₂O emission in the Tier 1 method is further divided into direct and indirect N₂O emissions in IPCC guidelines, in which the following parameters and conditions are needed: the quantity of nitrogen fertilizer used, yields of sugarcane, nitrogen content in the leaves of sugarcane and the climate region. In general, southern

Fig. 1 The scope of the system studied for new planting of sugarcane production



Taiwan, where Shanhua Works is located, is classified into the tropical region, because the Tropic of Cancer divides Taiwan at the middle. However, the classifications including warm, temperate and moist were applied in the Tier 1 method, according to the information provided by the flowchart in the IPCC guidelines.

To quantify GHG emissions with the Tier 3 method, the denitrification-decomposition (DNDC) model (Institute for the Study of Earth 2007) was used. As illustrated in Fig. 2, the DNDC model is a numerical model that simulates carbon and nitrogen biogeochemistry in agro-ecosystems incorporating data on climate, soils and farm management.

Table 2 Primary data sources

| Data categories | Sources |
|----------------------|--|
| Agricultural process | Agriculture and Food Agency 2006; Taiwan Sugar Corporation 1979; Water Resources Agency 2003–2005; Interview 2007; Chinese Fertilizer Association 2005 |
| GHG emissions | Bureau of Energy 2007; Eggleston et al. 2006; Working Group I, IPCC 2007 |
| Machineries | Taiwan Sugar Corporation 1979; Interview 2007; Chung Chuan Machinery Co., Ltd 2009 |
| Inputs of DNDC model | Taiwan Sugar Corporation 1979; Central Weather Bureau 2005–2007; Department of Soil and Environmental Sciences 1969 |

Table 3 Inventory data for sugarcane cropping system with 1 year new planting, 1 year ratoon and 1 year fallow cultivation

| Flows | Symbol | Unit | Quantity | Description |
|---|-----------------|-------------------------|--|---|
| Soil preparing(P1): Only for New Planting | | | | |
| Inputs | | | | |
| Fossil diesel | Dp | L/ha | 1.43×10^2 | Used by operation of agricultural machinery and transportation |
| Fertilizer: N | Fp ₁ | kg/ha | 60.0 | #2 Compound fertilizer (11-9-18) 5.56×10^2 kg/ha |
| Fertilizer: P | Fp ₂ | kg/ha | 50.0 | #2 Compound fertilizer (11-9-18) 5.56×10^2 kg/ha |
| Fertilizer: K | Fp ₃ | kg/ha | 50.0 | #2 Compound fertilizer (11-9-18) 5.56×10^2 kg/ha |
| Fallow Land | | ha | 1 | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xp | kg-CO ₂ /ha | 3.88×10^2 | Direct emission from fossil diesel used by agricultural machine |
| Methane (CH ₄) | Yp | kg-CH ₄ /ha | 2.18×10^{-2} | Direct emission from fossil diesel used by agricultural machine |
| Nitrous oxide (N ₂ O) | Zp | kg-N ₂ O /ha | 1.50×10^{-1} | Direct emission from fossil diesel used by agricultural machine |
| Prepared land | | Ha | 1 | |
| Sugarcane growing(P2): New Planting (N) and Ratoon (R) | | | | |
| Inputs | | | | |
| Water | Wg | L/ha | 2.47×10^6 | Irrigation |
| Fossil diesel | Dg | L/ha | 2.17×10^2 (N) 1.28×10^2 (R) | Used by operation of agricultural machines and transportation |
| Electric power | Eg | kWh/ha | 5.28×10 | Used by water pumps |
| Pesticide-Demeton-s-methyl | Pg ₁ | L/ha | 1.50 | |
| Pesticide-Oxydemeton methyl | Pg ₂ | L/ha | 1.25 | |
| Herbicide-2,4-D | Hg ₁ | kg/ha | 1.75 | |
| Herbicide-Glyphosate | Hg ₂ | L/ha | 7.50 | |
| Herbicide-Atrazine | Hg ₃ | kg/ha | 3.00 | |
| Herbicide-Ametryn | Hg ₄ | kg/ha | 2.00 | |
| Raticide | | | | |
| -Brodifacoum (Klerat) | Rg | kg/ha | 4.00 | |
| Fertilizer: N | Fg ₁ | kg/ha | 1.40×10^2 (N) 2.00×10^2 (R) | Ammonium sulfate (21-0-0) 6.61×10^2 kg/ha (N) Ammonium sulfate (21-0-0) 6.61×10^2 kg/ha + Compound fertilizer (11-9-18) 556 kg/ha (R) |
| Fertilizer: P | Fg ₂ | kg/ha | 0.00 (N) 50.0 (R) | No P containing fertilizer applied (N) Compound fertilizer (11-9-18) 556 kg/ha (R) |
| Fertilizer: K | Fg ₃ | kg/ha | 50.0 (N) 100.0 (R) | According to interview. However, what provide this amount of K is not given. (N) K fertilizer same as new planting + Compound fertilizer (11-9-18) 556 kg/ha (R) |
| Prepared land | | ha | 1 | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xg | kg-CO ₂ /ha | 5.92×10^2 (N) 3.50×10^2 (R) | Direct emission from fossil diesel used by agricultural machines |
| Methane (CH ₄) | Yg | kg-CH ₄ /ha | 3.31×10^{-2} (N) 1.96×10^{-2} (R) | Direct emission from fossil diesel used by agricultural machines |
| Nitrous oxide (N ₂ O) | Zg | kg-N ₂ O /ha | 2.28×10^{-1} (N) 1.35×10^{-1} (R) | Direct emission from fossil diesel used by agricultural machines |
| Sugarcane farm | | ha | 1 | |

