The Carbon and Water Footprint Assessment of Cassava-based Bioethanol Production in Thailand

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***Abstract*—** This study aims to evaluate carbon footprint (CF) and water footprint (WF) of bioethanol production from cassava in Thailand. Scope of the study is “cradle-to-gate” approach by evaluating all stages of product’s life cycle including feedstock cultivation, transportation, feedstock processing, ethanol conversion, and on-site waste management. This study has three present commercial cassava-based bioethanol case studies used cassava chip as feedstock from different region of Thailand and used different fuel in steam production such as fuel oil, biomass, and biogas. All three case studies used electricity from national grid and have wastewater treatment system. GHG emissions of bioethanol production from cassava of case study 1, 2, and 3 are 0.562, 1.058, and 0.734 kg-CO_2-eq/l-ethanol, respectively. WF of bioethanol from cassava of case study 1, 2, and 3 are 1.549, 1.532, and 1.653 m^3/l-ethanol, respectively.

***Keywords*—** Carbon footprint, Water footprint, Cassava, Ethanol

I. Introduction

Currently, environmental sustainability is a topical issue that receives plenty of attention from the media and from different governmental departments. The increasing of energy consumption in the world and the depletion of fossil fuel reserves has encouraged the researches and development on renewable and sustainable energy resources. Bioethanol is one of major role in renewable energy for transport since the price of oil has been growing. Consequently, water scarcity and climate change became significant issues for creating a stable sustainability strategy.

Carbon footprint is an indicator that estimates the climate change impact of product, service or activity, which according to Intergovernmental Panel on Climate Change (IPCC) is related to climate change issue. Typically, a carbon footprint is calculated by estimating not just the CO_2 emissions, but also any emissions of other greenhouse gases (GHG) such as methane and nitrous oxide as well. The water footprint (WF) is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. The water footprint is a geographically explicit indicator, showing not only volumes of water use and pollution, but also the locations.

The life cycle environmental assessment of cassava-based bioethanol in Thailand have been conducted in several studies [1]-[3], most of these studies suggested that utilization of biomass and biogas substituted of fossil fuel in steam production could reduce the environmental impact.

For GHG emission assessment of bioethanol production, the previous studies [4]-[7] showed the result that GHG emission from bioethanol depend on many factors, such as feedstock, farming practices, industrial location and technology, and by products processing and on-site waste management.

Water footprint assessment of bioethanol has been assessed in several studies [8]-[11] from different countries and different feedstock such as corn, sweet potatoes, sugarcane, and sweet sorghum. Most of these studies have been based on a pilot plant of ethanol. The result for actual commercial plant may be different from the pilot plant depending on capacity of production, plant technology, skill of operators, etc.

This study aims to evaluate carbon footprint (CF) and water footprint (WF) of bioethanol production from cassava in Thailand. The life-cycle inventory analysis was based on ISO14040 for all stages that related to the production of 1 liter of 99.8% ethanol from cassava included cultivation and harvesting of cassava, cassava transportation, cassava chip processing, ethanol conversion, and on-site waste management. WF of bioethanol production is calculated following the WF assessment manual by Hoekstra [12]. For inventory data that were used in this study, cassava chip production and bioethanol conversion input-output data were collected from primary source at actual site in Thailand.

In case the Thai government support bioenergy as a substitute for fossil fuel, the effect on environmental impact in bioethanol production is likely to increase and consequently the significant problem would be global warming and water scarcity in Thailand, provided GHG emissions and water resources are not appropriate managed.

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II. Methodology

A. Goal and Scope Definition

This study aims to assess the CF and WF of bioethanol production from cassava based on a life-cycle approach, the functional unit (FU) of this study is 1 liter of 99.8% bioethanol production from cassava.

Scope of life cycle assessment is “cradle to gate” including cultivation and harvesting of feedstock, feedstock transport, feedstock processing, ethanol conversion, by products processing and on-site waste management. The mixing process of ethanol to gasoline and combustion of using stage are not in this study scope.

B. Description of Case Studies

This study has three present commercial cassava-based bioethanol case studies. Table I summarizes the three case studies of cassava-based bioethanol plants that were selected in the study, the data obtained from actual site interview of bioethanol plants in Thailand.

