Effects of oil palm expansion through direct and indirect land use change in Tapi river basin, Thailand

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ABSTRACT
The Thai government has ambitious plan to further promote the use of biodiesel. However, there has been insufficient consideration on the environmental effects of oil palm expansion in Thailand. This paper focuses on the effects of oil palm expansion on land use. We analysed the direct land use change (dLUC) and indirect land use change (iLUC) caused by the oil palm expansion and its effects on ecosystem services supply.

Our analysis shows that between 2000 and 2009 dLUC related to oil palm expansion was more prevalent than iLUC. dLUC involved new oil palm plantations replacing cropland rather than natural ecosystems. Rubber was most frequently replaced by oil palm but there was also conversion of natural ecosystems. Later, between 2009 and 2012, iLUC strongly increased. Forests were cleared for rubber production as an indirect effect of oil palm expansion.

We also quantified the effects of land use change on selected ecosystem services. Oil palm expansion led to increased production of fresh fruit bunches; however, it reduced other crop production such as latex, rice and fruits. Biodiversity conservation was also negatively affected. Carbon storage was positively affected by conversion of unused land, rice and orchard area by oil palm, but negatively affected by the conversion of forests.

1. Introduction
Biofuels are increasingly considered as an alternative to fossil fuels, in spite of associated environmental and social impacts (Naylor et al. 2007; Silalertruksa et al. 2012; Kumar et al. 2013; Wattana 2014). The Royal Government of Thailand initiated a campaign in 2005 to promote biodiesel production and consumption (DEDE 2008, 2012; Preechajarn 2010; Preechajarn & Prasertsri 2012; Kumar et al. 2013). To meet the policy target, large amounts of palm oil, which is used as main feedstock for biodiesel production, are required. As a result, palm oil production and cultivation have doubled between 2005 and 2012 (FAOSTAT 2013; OAE 2013). This rapid increase in oil palm area is likely to continue in the coming years.

A range of environmental effects is associated with oil palm expansion. Several studies show that greenhouse gas (GHG) emissions may increase when forests or peatland are cleared for oil palm (Croezet et al. 2010; Danielsen et al. 2008; Gnanavelrajah et al. 2008; Mathews & Tan 2009; Lapola et al. 2010; Achten & Verchot 2011; Ernst & Young 2011; Kim & Dale 2011; Marshall et al. 2011; Sanchez et al. 2012; Silalertruksa & Gheewala 2012). Conversion of forests to oil palm plantations does not only release GHG emissions, but also leads to biodiversity loss (Lindeijer 2000; Mila I Canals et al. 2006; Danielsen et al. 2008; Michelsen 2008; Schmidt 2008; Geyer et al. 2010; Wilcove & Koh 2010; Yaap et al. 2010; De Baan et al. 2012). For instance, at least 60% of the bird species richness disappeared due to loss of their habitats by oil palm and rubber plantations in southern Thailand in 2004 (Aratrakorn et al. 2006). In addition, conversion of natural forests to oil palm plantations can affect the water flow regulation service provided by natural forests (Kumar et al. 2013) and increase flood risks (Nikolova et al. 2007; Kobiyaama 2011).

Hence, land use change caused by oil palm expansion threatens ecosystem functions and services provided by natural forests in Thailand. This land use change might have caused deforestation directly and indirectly (Kim & Dale 2011; Marshall et al. 2011; O’Hare et al. 2011; Finkbeiner 2014; Wicke et al. 2014; Creutzig et al. 2015). To what extent, however, is not clear. More information on the associated land use change and its effects on ecosystem services (ESS) in Thailand is therefore needed. Such a quantitative analysis is important for a better understanding of the environmental problems and to design problem-oriented solutions for policymakers. The objectives of this study, therefore, are to analyse direct land
use change (dLUC) and indirect land use change (iLUC) caused by oil palm expansion and to analyse its effects on selected ESS. Our result could therefore provide a better understanding of land use change and associated effects on a few selected ESS and support the policymakers to design the right policy that minimizes environmental impacts of oil palm expansion in Thailand.