Table 3 (continued)

| Flows | Symbol | Unit | Quantity | Description |
|--|----------------------------------|-------------------------|--|--|
| Sugarcane harvesting(P3): New Planting (N) and Ratoon (R) | | | | |
| Inputs | | | | |
| Fossil diesel | Dh | L/ha | 1.43×10^2 (N) 0.86×10^2 (R) | Use for operation of agricultural machinery and transportation |
| Sugarcane farm | | ha | 1 | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xh | kg-CO ₂ /ha | 3.90×10^2 (N) 2.34×10^2 (R) | Direct emission from fossil diesel used by agricultural machines |
| Methane (CH ₄) | Yh | kg-CH ₄ /ha | 2.18×10^{-2} (N) 1.32×10^{-2} (R) | Direct emission from fossil diesel used by agricultural machines |
| Nitrous oxide (N ₂ O) | Zh | kg-N ₂ O /ha | 1.51×10^{-1} (N) 0.91×10^{-1} (R) | Direct emission from fossil diesel used by agricultural machines |
| Sugarcane | | ton/ha | 80 (N) 40 (R) | |
| Land after using | | ha | 1 | |
| Sugarcane transportation(P4): New Planting (N) and Ratoon (R) | | | | |
| Input | | | | |
| Fossil diesel | Dt | L/ha | 1.36×10^1 (N) 0.96×10^1 (R) | Used by trucks |
| Sugarcane | | ton/ha | 80 (N) 40 (R) | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xt | kg-CO ₂ /ha | 3.71×10^1 (N) 2.60×10^1 (R) | Direct emission from fossil diesel used by trucks |
| Methane (CH ₄) | Yt | kg-CH ₄ /ha | 1.95×10^{-3} (N) 1.37×10^{-3} (R) | Direct emission from fossil diesel used by trucks |
| Nitrous oxide (N ₂ O) | Zt | kg-N ₂ O /ha | 1.95×10^{-3} (N) 1.37×10^{-3} (R) | Direct emission from fossil diesel used by trucks |
| Fertilizer manufacturing(P5): | | | | |
| Output | | | | |
| Carbon dioxide (CO ₂) | Xf | kg-CO ₂ /ha | 7.62×10^2 | Emission from fertilizer production from the cradle-to-gate life cycle stage |
| Methane (CH ₄) | Yf | kg-CH ₄ /ha | 1.74 | Emission from fertilizer production from the cradle-to-gate life cycle stage |
| Nitrous oxide (N ₂ O) | Zf | kg-N ₂ O /ha | 3.03 | Emission from fertilizer production from the cradle-to-gate life cycle stage |
| Fertilizer: N | Fp ₁ +Fg ₁ | kg/ha | 2.00×10^2 | #2 Compound fertilizer (11-9-18) 5.56×10^2 kg/ha and ammonium sulfate (21-0-0) 6.61×10^2 kg/ha |
| Fertilizer: P | Fp ₂ +Fg ₂ | kg/ha | 5.00×10 | #2 Compound fertilizer (11-9-18) 5.56×10^2 kg/ha |
| Fertilizer: K | Fp ₃ +Fg ₃ | kg/ha | 1.00×10^2 | #2 Compound fertilizer (11-9-18) 5.56×10^2 kg/ha and some unknown source (cut off) |
| Pesticide manufacturing(P6): | | | | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xpc | kg-CO ₂ /ha | 2.46×10 | Emission from pesticide production from the cradle-to-gate life cycle stage |
| Methane (CH ₄) | Ypc | kg-CH ₄ /ha | 5.83×10^{-2} | Emission from pesticide production from the cradle-to-gate life cycle stage |
| Nitrous oxide (N ₂ O) | Zpc | kg-N ₂ O /ha | 3.81×10^{-3} | Emission from pesticide production from the cradle-to-gate life cycle stage |
| Pesticide-Demeton-s-methyl | Pg ₁ | L/ha | 1.50 | |
| Pesticide-Oxydemeton methyl | Pg ₂ | L/ha | 1.25 | |

Table 3 (continued)