TABLE I
DESCRIPTION FOR EACH CASE STUDY

	Case 1	Case 2	Case 3
Feedstock cultivation area	Northeastern	Central	Central + Northeastern
Wastewater treatment	MUR	UASB	UASB
Biogas utilizing	✗	✓	✓
Fuel in steam production	Wood chip, Rice husk	Fuel oil, Biogas	Wood chip, Biogas

1. Case Study 1

This case study uses cassava chip from north-eastern region of Thailand as feedstock for ethanol production and has Methane Upflow Reactors (MUR) wastewater treatment system but not utilized the biogas as energy source for steam production. Biomass such as wood chip and rice husk uses as primary fuel for steam generation. All electricity required for ethanol production is purchased from national grid.

2. Case Study 2

This case study uses cassava chip from central region of Thailand as feedstock for ethanol production. This plant has Upflow Anaerobic Sludge Blanket (UASB) wastewater treatment system and utilized the biogas for steam production. Both biogas and fuel oil uses as primary fuel for steam generation in ethanol plant. All electricity required for ethanol production is purchased from national grid.

3. Case Study 3

This case study uses cassava chip from central and north-eastern regions of Thailand as feedstock for ethanol production. This plant has Upflow Anaerobic Sludge Blanket (UASB) wastewater treatment system and utilized the biogas for generating steam. Biogas and biomass uses as primary fuel for steam generation in the plant. All electricity required for ethanol production is purchased from national grid.

C. Product Life Cycle Inventory Data

In this study, cassava chip production and bioethanol conversion input-output data were collected from primary sources at actual sites in Thailand. The secondary data were use in cassava cultivation stage from the literature review [13]. A summary of data sources is shown in Table II. The details of each stage are described in following sections below.

1. Cassava Farming Stage

In this stage, the farming activities included land preparing, seed planting, fertilizing, weeding, and harvesting. The background data were gathered from literature review [13] and CO_2 emission from land use changes were excluded in this study. The harvested fresh cassava roots are transported to nearby cassava chip processing factories.

2. Cassava Chip Processing Stage

In this stage, the cassava chip processing activities included weight measurement of harvested cassava roots, cassava roots chopping, and cassava chip drying. The data in this stage were collected and averaged from actual cassava chip processing factories in Thailand.

3. Ethanol Conversion Stage

In this stage, the ethanol conversion in bioethanol plants included crushing, mixing, liquefaction, saccharification, fermentation, distillation, and dehydration. In this study, data were collected from actual cassava-based ethanol plants in Thailand. The emissions from combustion of fuel in steam production process, emissions from electricity used in plants and water emissions after wastewater treatment systems were accounted.

4. Transportation Stage

In this stage, the transportation activities included the transport of feedstock from the cassava field to the cassava chip factories, of cassava chip to the ethanol plant, and of chemical substances that were used in ethanol plant. The data in this data were collected from actual site interview.

TABLE II
DATA SOURCE FOR PERFORMING LCA ANALYSIS

Life cycle stage	Data source
Cassava farming	Secondary data from literature review [13]
Cassava chip processing	Primary data from cassava chip factories and on site interview
Ethanol conversion	Primary data from cassava-based bioethanol plants and on site interview
Transportation	Primary data from cassava-based bioethanol plant and on site interview

D. Carbon Footprint

Life Cycle Assessment (LCA) produces complete picture of inputs and outputs with respect to generation of air pollutions, water use and wastewater generation, energy consumption, GHGs emitted, or any other similar parameters of interest.

This assessment is often called as environmental LCA. For carbon footprint purpose, LCA assesses the GHGs emitted and embodied at each identified step of product's life cycle, also known as GHG accounting.

This carbon footprint (CF) method was developed for assessing the GHG emissions of good and services throughout their life cycle stage and assesses a single indictor for climate change by IPPC [14]. For assessing carbon footprint, the amount of GHG emitted, removed, or embodied in life cycle of product has to be estimated. CF is based on the GHG emissions identified and quantified in the stages of system boundary. The most common and significant GHGs are not only carbon dioxide (CO_2) but also methane (CH_4) and nitrous oxide (N_2O) as well.

To assess the CF of bioethanol from cassava, we used the following source of emission factor to estimate the GHG emissions: GHG emission factors from Thai national database and ecoinvent database [15]. The GHG emission factors for fuel, material, and chemical substances are listed in Table III. GHG emissions from fuel combustion calculated based on the IPCC Guidelines for National Greenhouse Gas Inventories [14].