2. Method

2.1. Study area

The Tapi river basin, a major basin in the southern part of Thailand, was selected as a case study to analyse the effects of oil palm expansion on selected ESS. This river basin covers a total area of 13,450 km² and spans three provinces: Surat-thani (69% of the basin), Nakhon-si-thammarat (17% of the basin) and Krabi (13% of the basin) (Figure 1) (Haii 2012). We selected this area because Surat-thani and Krabi are the first and second largest oil palm-producing provinces in Thailand, respectively. Note that this basin includes areas where the oil palm expansion has been ongoing for several decades (Krabi and Surat-thani) and areas where the expansion is more recent (Nakhon-si-thammarat).

2.2. Land use categories

The effects of land use change on ESS depend on the type of land use that is replaced. For instance, Thongrak and Kiatpathomchai (2011) indicated that in Thailand oil palm is mainly replacing rubber plantations, rice fields, abandoned rice fields and orchard plantations. However, local media (Anonymous 2010) reported the clearing of peatland for oil palm in the Tapi river basin. Siangjao et al. (2011) revealed that land conversion of unused land to oil palm plantations positively affects the carbon storage.

In our analysis, we derived land use data sets of the Tapi river basin from the Land Development Department (LDD), Ministry of Agriculture and Cooperatives. The LDD land use data are digital with scale of 1:50,000 for the year 2000 and of 1:25,000 for the years 2009 and 2012, and with polygons representing 191 different land use categories. We aggregated and reclassified land use categories from 191 to 12 categories for the purpose of our research. For example, natural evergreen forest, disturbed evergreen forest and forest plantation are aggregated together and reclassified to forest category. Next, the reclassified land use maps were converted to raster format (cell size 30 × 30). We followed the definition of land use and land use categories from LDD (LDD 1999).

The aggregated 12 land use categories include (1) forests (consisting of natural evergreen forest, disturbed evergreen forest and forest plantation). Note that more than 98% of total forest area in the Tapi river basin is the natural evergreen forest, (2) wetlands and peatland, (3) mangrove, (4) oil palm plantation, (5) rubber plantation, (6) orchard plantation, (7) rice field, (8) abandoned rice field, (9) unused land (consisting of grass and scrub land and marsh and swamps), (10) other agriculture (consisting of field crops, other perennials, horticultures, pasture land and farm houses, aqua-cultural land and mine pits), (11) water (compositing of natural water bodies and built-up reservoir) and (12) built-up area (compositing of commercial area, villages, transportation utilities and industrial area).

2.3. Modelling land use change

We analysed both dLUC and iLUC effects. dLUC refers to the direct conversion of land to oil palm plantations (Marshall et al. 2011). However, when cropland is replaced by oil palm, there may be an indirect effect on land use elsewhere when there is still a demand for these crops. In such cases, cropland or natural ecosystems elsewhere may be converted to substitute the cropland that were replaced by oil palm (Kim & Dale 2011; Finkbeiner 2014; Wicke et al. 2014; Creutzig et al. 2015). In some cases, also natural
ecosystems, such as forests and peatland, might be changed to cropland that are replaced by oil palm. This refers to iLUC in this study. We acknowledged the difficulties in singling of the different causes of land use change including indirect land use (Dendoncker et al. 2008; O’Hare et al. 2011; Ray et al. 2012; Verstegen et al. 2015). Therefore, we followed a two-pronged approach where we analyse both land use change patterns based on maps and farmer interviews for their motivation to engage in land use change, as elaborate below.