| Flows | Symbol | Unit | Quantity | Description |
|---|-----------------|-------------------------|--|---|
| Herbicide manufacturing(P7): Herbicides used for New Planting and Ratoon cultivation | | | | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xhc | kg-CO ₂ /ha | 1.42×10^2 | Emission from herbicide production from the cradle-to-gate life cycle stage |
| Methane (CH ₄) | Yhc | kg-CH ₄ /ha | 3.78×10^{-1} | Emission from herbicide production from the cradle-to-gate life cycle stage |
| Nitrous oxide (N ₂ O) | Zhc | kg-N ₂ O /ha | 2.21×10^{-2} | Emission from herbicide production from the cradle-to-gate life cycle stage |
| Herbicide-2,4-D | Hg ₁ | kg/ha | 1.75 | |
| Herbicide-glyphosate | Hg ₂ | L/ha | 7.50 | |
| Herbicide-atrazine | Hg ₃ | kg/ha | 3.00 | |
| Herbicide-ametryn | Hg ₄ | kg/ha | 2.00 | |
| Herbicide manufacturing(P7): Herbicides used for Fallow cultivation | | | | |
| Carbon dioxide (CO ₂) | Xhc | kg-CO ₂ /ha | 1.00×10^2 | Emission from herbicide production from the cradle-to-gate life cycle stage |
| Methane (CH ₄) | Yhc | kg-CH ₄ /ha | 2.38×10^{-1} | Emission from herbicide production from the cradle-to-gate life cycle stage |
| Nitrous oxide (N ₂ O) | Zhc | kg-N ₂ O /ha | 1.56×10^{-2} | Emission from herbicide production from the cradle-to-gate life cycle stage |
| Herbicide-Glyphosate | Hg ₂ | L/ha | 7.50 | |
| Herbicide-Atrazine | Hg ₃ | kg/ha | 3.00 | |
| Raticide manufacturing(P8): | | | | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xrc | kg-CO ₂ /ha | 4.46×10 | Emission from raticide production from the cradle-to-gate life cycle stage |
| Methane (CH ₄) | Yrc | kg-CH ₄ /ha | 1.06×10^{-1} | Emission from raticide production from the cradle-to-gate life cycle stage |
| Nitrous oxide (N ₂ O) | Zrc | kg-N ₂ O /ha | 6.92×10^{-3} | Emission from raticide production from the cradle-to-gate life cycle stage |
| Raticide-Brodifacoum (Klerat) | Rg | kg/ha | 4 | |
| Power generation(P9): | | | | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xe | kg-CO ₂ /ha | 3.37×10^1 | Direct emission from electric power generated |
| Electric power | Eg | kWh/ha | 5.28×10^1 | Used for water pumps |
| Fossil diesel refining(P10): | | | | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | Xd | kg-CO ₂ /ha | 2.35×10^2 | Emission from fossil diesel production from the cradle-to-gate life cycle stage |
| Methane (CH ₄) | Yd | kg-CH ₄ /ha | 6.21×10^{-1} | Emission from fossil diesel production from the cradle-to-gate life cycle stage |
| Nitrous oxide (N ₂ O) | Zd | kg-N ₂ O /ha | 6.00×10^{-2} | Emission from fossil diesel production from the cradle-to-gate life cycle stage |
| Fossil diesel | Dp+Dg+Dh+Dt | L/ha | 5.16×10^2 | Total fossil diesel used |
| Soil: New Planting (N), Ratoon (R) and Fallow (F) | | | | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | | kg-CO ₂ /ha | 0.00 | Direct emissions from soil (Tier 3 method) |
| Methane (CH ₄) | | kg-CH ₄ /ha | 0.00 | Direct emissions from soil (Tier 3 method) |
| Nitrous oxide (N ₂ O) | | kg-N ₂ O /ha | 1.02×10^1 (N) 0.99×10^1 (R) 0.38×10^1 (F) | Direct emissions from soil (Tier 3 method) |

Table 3 (continued)

| Flows | Symbol | Unit | Quantity | Description |
|-----------------------------------|--------|-------------------------|-----------------------|---|
| During fallow: Fallow only | | | | |
| Inputs | | | | |
| Fossil diesel | | L/ha | 83.3 | Used for operation of agricultural machines |
| Herbicide-glyphosate | | L/ha | 7.5 | |
| Herbicide-atrazine | | kg/ha | 3.0 | |
| Outputs | | | | |
| Carbon dioxide (CO ₂) | | kg-CO ₂ /ha | 2.27×10 ² | |
| Methane (CH ₄) | | kg-CH ₄ /ha | 1.27×10 ⁻² | |
| Nitrous oxide (N ₂ O) | | kg-N ₂ O /ha | 8.77×10 ⁻² | |

The results of emissions from soil quantified using Tier 1 and 3 methods are shown simultaneously in this study.

2.2.1 Indirect emissions related with the sugarcane industry

The emissions from power generation (P9), chemical manufacturing (P5~8) and fossil diesel refining (P10) are classified as indirect emissions from the sugarcane industry. Some of the indirect emission sources are disregarded in this study due to lack of data. For example, electric power is used to pump water for irrigation and GHGs are emitted in power conversion processes as well as from the cradle-to-gate life cycle stages of the fuel. However, the upstream processes (for example, extraction and transportation of fuels) of power generation are cut off from the model in our case study. According to Tokyo Electric Power Company (TEPCO 2009), an additional 10 to 30% of the direct GHG emissions occurred in the life cycle of the fuels including transportation, construction of capital goods such as the power plants and maintenance of the power generators. Because Taiwan is a neighbor of Japan, this figure could provide a rough magnitude of underestimation by this cut-off.

Chemicals are used to maintain good growth conditions and the suitable pest-free environment. For example, fertilizer is applied to provide sugarcane with nutrients and chemicals, such as herbicides, pesticides and raticides, are used to protect sugarcane against sickness and damage.

The formula used for estimation of emissions is shown in Eqs. 3 and 4 for power and chemicals (including fossil diesel), respectively.

$$E_p = Q_p \times EF_p \quad (3)$$

$$E_c = Q_c \times \phi_c \quad (4)$$

where

E_c : GHG emission inventories (emissions from resource extraction to P1~P4) of chemicals and fossil diesel, kg-CO₂-equiv.

E_p : GHG directly emitted from power generation, kg-CO₂-equiv.

EF_p : GHG emission factor of electricity in Taiwan, kg-CO₂-equiv./kWh

($EF_p=0.638$ kg-CO₂-equiv./kWh in 2006 (Bureau of Energy 2006))

ϕ_c : GHG emission inventory of chemicals and fossil diesel, kg-CO₂-equiv./kg or kL

Q_c : chemicals and fossil diesel used, kg or kL

Q_p : electricity generated, kWh

The GHG emission inventories are collected from GEMIS 4.4 (GEMIS Version 4.4 2009) using data from the literature (Patyk and Reinhardt 1997; Institut für Energie- und Umweltforschung 2002; Institut für angewandte Ökologie et al. 2004; Kaltschmitt and Reinhardt 1997) and Sheehan et al. (1998) for chemical manufacturing and fossil diesel refining, respectively.