TABLE III
EMISSION FACTORS FOR MATERIALS AND CHEMICAL SUBSTANCES

Materials and chemical substances	GHG emission factor (kg-CO_2eq./kg)
Urea	3.3036
Sodium hydroxide	1.1148
Sulfuric acid	0.1219
Enzyme	1.1500
Yeast	0.6170
Aluminium sulphate	0.5311
Poly aluminium chloride	0.2770
Chlorine	1.0548
Wood chip	0.0818
Fuel oil	0.3057
Diesel	0.3282

E. Water Footprint

The concept of water footprint (WF) was introduced by Hoekstra in 2002. WF is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. The WF consists of three components: blue, green, and grey water footprint [12].

1. Blue Water

The blue water footprint is volume of surface and groundwater consumed as a result of the production of a good or service. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. It also includes water abstracted from surface or groundwater in a catchment and returned to another catchment or the sea. It is the amount of water abstracted from groundwater or surface water that does not return to the catchment from which it was withdrawn.

2. Green Water

The green water footprint is volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood [12].

3. Grey Water

The grey water footprint is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards.

The WF of cassava cultivation stage is calculated followed the WF assessment manual by Hoekstra (2011). At first step, evapotranspiration (Etc) is calculated over the growing stage of crop using CROPWAT 8.0 model which was developed by the Food and Agriculture Organization of the United Nation (FAO). Crop water requirement (CWR), and irrigation are evaluated base on climatological data for the period 1985-2014 from the Meteorological Department of Thailand, soil data from FAO, and crop data from literature review [16], [17], [18]. In this study, the CWR is calculated on the basis of following assumption:

- No irrigation [13]
- Plantation date is at 1st May [19]
- Soil is Red Sandy Loam [20]

For calculating of green and blue WF of cassava cultivation stage, calculation is the crop water use from CROPWAT 8.0 model divided by crop yield. For calculating of grey WF, calculation is following equation (1): multiplying of chemical application rate (AR) and the leaching run off fraction (α) divided by the maximum acceptable concentration (C_{max}) minus the natural concentration for pollutant considered (C_{nat}) and the divided by crop yield (Y).

$$WF_{grey} = \frac{(\alpha \times AR)/(C_{\max} - C_{nat})}{Y} \quad (1)$$

The total WF of bioethanol production from cassava is sum of blue, green, and grey WF from cassava cultivation stage plus sum of blue and grey water from bioethanol conversion stage.

III. RESULTS AND DISCUSSIONS

A. Carbon Footprint

The CF for three case studies is shown in Fig. 1. GHG emissions per 1 liter (20.5 MJ) of bioethanol from cassava of case study 1, 2 and 3 are 0.562, 1.058, and 0.734 kg-CO_2-eq/l-ethanol, respectively. These result showed that cassava-based ethanol production in Thailand proposes the carbon footprint reduction of their product depends on the plant type.

Case study 2 has the highest GHG emissions because of fuel oil that used as fuel in the steam production have high CO_2 emission compared to another case studies use biomass and biogas as fuel in steam production. If biomass was fuel that used in the boiler to produce steam from waste, it gave no environmental burden but the data of biomass production was included. CO_2 emission from combustion process was excluded according to carbon neutral rule.

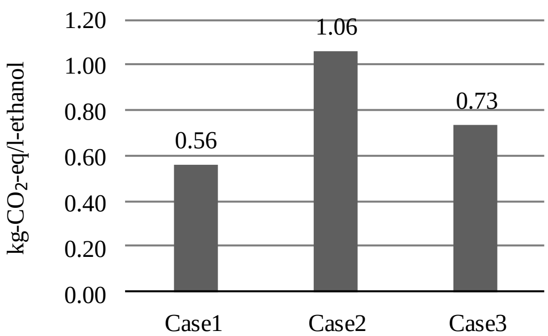


Fig. 1 Carbon footprint of three case studies

Focusing on CF of steam production, GHG emissions for produces 1 liter of bioethanol from the steam production of case study 2 is 0.552 kg-CO_2-eq/l-ethanol while the case study 3 is 0.192 kg-CO_2-eq/l-ethanol, reduce the GHG emission by 65 %.

