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Hydrological impact of biofuel production: A case study of the Khlong Phlo Watershed in Thailand

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ABSTRACT

This study evaluates the potential impact of increased biofuel production on the hydrology of a small watershed, Khlong Phlo, in the eastern part of Thailand. The water footprint of biofuel energy was estimated for three crops in order to identify the most water-efficient crop. The Soil and Water Assessment Tool (SWAT) model was used to evaluate the impact of land use change (LUC) caused by the expansion of biofuel crops on the components of water balance and water quality in the studied watershed. Several LUC scenarios consisting of oil palm (biodiesel), cassava and sugarcane (bio-ethanol) expansion were evaluated. The water footprint results indicated that cassava is more water-efficient than the other two crops considered. Simulation results revealed that although oil palm expansion would have negligible alteration in evapotranspiration (0.5 to 1.6%) and water yield (−0.5 to −1.1%), there would be an increased nitrate loading (1.3 to 51.7%) to the surface water. On the contrary, expansion of cassava and sugarcane would decrease evapotranspiration (0.8 to 11.8%) and increase water yield (1.6 to 18.0%), which would lead to increased sediment (10.9 to 91.5%), nitrate (1.9 to 44.5%) and total phosphorus (15.0 to 165.0%) loading to surface water. Based on the results, it can be concluded that land use change for biodiesel production would affect water quality, while both the water balance components and water quality would be affected by the expansion of bio-ethanol crops. Overall, the study indicates that biofuel production would have a negative impact on the water quality of the studied watershed. Further research at large scale (e.g. basin level) and on the economic aspect is recommended, in order to contribute to developing suitable land use and energy policies.

1. Introduction

Biofuels are fuels used for transport and are derived from biomass (Dufey, 2006). There are two types of liquid biofuel for transport: bio-ethanol and biodiesel. Starchy crops, sugar crops and cellulosic material are used to produce bio-ethanol, whereas biodiesel is produced from oil crops. Many countries (like the USA, Brazil, China, India, Thailand, Malaysia etc.) are promoting biofuel so as to cut down fossil fuel consumption, to decrease oil import, to reduce greenhouse gas emission, and to reduce the poverty level of rural communities (Dufey, 2006; De Fraiture et al., 2008). The global biofuel production, which was around 57 billion liters at the end of 2007, is projected to increase almost threefold by 2017 (OECD-FAO, 2008). Under conditions of increased biofuel production, land use is likely to incur significant changes as large amounts of land would be required for plantations (UNEP, 2008). For example, around 43 and 38% of the present cropland in the United States and Europe (respectively) will be needed to substitute just 10% of petrol and diesel fuel (IEA, 2005). Similarly De Fraiture et al. (2008) estimated that by 2030, biofuel would need 30 million additional hectares of cropped area globally to share 7.5% of the total global gasoline demand (1,747 billion liters). It is very likely that the expansion of biofuel crops (oil palm, sugarcane, soybeans, etc.) will replace native rainforests and wetlands (Muller et al., 2007) due to shortage of land to expand agriculture. In Asian countries like Malaysia and Indonesia, the cultivation of oil palm for biofuel production has already replaced a large part of the forest land cover (Meijerink et al., 2008).

The Thai government has plans to increase the share of renewable energy in the total energy consumption from 0.5% in 2002 to 20.3% (4.1% from biofuel) by 2022 (Preechajarn and Prasertsri, 2010). In Thailand, biofuel is projected to replace 4,928 million liters of fossil fuel annually by the year 2022 (Prasertsri and Kunasirirat, 2009). To meet increasing biodiesel demands, the "Committee on Biofuel Development and Promotion" targets to increase oil palm coverage by 0.4 million ha by 2012 (APEC, 2008) through orchard replacement which is already happening in the northern, northeastern, eastern and southern regions of Thailand (Prasertsri and Kunasirirat, 2009). There are also government plans of expanding

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the oil palm land cover to 1.6 million ha by 2023 (Siriwardhana et al., 2009). In 2008 land coverage for oil palm, cassava and sugarcane was 0.5, 1.1 and 1.2 million ha, respectively (OAE, 2008). At present, all the feedstock left after satisfying exports and the domestic demand is used for biofuel production. A tonne of fresh bunch palm approximately yields 170 kg of crude palm oil and 50 kg of palm kernel. In 2008, about 25% of crude palm oil was utilized for biodiesel production while the rest was used for human consumption and others (including domestic use and export) (Silalertruksa and Gheewala, 2011). Both the fresh roots and dried chip of cassava can be used for bio-ethanol production. In 2008, about 37% of cassava was locally utilized in various industries including bio-ethanol (7%), starch production (21%) and cassava chips/strips and pillets (9%), while the remaining cassava was exported (DEDE, 2009). Molasses, a viscous by-product of the sugar-milling, currently plays an important role in the major feedstock for producing ethanol in Thailand. A tonne of sugarcane approximately yields 104 kg of sugar and 46 kg of molasses (OCSB, 2011). In 2008, about 78% of molasses was locally utilized in various industries including bio-ethanol (37%), animal feed and Monosodium glutamate (MSG) production (11%) and distilleries (30%), while the remaining molasses was exported (DEDE, 2009). Cane juice of sugarcane is one of the most crucial products for bio-ethanol production, but as of 2010 less than 1% of the sugarcane is used for bio-ethanol production and the rest for producing sugar (USDA, 2011). Nevertheless it is projected that of the total sugarcane yield 27% will be utilized for domestic sugar production, 44% for export and 59% for bio-ethanol (DEDE, 2009). With the current diversion of 3 million tonnes of cassava and 2 million tonnes of molasses annually, the bio-ethanol production potential of Thailand is roughly 3×10^6 L/d. The projection of 9×10^6 L/d of bio-ethanol by 2022 implies that in order to maintain domestic demand and export unaffected, Thailand needs either to intensify agriculture or expand the land for feedstock production. Thus, to meet the demand for biofuel, there would need to be considerable land use changes, which would add stress to the already limited water resources (Hoogeveen et al., 2009).