2.2.2 Atmospheric CO₂ absorption by sugarcane

The calculation of the atmospheric CO₂ absorption (A_{CO_2}) is carried out by calculating carbon content in the stem of sugarcane (i.e., clean sugarcane, A_{C-stem}). This is because the roots, leaves and cane top are going to be left in the field after harvesting. The atmospheric CO₂ absorption is calculated by using Eq. 5.

$$A_{CO_2} = A_{C-stem} \times \frac{44}{12} \quad (5)$$

2.2.3 Characterization of global warming impact

The global warming impact is characterized using the global warming potential (GWP) with a time horizon of

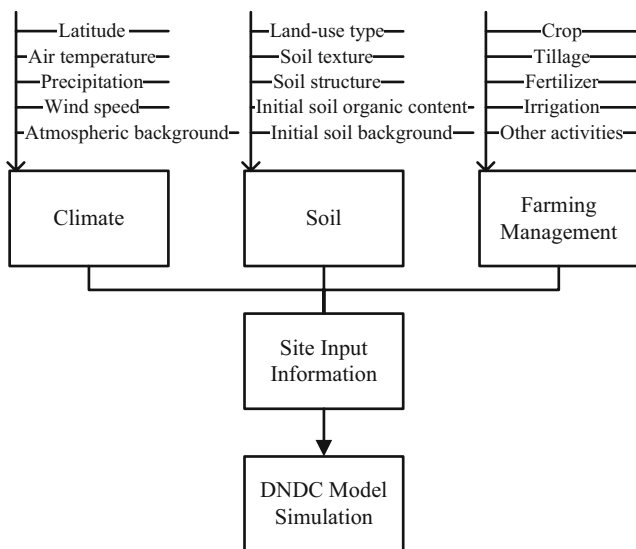


Fig. 2 Simulation flow and input data in DNDC model. The figure was organized in this study by consulting the literature (Institute for the Study of Earth 2007)

100 years. It should be noted that the methane emitted to the air will eventually be converted into CO_2 ; however, GWP does not include the impacts from the secondary compound.

2.3 Sensitivity analysis

The sensitivity of the results to the parameters in the inventory model is analyzed to understand the characteristics of the constructed model and the results obtained. The one-at-a-time (OAT) method, which varies only one parameter at a time, is used to understand to what the extent to which of the final results is sensitive to the fluctuation (or inaccuracy) of the value assigned to the parameters.

2.4 Equivalent impact level (EIL) lines

The quantified impact of focus (i.e., GHG emission in this case study) could be also be sensitive to changes in values of parameters related to irrigation, the number of times agricultural activities are carried out and the chemicals used. In the OAT method, correlations between parameters are disregarded. Nevertheless, in a study related to agricultural processes, the correlations between parameters are actually important. In particular, yield is correlated with the amount of fertilizer used, the number of times agricultural activities are carried out and the quantity of water for irrigation. For such obviously correlated parameters, the relationships between the correlation and changes in GHG emissions can be presented using equivalent impact level (EIL)

lines. The level lines are drawn by plotting the yield that would result in equivalent GHG emissions per ton of raw sugarcane as a function of values of chosen parameters that may influence the yield. The two lines were obtained by using different models, i.e., Tier 1 and 3 models, for the calculation of direct emissions from soil.

To obtain the level line, the first procedure is to choose a value (E_{tonL}) of GHG emission per ton of raw sugarcane. Then, a value of the parameter of focus (X_{agri}) and the yield of clean sugarcane (Y_1) are set. Next, GHG emission per hectare of sugarcane farm (E_{ha}) is calculated using the Tier 1 and 3 methods, which is further divided by E_{tonL} to gain new yield of clean sugarcane (Y_2). If the discrepancy between Y_1 and Y_2 remains significant, Y_1 is updated and the following calculations are repeated until it becomes insignificant. Finally, the converged yield for X_{agri} is plotted on the figure. The procedure above is iterated until the number of the points is sufficient to form a level line at E_{tonL} . The deductive method of level line is summarized as a flow chart in Fig. 3.

3 Results

3.1 Greenhouse gas emissions and absorption

The GHG emissions and absorption in sugarcane production by gas are listed in Table 4, which shows that approximately 107 and 248 $\text{kg-CO}_2\text{-equiv.}$ per ton of raw sugarcane production is emitted in total when emissions from soil are calculated by the Tier 1 and 3 methods, respectively. Because 386 $\text{kg-CO}_2\text{-equiv.}$ is absorbed, the net GHG emissions are found to be negative at -280 and -139 $\text{kg-CO}_2\text{-equiv.}$ per ton of raw sugarcane when the Tier 1 and 3 methods are applied, respectively. Among the three kinds of gases emitted, N_2O contributes the most at approximately 60 and 85% of the total global warming potential when the Tier 1 and 3 methods are applied, respectively.

Figure 4 shows the GHG emissions breakdown by process. Obviously the emissions from soil contribute the most, followed by emissions from the background process, namely the fertilizer manufacturing (P5), in which the contributions of N_2O and CO_2 are significant (around 53 and 45% of total emissions from P5). The emissions from main agricultural processes (P1~P3) are small but not negligible. On the other hand, the emissions from pesticide, herbicide and raticide manufacturing (P6~P8), power generation (P9) and fossil diesel refining (P10) are less significant. Note that all the emissions presented are from non-renewable resources, which means those are additional emissions associated with the production of sugarcane.

Among the utilities used in the agricultural processes, GHG emissions from fossil diesel, chemicals, power and soil accounted for 20.7, 28.3, 0.5 and 50.4%, respectively, as shown in Fig. 5, in which the result from Tier 3 method was used for the value in soil emissions. Emission from soil is identified as the major source to release GHGs, followed by emissions from chemicals and fossil diesel.

Regarding GHG emissions from soil, Fig. 4 shows that the results from the Tier 3 method using the DNDC model are less than half of the results from the IPCC Tier 1 method. The DNDC model is validated with measured data for several types of soils and land use (Beheydt et al. 2007); however, the 22 validated cases do not include sugarcane farms in tropical and temperate climate regions with the type of soil found in southern Taiwan. Therefore, although Tier 3 results offer localized results, the reliability of the results is not clear for the conditions in this study.

Understanding that emissions in this category are very important, and that sugarcane in tropical and temperate regions is an important potential resource, it is strongly recommended that field measurements for sugarcane farms in tropical and temperate areas be performed to validate the use of Tier 3 methods.