a. dLUC: We analysed dLUC between 2000 and 2009 and between 2009 and 2012, based on the land use data sets. Conditional analysis in ArcGIS 10.0 was used to identify different types of land use that are converted to oil palm cultivation in the study area. This land use change (in hectares) is considered as ‘gross change’. Land use change is, however, dynamic. While in some places certain land use types are converted to oil palm production, in other places oil palm plantations may be converted to other land use types. For instance, suppose that the maps indicate that 90,000 ha of rubber were converted to oil palm production (gross change) and that meanwhile 20,000 ha of oil palm were converted to rubber production. To calculate ‘net change’, we subtracted this 20,000 from the gross change. We thus considered only the positive net change as dLUC effect of oil palm expansion.

b. iLUC: We identified the iLUC effects in the Tapi river basin using the same procedure as for the dLUC analysis. We thus identified land conversions and calculated the net and gross area change for some other crops (i.e. rubber, orchards and rice). We only considered the positive net change as iLUC effect of oil palm expansion. Note that we ignored iLUC effects outside the Tapi river basin.

c. Interview farmers: Drivers of land use change are complex, in particular indirect land use change. As a supplement to our spatial analysis, we therefore interviewed farmers in order to better understand their decisions and motivations towards LUC in the Tapi river basin.

We categorized farmers into three groups: (1) farmers who recently started oil palm cultivation, (2) farmers who recently started rubber cultivation and (3) farmers who recently started both rubber and oil palm cultivation, and switched in some plots from rubber to oil palm. Farmer characteristics are presented in Table 1. The Tham-Phannara and Thungyai districts in Nakhon-si-thammarat were selected as sampling sites because our LUC analysis identified these districts as hotspots of deforestation associated with dLUC and iLUC. In total, 37 randomly selected farmers were interviewed. Note that the two most important oil palm-producing provinces in the Tapi river basin are Suratthani and Krabi. However, oil palm has been cultivated in these provinces at large scale for several decades. Therefore, we considered Nakhon-si-thammarat province is more relevant for analysing the effects of LUC with farmer interviews. We, however, used farmer interviews from Prasaeng and Bannaderm districts, Suratthani province (conducted in June 2012) from Nualnoom (2014) to compare our results.

2.4. Modelling ESS

In accordance with the ESS typology presented in The Economics of Ecosystems and Biodiversity study (TEEB 2010; Mace et al. 2012), we selected (1) food (i.e. rice and fruits) and non-food (i.e. fresh fruit bunch (FFB) and latex), (2) carbon storage and (3) biodiversity conservation to represent the provisioning, regulating and habitat services categories, respectively. The analytical approaches, indicators, input data set and data sources for modelling and quantifying changes in selected ESS are summarized in Table 2.

These ESS were selected because they have been mentioned by local sources (websites and farmers) and/or in scientific literature and reports. For instance, Siangjiao et al. (2011) and Silalertruksa and Gheewala (2012) reported that stored carbon is released to the atmosphere when forests or peatland are cleared for oil palm. Losses of natural forests and peatland that are important habitats for living species can eventually cause negative impacts on biodiversity (Aratrakorn et al. 2006; Danielsen et al. 2008; Koh & Wilcove 2008; Geyer et al. 2010; Mastrangelo & Gavin 2012; Johnson & Zuleta 2013). Moreover, they could potentially affect water flow regulation

| Group | Characteristics | Objectives | Sample (number of persons) |
|-------|-----------------|------------|---------------------------|
| 1     | Farmers who recently started oil palm cultivation | To better understand the reasons for direct land use change | 14 |
| 2     | Farmers who recently started rubber cultivation | To better understand the reasons for indirect land use change | 13 |
| 3     | Farmers who recently started both oil palm and rubber cultivation, and switched in some plots from rubber to oil palm | To better understand the reasons for both direct and indirect land use change | 10 |

To better understand their decisions and motivations towards LUC in the Tapi river basin.