TABLE IV
CARBON FOOTPRINT OF 1 LITER ANHYDROUS ETHANOL PRODUCTION

	Bioethanol using different fuel in steam production			
	Biomass and biogas		Coal and biogas [4]	
	kg-CO_2-eq/l-ethanol	%	kg-CO_2-eq/l-ethanol	%
Cassava chip	0.292	40	0.372	34
Chemical	0.042	6	0.154	14
Electricity	0.183	25	0.120	11
Steam	0.192	26	0.411	37
Process water	0.001	0	0.007	1
Transportation	0.025	3	0.033	3
Total	0.735	100	1.097	100

Table IV shows the comparison between case study 3 in this study and literature review [4] in case of cassava-based bioethanol plant that using coal and biogas as fuel in steam production. From this table, it can be seen that substitution of biomass such as wood chip for coal as fuel in boiler combustion to produces a steam has shown to be better for carbon footprint reduction.

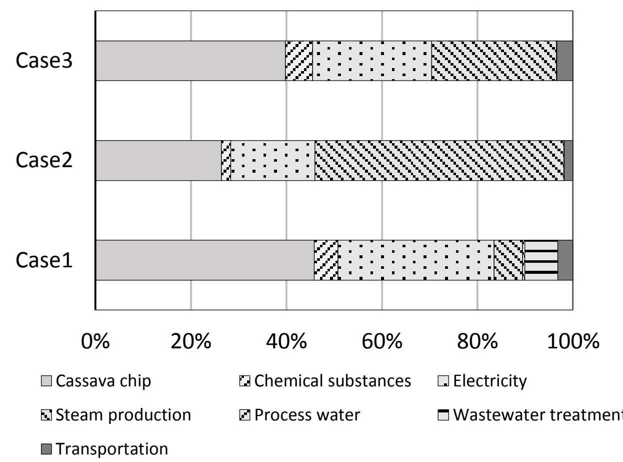


Fig 2 CF contribution for three bioethanol plants cases

Case study 1 has the lowest GHG emissions because the wastewater that generated before the treatment is lower in Chemical Oxygen Demand (COD) compared to other case studies. COD of case study 1 is approximately 14 kg/m^3 while the case study 2 and 3 are 40 kg/m^3. This effect causes the case study 1 generated biogas less than other cases.

If the case study 3 has a new scenario that was not utilizing biogas from wastewater treatment system, CF of this new scenario is 0.746 kg-CO_2-eq/l-ethanol. From this result, the study showed that the biogas utilizing could reduce the GHG emissions.

TABLE V
GHG EMISSION RESULT COMPARED IN DIFFERENT STUDIES

Bioethanol feedstock	Region	GHG emission
Cassava chip	Thailand	0.552- 1.058 kg-CO_2-eq/l-ethanol
Corn [21]	China	9.171 kg-CO_2-eq/l-ethanol
Sugarcane [5]	Brazil	0.436 kg-CO_2-eq/l-ethanol

As Table V indicates, the GHG emissions of bioethanol production results of different studies, including Thailand and other countries, are compared. The result showed that the GHG emissions are from cassava-based ethanol in Thailand more than sugarcane bioethanol in Brazil but extremely lower than corn bioethanol in China.

B. Water Footprint

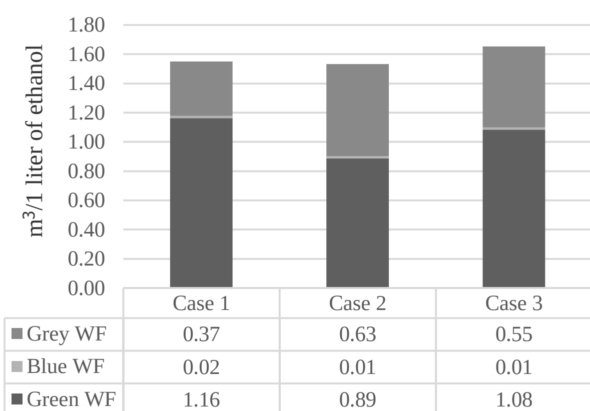
Cassava cultivation areas for the study are from two regions of Thailand (north-eastern and central). The environmental impact of herbicide and pesticide using has not been included. For crop water use calculation, cassava's crop coefficient (K_c) of initial stage, mid-season stage, and late season stage are 0.28, 1.13, and 0.61 respectively and more than 99 % of farmer does not use water irrigation for cassava farming. Growth stage are 150 days in initial stage, 40 days in development stage, 110 days in mid-season stage, and 60 days in late season stage. For grey WF calculation, The nitrogen leaching run off fraction is assumed to be 0.1 and the maximum acceptable concentration for nitrate in fairly clean fresh surface water resources used for industry and consumption but requires special water treatment process before using is 0.005 kg/m^3. Table VI shows average fertilizer application rate and nitrogen leaching for cassava cultivation.