The GHG emission from fertilizer (P5) is the main source among the chemicals, consisting of nitrogen, phosphorus and potassium fertilizers. The emissions from nitrogen fertilizer manufacturing entail about 89% of total GHG emissions from fertilizer. With regard to emissions from nitrogen fertilizer manufacturing broken down by gas, the greatest contributor to global warming impact is N_2O , accounting for about 59%, followed by CO_2 , which contributes about 39% of the total. Those figures, however, might be different in the current situation. The Canadian Industry Program for Energy Conservation reports its fuel

Fig. 3 Deductive method of an equivalent impact level line for greenhouse gas emissions

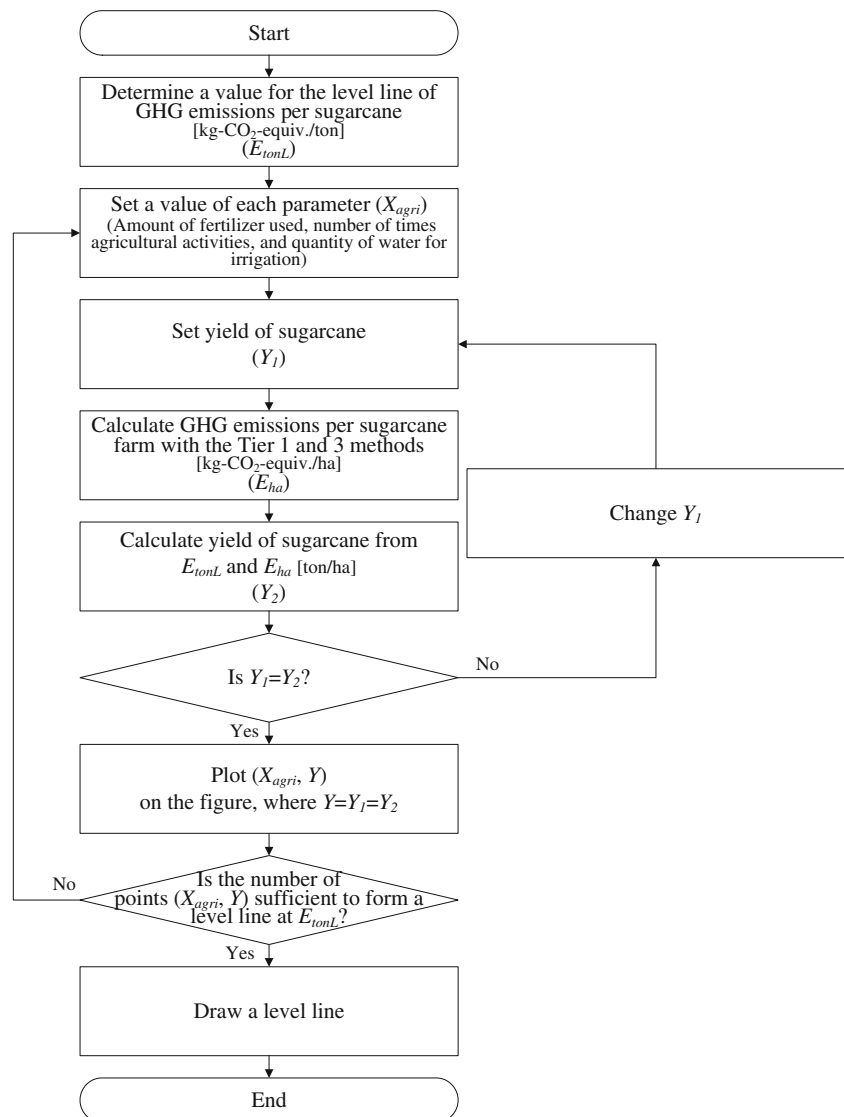


Table 4 Greenhouse gas emissions and absorption from 1 ton of raw sugarcane production by gases

| | Gas | Amount (kg) (a) | GWP ₁₀₀ (b) | kg-CO ₂ -equivalent (a) × (b) |
|-------------------|--------------------|----------------------------|---------------------------|---|
| Emissions | CO ₂ | 3.59 × 10 | 1 | 3.59 × 10 |
| | CH ₄ | 4.43 × 10 ⁻² | 25 | 1.11 |
| | N ₂ O | 2.35 × 10 ⁻¹ ** | 298 | 6.99 × 10 ** |
| | | 7.07 × 10 ⁻¹ * | | 2.11 × 10 ² * |
| | Total GHG emission | | | 1.07 × 10 ² ** |
| Absorption | CO ₂ | 3.86 × 10 ² | 1 | 3.86 × 10 ² |
| | | | | 2.48 × 10 ² * |
| Net GHG emissions | | | | -2.80 × 10 ² ** |
| | | | | -1.39 × 10 ² * |

Method used for calculation of N₂O emission from farmland: * Tier 1, ** Tier 3

efficiency improvement during 1991–2002 as 16% (CIPEC 2003) in Canada, one of the major producers and exporters. Aside from a reduction in CO₂ emission from energy use, the improvement could result in a simultaneous reduction in N₂O emission, which was found to be a major source within this category. This issue is reconsidered in the following sensitivity analysis section.

Among the GHG emissions related with fossil diesel consumption, sugarcane growing and harvesting emit more GHG emissions, accounting for 36% and 24% of the entire emissions in this category.

3.2 Sensitivity analysis

The results of sensitivity analysis are shown by a tornado graph in Fig. 6, in which the emission from soil is simulated by the Tier 3 method. Instead of a uniform perturbation range (for example, 1% of the value) that is

often used, in this study, we examined each parameter by assuming lower and higher limits. The values for 10 parameters out of 96 were shown in Table 5, chosen by the extent of sensitivity of the results to the changes in the parameter. Although identification of upper and lower values of the parameters could introduce subjectivity in the analyses, our approach, in return, better reflects our knowledge based on the characteristics of the parameters.