Table 1. Overview of interviews with farmers in the Tham-Phannara and Thungyai districts in Nakhon-si-thammarat (Tapi river basin).
Table 2. Indicators, approaches and input data used to quantify changes in selected ecosystem services.

| Ecosystem services | Indicator | Approach | Data | Source of data |
|--------------------|-----------|----------|------|---------------|
| (1) Food and non-food production | Production change (ton) | \( P \times A \) | Annual crop productivity in the basin in 2000, 2009 and 2012 | OAE (2009; 2013); Results from dLUC and iLUC analysis (this study) |
| – Rice production | | | Area of land use change in the basin due to oil palm expansion (dLUC and iLUC), in ha |
| – Fruits production | | | |
| – FFB production | | | |
| – Latex production | | | |
| (2) Biodiversity conservation | Habitat loss (ha) | \( A_{\text{eco}} \) | Loss of natural ecosystems, in ha, caused by oil palm expansion (both dLUC and iLUC) |
| (3) Carbon storage | Carbon stock change (ton C) | \((C_{\text{biomass}} + C_{\text{dom}} + C_{\text{tot}}) \times A\) | Carbon stock pools \((C_{\text{biomass}}, C_{\text{dom}} \text{ and } C_{\text{tot}})\) for specific land use |
| | | | Area of land use change in the basin due to oil palm expansion (dLUC and iLUC), in ha |

provided by natural forests (Nikolova et al. 2007; Kobiya 2011; Kumar et al. 2013). Note that the water flow regulation service is not a main focus in this study. However, we discussed the implication of land use change on hydrology services in the discussion section (see Section 4.1).

Information on the selected services are crucial for policymakers, and for land use and development planning in order to minimise negative impacts on the environment and society (Maler et al. 2008; Klug 2012; Inge et al. 2013; Kang et al. 2013).

2.4.1. Food and non-food production

We used the production change (in ton) as indicator for modelling food and non-food provisioning services (Table 2). The growing period, the period between crop establishment and maturity, varies among crops. For instance, the growing period for oil palm is typically 3 years and for rubber is 7 years (OAE 2011a). Therefore, for the period between 2000 and 2009 (9 years of change), all crops (i.e. FFB for oil palm, latex for rubber, rice for rice fields and fruits for orchards) that were new in 2000 were taken into account in our analysis. This is because by the year 2009 they had reached maturity. For the period between 2009 and 2012 (4 years of change), orchard and rubber plantations that were established in 2009 were excluded from our analysis because by the year 2012 they had not reached maturity. In the latter case, only oil palm and rice were, therefore, considered.

2.4.2. Biodiversity conservation

Accounting for aspects of biodiversity is complex and as such experimentation of biodiversity accounting in Thailand is scarce. UNEP-WCMC (2015) indicates that information on ecosystem diversity from a spatial analysis can inform the biodiversity account. We therefore assessed the biodiversity conservation service based on habitats loss. In our assessment, only the declination of natural ecosystems from the land use analysis was taken into account in the model because of their role as important habitats for living species.

2.4.3. Carbon storage

Carbon stock change is used as an indicator for modelling carbon storage service. Our analytical approach is based on the stock difference method from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Volume 4 on Agriculture, Forestry and Other Land Use (IPCC 2006). The IPCC Guidelines, however, do not provide default values of carbon stock pools (i.e. above- and below-ground biomass, dead organic matter and soil organic carbon) for all the land use types defined in this study. Meanwhile, many local studies on carbon stock pools for specific types of land use are available for Thailand. We, therefore, assessed the carbon stock of different land use units based on information from
these local and national studies (see Table A1) and we applied a lookup table approach to analyse total carbon stocks per land use type (Remme et al. 2014; Sumarga & Hein 2014).

3. Results

3.1. Land use

In the year 2000, rubber plantations covered 48% of the Tapi river basin (Figure 2). Forest areas covered 29% and oil palm plantations covered only 7% of the basin. Other natural land (i.e. mangrove forests and peatland) was rare and covered less than 0.3% of the basin. The area under oil palm plantations doubled between 2000 and 2009, with an average annual expansion rate of 12% (Figure 2). The increase in oil palm areas is a result of policies promoting the use of biodiesel at national level and enhancing oil palm development at provincial level (see our discussion in Section 4.2). On the other hand, the total area of rubber plantations, rice and abandoned rice fields decreased considerably since 2000. The total area used for rubber cultivation, however, moderately changed. By the year 2009, 41% of the basin was still used for rubber cultivation. The areas of natural forests and mangroves increased by 2% and 91%, respectively, between 2000 and 2009, albeit from very small initial areas. This increase may be related to enhanced mapping methods in 2009 compared to 2000. Note that the Cabinet of the Thailand government’s resolution regarding recalling of natural conservation areas on 30 July 1998, which remained effective until 2012 (Srisaowalak 2010), that promoted the protection of these natural ecosystems.