TABLE VI
AVERAGE FERTILIZER APPLICATION RATE AND NITROGEN LEACHING

Region	Fertilizer application rate (kg/rai)			Nitrogen leaching
	N	P_2O_5	K_2O	
Northern	10.47	4.35	5.01	1.047
Northeastern	10.97	8.04	9.54	1.097
Central	23.69	12.43	14.93	2.369

WF of cassava varies in the different regions. From the result, it showed that the yield, climate, and fertilizer application have an effect on WF of bioethanol. WF of fresh cassava compared to other studies is shown in Table VII. From this table, the WF in this study is lower than literature review because cassava farming in Thailand has no water irrigation [13].

Focusing on bioethanol production stage, the average water use for produce 1 liter of ethanol from this study is 0.014 m^3 that include process water and softener water in steam production. Average generated wastewater from this study 0.00752 m^3/l of ethanol. The total green, blue, and grey WF of three case studies of cassava-based bioethanol production in this study are shown in Fig 3. WF per 1 liter of bioethanol from cassava of case study 1, 2 and 3 are 1.549, 1.532, and 1.653 m^3, respectively. More than 95% of grey WF is from cassava cultivation stage.



	Case 1	Case 2	Case 3
Grey WF	0.37	0.63	0.55
Blue WF	0.02	0.01	0.01
Green WF	1.16	0.89	1.08

Fig 3. Water footprint of three case studies

Case study 1 has the highest blue WF because this case use more process water compared to another case. In contrast, the wastewater that generated before the treatment is lower in Chemical Oxygen Demand (COD) compared to other case studies also. Focusing on grey WF, amount of generated wastewater of the case study 2 is lowest of all three case studies, but the case study 2 has highest grey WF because the cassava feedstock from central region in Thailand that have highest nitrogen fertilizer application rate.

TABLE VII
WATER FOOTPRINT OF FRESH CASSAVA

Region	WF of fresh cassava (m^3/ton)			
	Green	Blue	Grey	Total
This study	178.08	0	78.58	256.96
Northern Thailand [22]	192.00	232.00	85.00	509.00
Thailand [11]	415.70	183.80	0	599.50
Global [23]	550.0	0	13.0	563.00

IV. CONCLUSION

In this study, the results show that CF very important to different cassava-based ethanol plant. Using fossil fuel such as fuel oil and coal as primary fuel in the steam production greatly effects to GHG emissions enlargement. In contrast, using biomass such as wood chip and rice husk substitutes for fossil fuel as primary fuel in steam production greatly effects to GHG emissions reduction. However, the utilization of biogas in steam production insignificantly reduces the GHG emissions, if primary fuel in steam production is biomass. The highest blue WF of bioethanol from cassava for case study 1 is 0.016 m^3/l-ethanol. By the way the case study 1 has lowest CF compare to other case studies because this case used more process water that cause generated wastewater before the treatment is lowest in COD. The result of WF in this study should be determined by other factors such as soil, climate, and plantation date.

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REFERENCES

[1] T. L. T. Nguyen and S. H. Gheewala, "Life cycle assessment of fuel ethanol from cassava in Thailand," *The International Journal of Life Cycle Assessment*, vol. 13, no. 2, pp. 147-154, 2007 http://dx.doi.org/10.1065/lca2007.06.343.

[2] T. Silalertruksa and S. H. Gheewala, "Environmental sustainability assessment of bio-ethanol production in Thailand," *Energy*, vol. 34, no. 11, pp. 1933-1946, 2009. http://dx.doi.org/10.1016/j.energy.2009.08.002

[3] S. Papong and P. Malakul, "Life-cycle energy and environmental analysis of bioethanol production from cassava in Thailand," *Bioresource technology*, vol. 101 Suppl 1, no. pp. S112-8, 2010.