Figure 6 indicates that the result is most sensitive to the changes in parameters related with yields of sugarcane in ratoon and new planting cultivation, and to changes in the fertilizers’ consumption, especially for nitrogen fertilizer. The GHG emissions could vary within the range of 54.4–111.4 kg-CO₂-equivalent per ton of raw sugarcane, assuming variation of only one parameter at a time.

The top ten important parameters in this model (hereafter referred to as the Tier 3 model) are also used in the other model that applied the Tier 1 method for quantification of N₂O emission from soil (hereafter, the Tier 1 model). In Table 5, the sensitivity rank of the parameters in the Tier 1 model is added to elucidate the differences in the two models. Table 5 shows that most of the parameters in the Tier 3 model disappear from the top ten when the Tier 1

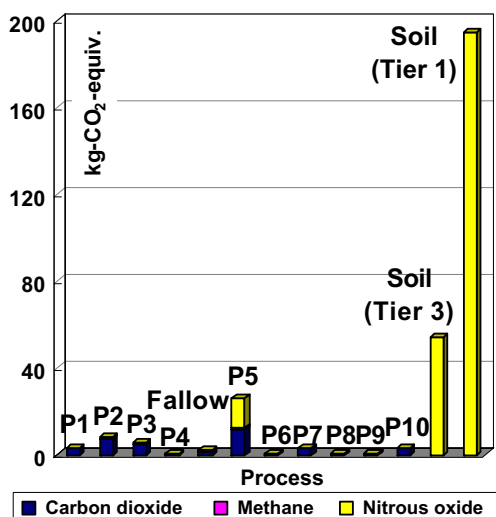


Fig. 4 Greenhouse gas emissions from 1 ton of raw sugarcane production by process

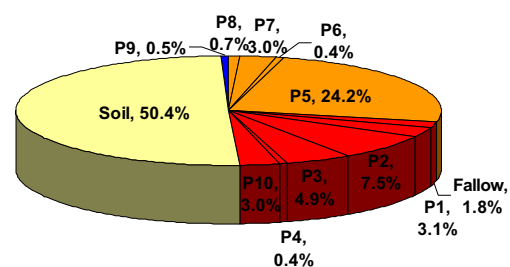


Fig. 5 Greenhouse gas emissions with the Tier 3 method by utilities in sugarcane industry. The utilities include 1) fossil diesel (P1–4, P10, fallow), 2) chemicals (P5–8), 3) power (P9) and 4) soil

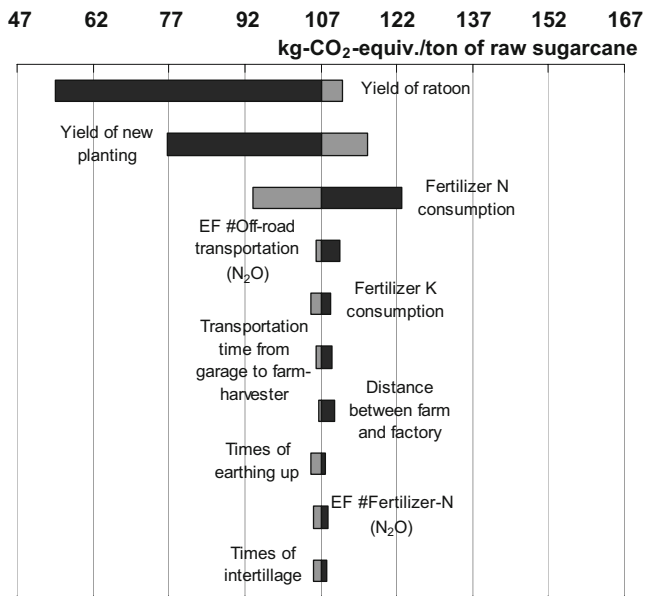


Fig. 6 Sensitivity analysis results using upper and lower values from Table 5 (based on Tier 3 calculation for emission from soil). Only the top 10 out of 96 parameters are displayed, ranked by the extent of sensitivity of the result (i.e., 107 kg-CO₂-equiv. / ton of raw sugarcane). Bars with lighter and darker colors show the value when lower and upper boundaries of the parameter are applied while maintaining other parameters at a base value, respectively

model is used. This change in rank occurs because the parameters related to the emission of N₂O are sensitive in both models and more parameters are introduced in the Tier 1 model as emission factors for various N₂O emission paths (ranked 1st, 2nd and 5th) and the parameters that affect those emission factors, such as the fraction of leached nitrogen in the added or mineralized nitrogen (6th), the nitrogen content in the leaves of sugarcane and weed (7th and 9th), and the biomass production of weed (10th).

Sensitivity of the results to the emission factor of nitrogenous fertilizer is more important in the Tier 3 model because emission from soil is smaller in Tier 3 model compared to the results from the Tier 1 model. Even so, its influence is limited to as low as No. 9. As mentioned before, the emission factor for nitrogenous fertilizer production could have been lowered since the data we use was reported. However, we set only a 10% range for the emission factor of N₂O due to fertilizer production, because most of the fertilizer in Taiwan is either produced domestically or imported from mainland China and from Saudi Arabia, not from Canada where a 16% fuel energy efficiency improvement is mainly due to the utilization of LNG fueled generators as a substitute for coal and oil fueled generators was reported.

Yields of sugarcane and consumption of nitrogen fertilizer are in the top 10 in sensitivity analyses with either of the models; consequently, a closer investigation of those two parameters is suggested when applying the results for end products such as bio-ethanol, biopolymers and sugar. In this study, we propose a further analysis using the EIL lines as presented in the next section.