Between 2009 and 2012, oil palm still expanded at the expense of rice, abandoned rice, orchards and unused land. We calculated an average annual expansion rate for oil palm at 2% for the period 2009–2012. This expansion rate was lower than that for the period 2000–2009.

3.2. Direct land use change

We analysed dLUC caused by oil palm expansion in the Tapi river basin during the study periods (2000–2009 and 2009–2012; see Table 3). Palm oil was expanded at the expense of several different land use types (Figure 3). Moreover, the losses of rubber, orchards and rice fields caused iLUC effects (see Section 3.3).

Approximately one-third of the oil palm area in 2009 were existing plantations that were planted before the year 2000 (Figure 3). Two-thirds were more recent plantations. A significant number of rubber plantations were replaced by oil palm plantations. This accounts for 68% of the new oil palm area in 2009 (net change). About 12% of the oil palm was planted on unused land. Forest conversion was relatively low (4% of oil palm plantations). However, expressed as the percentage of forest loss, this type of conversion was much more substantial.

Also, in the second period (2009–2012), new oil palm was mostly established on cropland rather than on natural land. In the year 2012, almost the whole oil palm area (96%) consisted of plantations that already existed before 2009. The small

Figure 2. Land use maps in 2000, 2009 and 2012 (modified from original land use maps by LDD).
The area of new oil palm plantations replaced rubber (28% of the new oil palm area in 2012), unused land (17%) and orchards (17%) (net changes). Forest conversion involving dLUC to oil palm was again relatively low at 3.5% of the new oil palm area in 2012. When expressed as the percentage of forest loss, its magnitude was much higher than number is found.

### 3.3. Indirect land use change

We analysed the iLUC effects of oil palm expansion into rubber, rice and orchard areas (Table 4 and Figure A1). We observed that the iLUC effects as a result of rice and orchard conversions were insignificant; there is not much land conversion to rice and orchards elsewhere in the basin (Table A2 and...
For rubber, this is different. Palm was replacing rubber in large areas in the basin. As a result, rubber was planted elsewhere in the basin by replacing other land use types. We, therefore, focused on the iLUC effects of oil palm expansion into rubber areas.

In the first study period (2000–2009), new rubber mainly replaced forests (natural ecosystems), accounting for 23% of new rubber area in 2009 (gross change), followed by oil palm (21%), orchards (15%) and rice (13%) (Figure A1). On the other hand, large areas of rubber (40,000 ha) were replaced by forests as a result of the cabinet resolution on natural reserve land recall (Srisaowalak 2010) that considering these rubber areas as the rubber–forest plantations after the recall. This explains the negative net change that we calculated for forests in Table 4. This implies that there was no net iLUC effect in this period, as a consequence of the above-mentioned cabinet resolution. In summary, the iLUC effects of oil palm expansion resulted in a net loss of cropland (17,000 ha) rather than natural ecosystems (260 ha).

For the second period (2009–2012), we calculated a large increase in deforestation. The net change in forest area indicates that forests were frequently cleared for rubber development (41% of rubber area in 2012), followed by orchards (22%) and rice (15%). The loss of natural ecosystems in the second period is 36 times as large as in the first period.

Furthermore, we analysed the slopes of rubber and oil palm plantations to better understand conversion of forests either to rubber or oil palm. Rubber can be planted at relatively steep slopes (> 20°; Figure A2).