Land use change for increased biofuel production can have considerable impact on water resources and the aquatic environment. Replacing existing crops with biofuel crops can influence effective rainfall apart from altering the soil and climate due to a change in evapotranspiration and interception, which can have significant implications for surface runoff and groundwater recharge (Stephens et al., 2001). Large scale, intensive biofuel crop production requires a substantial amount of fertilizers (NRC, 2007; Evans and Cohen, 2009). Excessive use of agricultural fertilizers and their transport to water bodies through leaching and surface runoff can cause environmental problems like eutrophication and increase the level of nitrate and nitrite, which make water resources unusable for other purposes. Land use change due to biofuel production may have a significant impact on water quality (Hill et al., 2006; NRC, 2007; FAO, 2008; Schilling et al., 2008; Cruse and Herndl, 2009; Evans and Cohen, 2009; Gopalakrishna et al., 2009; Thomas et al., 2009; Twomey et al., 2009; Blanco-Canqui, 2010; De La Torre Ugarte et al., 2010; Delucchi, 2010). It is likely that, with increasing biofuel production, there will be severe impacts on hydrological processes and water cycle dynamics, but the quantification of these changes are complex (Uhlenbrook, 2007; IWMI, 2009; Meijerink et al., 2008; Engel et al., 2010).These impacts of various biofuel crop-production systems will be a function of feedstock of choice, watershed management and soil and climate conditions (Engel et al., 2010). Biofuel production can be sustainable if it has minimal hydrologic and water quality implication hence, there is a need of scientific assessment of regional feedstock production impacts on water resources and water quality which is recommended by many researchers (Shannon et al., 2008; Gopalakrishna et al., 2009; Engel et al., 2010).

In order to reduce the impact on water resources, it is necessary to find the most water-efficient crop to produce biofuel. The concept of water footprint has been in use only recently by researchers for biofuel production (Gerbens-Leenes et al., 2009; Yang et al., 2009; Mekonnen and Hoekstra, 2011). The water footprint is defined as "the total annual volume of fresh water required to produce the goods at the place of origin" (Hoekstra and Chapagain, 2007) and consists of three components: green, blue and grey water footprints. Green water footprint is rainwater that evaporated during production, mainly during crop growth; blue water footprint is irrigated surface water and groundwater which evaporates during crop growth; and grey water footprint is the amount of water needed to dilute pollutants discharged into the natural water system to the extent that the quality of the ambient water remains above agreed water quality standards (Gerbens-Leenes et al., 2009). The water footprint of biofuel energy depends upon the crop being cultivated, the yield of the crop, climatic conditions at the location of its production, and agricultural practices (Gerbens-Leenes et al., 2009; Yang et al., 2009).

Computer simulation models can be an effective tool to quantify the effects of biofuel crop production on hydrology and water quality at various spatial scales ranging from individual fields to watersheds and large river basins, and temporal scales ranging from individual storm events to annual and decades (Engel et al., 2010). The Soil and Water Assessment Tool (SWAT) is one of the models that has been extensively used to evaluate impacts of various land use, management and climate conditions on hydrologic and water quality response of agricultural and mixed land use watersheds (Borah and Bera, 2003). Love and Nejadhashemi (2011) applied the SWAT model to examine the possible long term water quality implication of large-scale biofuel crop expansion in agricultural watersheds of Michigan. Schilling et al. (2008) used SWAT to evaluate the potential impacts on the water balance components and water quality due to biofuel crop expansion in an agricultural watershed of west-central Iowa. Zhai et al. (2010) also applied SWAT to simulate the hydrologic and water quality impacts of increased biofuel production in the Upper Mississipi River Basin.

In this paper, the potential impact of land use change due to biofuel production on the hydrology and water quality of a small watershed, Khlong Phlo, in the eastern part of Thailand, was evaluated. The study first estimates the water footprint of biofuel energy from three main crops: oil palm (*Elaeis guineensis Jacq.*), cassava (*Manihot esculenta Crantz*) and sugarcane (*Saccharum officinarum*) grown in the study area, and then analyzes the impact of land use change due to an expansion of the biofuel crops on annual and monthly water balance components, and on the water quality in the Khlong Phlo watershed using the SWAT model.

2. Materials and methods

2.1. Study area

Khlong Phlo is a subbasin of the Khlong Prasae basin located in the eastern part of Thailand (Fig. 1). The studied watershed lies within 12°57′–13°10′N and 101°35′–101°45′E and encompasses a total land area of 202.8 km^2 above the stream gauge station Z.18 operated by the Royal Irrigation Department (RID). The elevation of the watershed ranges from 13 m above mean sea level at its lowest point to 723 m at its highest point. The annual mean temperature ranges from 27 to 31 °C and the relative humidity ranges from 69 to 83%. The watershed receives an average annual rainfall of 1,734 mm, of which 85% falls from May to October. The average discharge of the Phlo Stream at Z.18 is 6.7 m^3/s in May–October (wet season) and 0.7 m^3/s in November–April (dry season).