As mentioned previously, the upstream emissions of power generation were cut off in this study. The sensitivity analysis together with the hot-spot analysis results show that the additional 10–30% emission associated with power only has an insignificant influence on our results.

3.3 Equivalent impact level (EIL) line

It is noteworthy that the result is also sensitive to changes in values of parameters related to irrigation, the number of times agricultural activities are carried out and the chem-

Table 5 The lower, base and upper values of the parameters in the sensitivity analysis

| Parameters | Lower | Base | Upper | Sensitivity rank | |
|--|----------|----------|----------|------------------|--------|
| | | | | Tier 1 | Tier 3 |
| Yield of ratoon (ton/ha) ^{(a)(b)(c)} | 35 | 40 | 162.5 | 3 | 1 |
| Yield of new planting (ton/ha) ^{(a)(b)(c)} | 70 | 80 | 130 | 4 | 2 |
| Fertilizer N consumption (kg/ha) ^{(a)(c)(d)} | 160 | 200 | 250 | 8 | 3 |
| EF #Off-road transportation (N ₂ O) (kg/TJ) ^(e) | 14.3 | 28.6 | 85.8 | 13 | 4 |
| Fertilizer K consumption (kg/ha) ^{(a)(c)(d)} | 0 | 100 | 200 | 16 | 5 |
| Transportation time from garage to farm-harvester (hr) ^{(b)(c)} | 0.167 | 0.417 | 1.00 | 17 | 6 |
| Distance between farm and factory (m) ^{(b)(c)} | 0.100 | 3.00 | 25.0 | 18 | 7 |
| Times of earthing up ^{(a)(c)} | 1 | 2 | 3 | 24 | 8 |
| EF #Fertilizer N (N ₂ O) (kg/kg) ^(f) | 1.36E-02 | 1.51E-02 | 1.66E-02 | 20 | 9 |
| Times of intertillage ^{(a)(c)} | 1 | 2 | 3 | 19 | 10 |

The upper and lower values refer to (a) Taiwan Sugar Corporation 1979; (b) assumption; (c) interview; (d) Chinese Fertilizer Association 2005; (e) Eggelston et al. 2006; (f) GEMIS 2009

icals used. For such obviously correlated parameters, the relationships between the correlation and changes in GHG emissions are presented using equivalent impact level (EIL) lines as presented in Fig. 7.

The EIL lines represent the minimum yields that are required if the impact is to be maintained at the current level of impact, when the parameter is modified on the horizontal axis. Therefore, the EIL lines could be used to introduce considerations of environmental impacts, ex. GHG emissions in our case study, when decisions about the modification of agricultural processes are made. For example, if yield could be increased as much as 5 ton per hectare in the three year cropping cycle through +5% of additional nitrogenous fertilizer, it could result in a reduction of life cycle GHG emissions per ton of sugarcane, because Fig. 7a shows that the assessed situation is located over the level line for nitrogenous fertilizer.

3.4 Application of results from the EIL line

The EIL line aims to provide guidance in reconsideration of agricultural options. The case study presented in this paper demonstrates such investigation by taking

GHG emissions to represent the environmental impact being focused. However, other impact categories are also considered crucial in evaluation of biomass resource in general. For example, water consumption would be of particular importance in Taiwan. Just as in the case of GHG emissions, emissions of other pollutants and consumption of resources can be explored using EIL lines as demonstrated in this study. Synthesizing an EIL line for an aggregated impact would also be straightforward if impact aggregation methods are available.

Land use is an impact category which requires special attention in our methodology. Land use impact category includes land occupancy and land use change. Land occupancy is not within the scope of analysis using EIL lines, because yield (i.e., production per hectare of land) is chosen as the vertical axis of the coordinate. The results from EIL lines and planned land occupancy should be used together in planning of biomass resource development. Importance of land use change impact has been elucidated in a recent study (Searchinger et al. 2008), in which evaluation of the carbon stock released from the original state of use after the change is highlighted. As mentioned previously, the assumption