This is not the case for oil palm. Planting oil palm on slopes > 10° increases the costs of good farm management to minimize soil erosion and nutrient leaching, and makes it more difficult to harvest oil palm fruits (RSPO 2007). This could explain why in some regions more forest is converted to rubber than to oil palm.

We realized that rubber expansion associated with iLUC is not only limited to the Tapi river basin, but can also take place elsewhere, in particular the northern and northeastern regions of Thailand that are in line with the government’s campaign. For instance, the Department of Agriculture (DOA) promoted rubber development in the north and northeastern regions from 2004 to 2013. This rubber promotion may be connected with the loss of rubber area (to oil palm plantations) in the south of Thailand, including the Tapi river basin. In these regions, DOA provided free rubber seedlings and technical supports to more than 140,000 farmers, resulting in more than 400,000 ha of rubber plantations (Boonnum & Chantuma 2010; Chareonsuk 2011). As mentioned earlier, iLUC effects related to rubber development in the north and northeastern regions outside the Tapi river basin are not included in our analysis. The iLUC effect is estimated to have occurred in 3.2% of total area of the basin.

3.4. Farmers’ decisions on land use change

In the following, we summarized the results of the farmer interviews with three groups of farmers (Table 1). Detailed results are presented in Tables A3, A4, A5.1 and A5.2.
3.4.1. Group 1: farmers who recently started oil palm cultivation

Almost all farmers reported that the ages of their oil palm plantations were in the range of 3–15 years. These farmers started their oil palm plantations during the period 2002–2008, corresponding to the study period of our land use change analysis. From the interviews, rubber plantations were most frequently cleared for oil palm, followed by unused land and rice. However, oil palm expansion into degraded forests is also reported. The degraded forests were given to farmers free of charge under a responsibility of the Agricultural Land Reform Office (ALRO). The findings from the interview of group 1 strongly support the results of direct land use change analysis for the period 2000–2009. Most of the farmers decided to plant oil palm because of the profitability of the crop and considering the suitability of their land for oil palm. This result is supported by Nualnoom (2014), who states that farmers decided to switch from other crops, such as rice and rubber, to oil palm because oil palm provides better financial contributions and the suitability of their land for oil palm. Only a few farmers were not satisfied with oil palm because productivity had declined due to flooding. Another concern for farmers was the variability of palm oil, FFB prices and the recent reductions in prices. From the interviews, farmers usually burnt the leftover biomass residues before planting oil palm. Inevitably, large emissions of air pollutants and GHGs are emitted when burning the biomass (Kanakkaew & Kim Oanh 2011; Permadi & Kim Oanh 2012). Note that emission of open burning biomass is not our main focus. However, we discussed the implication of open burning on air pollution in the discussion section (see Section 4.1).

However, they did not intend to change oil palm for other crops at the time of interviews (July 2015), not even if the price of FFB would further decline. In view of the investment, they made in planting oil palms and in anticipation of better prices in the future. Most of the farmers had no plans for expansion, even if the FFB price would increase, because they lacked resources or access to credits to buy new land for that purpose. Only four farmers (out of a total sample of 14) had sufficient access to capital and wanted to expand the oil palm area.

3.4.2. Group 2: farmers who recently started rubber cultivation

In group 2, the interviewed farmers mainly planted rubber during 2000–2005, which largely covers the period of our initial land use change analysis. The interviews confirm that rice fields were most often replaced by rubber plantations, followed by unused land. Clearing degraded forests (from ALRO) for rubber plantations was also reported during the interviews.

The farmer interviews support the result of the indirect land use change analysis for the period 2000–2009. The main reason for planting rubber is that the farmers’ land are more suitable for rubber compared to other crops and favourable returns on investments in rubber in this period. Most farmers were satisfied with rubber and mentioned that they could earn extra income from selling the rubber woods after the end of the lifetime of the plantation. Unstable price (both decreases and increases) had a small influence on the farmer’s decisions to change their investments in rubber: mainly because of a lack of available land and credits. Some of them wished to increase their income by expanding the rubber areas.