[4] Y. Moriizumi, et al., "Effect of biogas utilization and plant co-location on life-cycle greenhouse gas emissions of cassava ethanol production," *Journal of Cleaner Production*, vol. 37, no. pp. 326-334, 2012.

[5] L. Wang, et al., "Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward," *Renewable and Sustainable Energy Reviews*, vol. 40, no. 0, pp. 571-582, 2014. http://dx.doi.org/10.1016/j.rser.2014.07.212

[6] L. T. Le, et al., "Energy and greenhouse gas balances of cassava-based ethanol," *Biomass and Bioenergy*, vol. 51, no. pp. 125-135, 2013.

[7] B. Liu, et al., "Energy balance and GHG emissions of cassava-based fuel ethanol using different planting modes in China," *Energy Policy*, vol. 56**,** no. 0, pp. 210-220, 2013.
http://dx.doi.org/10.1016/j.enpol.2012.12.052

[8] W2. Gerbens-Leenes and A. Y. Hoekstra, "The water footprint of sweeteners and bio-ethanol," *Environment International*, vol. 40**,** no. 0, pp. 202-211, 2012.
http://dx.doi.org/10.1016/j.envint.2011.06.006

[9] P. Chooyok, N. Pumijumnog, and A. Ussawarujikulchai, "The Water Footprint Assessment of Ethanol Production from Molasses in Kanchanaburi and Supanburi Province of Thailand," *APCBEE Procedia*, vol. 5**,** no. 0, pp. 283-287, 2013.
http://dx.doi.org/10.1016/j.apcbee.2013.05.049

[10] .-H. Su, et al., "Water footprint analysis of bioethanol energy crops in Taiwan," *Journal of Cleaner Production*, vol. 88**,** no. 0, pp. 132-138, 2/1/ 2015.

[11] S. Pongpinyopap, T. Mungcharoen, *"Water footprint of bioethanol production from cassava in Thailand (in Thai version),"* 2011.

[12] Arjen Y. Hoekstra, et al., *The Water Footprint Assessment Manual*. Washington, DC, Earthscan, 2011.

[13] Research Unit for Energy Economic & Ecological Management, *Life cycle of water from sugarcane and cassava plantation for ethanol production*. Chaing Mai University, 2011.

[14] IPPC, *IPCC Guidelines for National Greenhouse Gas Inventories*. IGES, Japan, International Plant Protection Convention, 2006.

[15] Ecoinvent, *Swiss Center for Life Cycle Inventories,* Switzerland, 2006.

[16] P. Namkwang, B. Kwanyuen, *"The study on water requirement and optimal water application of cassava (in Thai version)*," 2012.

[17] Richard G. Allen, et al., *Crop evapotranspiration - Guidelines for computing crop water requirements*. Rome, FAO - Food and Agriculture Organization of the United Nations, 1998.

[18] Office of Agricultural Economics, *Agricultural Statistics of Thailand 2013*,http://www.oae.go.th/download/download_journal/yearbook56.pdf , 2014.

[19] Food and Agriculture Organization of the United Nations, *Status of cassava in Thailnad: implication for future research and development*, http://www.fao.org/docrep/009/y1177e/Y1177E04.htm#ch3, 2014.

[20] FAO, "CROPWAT 8.0 Model," 2009.

[21] Q. Yang and G. Q. Chen, "Greenhouse gas emissions of corn–ethanol production in China," *Ecological Modelling*, vol. 252**,** no. 0, pp. 176-184, 2013.
http://dx.doi.org/10.1016/j.ecolmodel.2012.07.011

[22] R. Kongboon and S. Sampattagul, "The water footprint of sugarcane and cassava in northern Thailand," *Procedia - Social and Behavioral Sciences*, vol. 40**,** no. 0, pp. 451-460, 2012.
http://dx.doi.org/10.1016/j.sbspro.2012.03.215

[23] M. M. Mekonnen and A. Y. Hoekstra, *The green, blue and grey water footprint of crops and derived crop products, Value of Water Research Report Series No. 47.* UNESCO-IHE, Delft, The Netherlands, 2010.