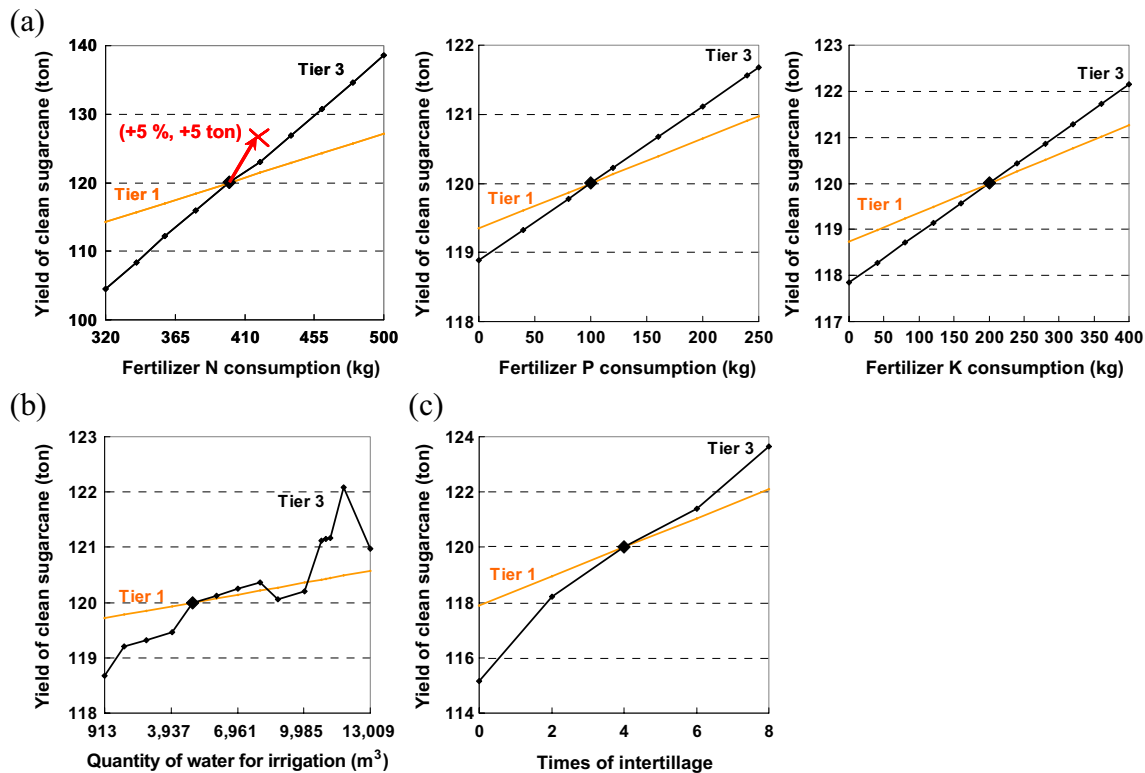


Fig. 7 Equivalent impact level lines for greenhouse gas emissions. Yields of sugarcane that make the greenhouse gas emission per ton of raw sugarcane equivalent with the emission in the base calculation are

shown as a function of (a) quantity of fertilizer used, (b) quantity of water for irrigation and (c) times of intertillage

applied in our case study assumed a steady state; i.e., no change in the carbon stock. If this assumption is to be modified, the carbon stock change needs to be accounted for. Similar perspectives could be taken for other kinds of impacts associated with pollutants released in land reclamation or construction of new processing facilities.

To account for land use change impacts, two approaches can be taken. The first approach is to conduct break-even (payback) analysis considering an impacts over time dimension. For example, if the net GHG emission excluding release of carbon stock due to land use change is negative for the products derived from the sugarcane, the released carbon should be eventually be paid back after several cropping cycles, as already demonstrated in the preceding study (Searchinger et al. 2008). In this case, the break-even analysis should be conducted separately from the analysis using an EIL line. Another approach would be to equalize the impact to the products produced over a certain depreciation period. For example, if 10 cropping cycle are chosen, the impacts associated with the land use change should be allocated to 1,200 tons of sugarcane produced in 30 years. If this approach is taken, it becomes possible to use EIL lines in an analysis where land use change needs to be considered. However, no general guidance is found for setting a depreciation period for land use change.

In this study, all the presented information related to sugarcane variation is based on the general situation in Taiwan, which is a mixture of ROC 10, ROC16, ROC24, etc. The first three are the main sugarcane variations grown in Taiwan in recent years (Wang 2005). However, it should be noted that different variations would have different content of sugar and of other substances such as cellulose and protein that are crucial in the production of final products. Furthermore, different variations would also show different yields over multiple years in the cropping system. Considering that the breed improvement of sugarcane is actively aiming at leveraging the advantage of sugarcane as a valuable resource in an ongoing fashion, an extensive study on different variations would benefit the future design of bio-resource cultivation strategies; however, such analysis is beyond the scope of this paper. Those who attempt to apply the results presented in this study must pay attention to possible differences in variations.

4 Conclusions

The net GHG emissions associated with sugarcane production in Taiwan is about -280 kg-CO₂-equiv. per ton of raw sugarcane. Among the net GHG emissions, the GHG emissions and absorption are about 107 and -386 kg-CO₂-

equiv. per ton of raw sugarcane production respectively. The highest emission source is the denitrification reactions in the ecological system of soil during sugarcane cultivation, which accounts for 50.4% of total GHG emissions. The intermediate emission sources are fertilizer manufacturing and refining and the use of fossil diesel, contributing to 28.3% and 20.7% of the total GHG emissions, respectively. Power generation contributes less than 1% of the total GHG emissions.

According to sensitivity analysis using the OAT method, the total amount of GHG emissions was most sensitive to possible changes in yields of sugarcane in ratoon and new planting cultivation. Variations in consumption of nitrogen fertilizer were also found to be important. Application of nitrogen fertilizer leads to significant N₂O emission from soil and, because the GWP₁₀₀ of N₂O is large, it affects the result significantly. However, the result from the OAT method might be inaccurately representing the sensitivities, because of the inherent correlations among the parameters. Consequently, a closer investigation of nitrogen fertilizer application is suggested when applying the results for end products such as bio-ethanol, biopolymers and sugar.

To more correctly evaluate how parameters affect the GHG emission changes, a decision tool called EIL lines is proposed. It articulates the sensitivity of correlated parameters such as fertilizer application and yield and, at the same time, can be used to assess consequential changes in impacts when agricultural parameters are modified for aiming at a reduction of impact. EIL lines for equivalent GHG emissions are provided for the case study to support decisions in improvement of agricultural processes. If the envisioned yield as a result of modification of agricultural parameters such as irrigation, tillage and fertilization is maintained above the respective EIL line, GHG emission per ton of sugarcane would not be increased.

5 Recommendations and perspectives

Results from this study require appropriate modification if they are to be used for studies considering development of new farms transformed from other form of nature, or studies in other regions. Such modifications would be straightforward, because all inventory data and assumptions are presented in this paper. Essentially, the functional unit used in this study is the unit amount (by weight) of sugarcane. If some specific content (for example, sucrose or cellulose) is important in a study which attempts to use results from this study, variations in content over cultivation methods and cultivar of sugarcane must be considered further.

Acknowledgement The study was supported in part by a Grant-in-Aid for Young Investigators (C034) from National Cheng Kung University. Preliminary results were presented at the 3rd annual meeting of the Institute of Life Cycle Assessment, Japan, in March 2008. Useful comments from participants in the conference, Mr. Satoshi Ohara of Asahi Breweries and the farmers of Shanhua work place of Taiwan Sugar Corporation are deeply appreciated.

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