3.4.3. Group 3: farmers who recently started both oil palm and rubber cultivation, and switched in some plots from rubber to oil palm

The farmers’ decisions and motivations to change land use in group 3 are similar to those in groups 1 and 2. Group 3 consists of only large-scale farmers who converted part of their rubber areas to oil palm. The main reason for this is that their lands are suitable for oil palm and they anticipated this crop to bring higher returns. Another reason to expand their oil palm areas was the relative ease of oil palm management practices (i.e. a lower labour requirement and less plant diseases). Some farmers clearly indicated that they wanted to expand rubber plantations into either unused land or degraded forests from ALRO. Next, we compared the cost–income of oil palm and rubber for the year 2014: the net profits of oil palm were slightly higher than of rubber (see Table A.5.2). Note that cost–income of oil palm and rubber may vary among regions within the Tapi river basin and among different years.

3.5. Effects of land use change on ESS

3.5.1. Food and non-food provisioning service

3.5.1.1. FFB production. The area of oil palm plantations in the Tapi river basin increased from 97,950 ha in 2000 to 200,191 ha in 2009 and to 220,115 ha in 2012. Our land use change analysis shows that the oil palm area in the Tapi river basin increased with approximately 102,000 ha between 2000 and 2009 and with 20,000 ha between 2009 and 2012. This expansion led to an increase in annual average FFB production of almost 1.92 million tons in the period of 2000–2009 and of 1.12 million ton in the period of 2009–2012 (Table 5).
3.5.1.2. Latex production. Table 6 shows that the rubber plantations decreased from 644,514 ha in 2000 to 554,544 ha in 2009. Oil palm expansion caused a decrease in rubber areas approximately of 90,000 ha between 2000 and 2009. As a result, annual latex production in the Tapi river basin decreased by approximately 121,000 ton. Latex can usually be produced after 7 years of rubber cultivation. For the 2009–2012 period, we assumed that rubber plantations started in 2009 had not yet produced latex. This results in an increase in annual latex production of around 22,200 ton.

3.5.1.3. Rice production. Large areas of rice fields were replaced directly by oil palm and indirectly by rubber over the study periods because farmers generate lower profits from rice. In 2012, the net profits of rice, FFB and latex were about 4900 Thai Baht (THB)/ha, 38,300 THB/ha and 34,100 THB/ha, respectively (OAE 2013). The decrease in rice area resulted in a reduction in rice production of around 27,200 ton between 2000 and 2009 and around 17,600 ton between 2009 and 2012 in the Tapi river basin.

3.5.1.4. Fruit production. The net profit of fruits production (22,400 THB/ha) was lower than that of FFB and latex productions (OAE 2013). Thus, a number of orchard plantations were replaced directly by oil palm and indirectly by rubber over the study periods. There was a decrease of about 800 ha of orchard plantations from 2000 to 2009 (Table 5) and about 7600 ha of orchard plantations from 2009 to 2012. In the period of 2000–2009, this reduction in orchard area led to a loss in fruit production in the basin approximately by 61,100 ton. In the period of 2009–2012, we assumed that orchard plantations started in 2009 had not yet produced fruits. We therefore calculated the loss in fruit production in the basin approximately by 67,800 ton.

3.5.2. Biodiversity conservation

During the period 2000–2009, large areas of unused land (12,000 ha) and forests (4000 ha) were directly cleared for oil palm plantations. In addition, a smaller area (<850 ha) of wetlands and peatland (which cover only small parts of the basin) was affected. We did not record any conversions of forests and unused land as part of iLUC in this period, but we did find a small area of wetlands and peatland that was indirectly affected (290 ha). However, the effects on biodiversity strongly increased in the second period (2009–2012). Large areas of forests (~9000 ha) were converted or replaced by other crops, particularly rubber, with iLUC being much more important than dLUC. Given that forests are important habitats for many species (UNEP-WCMC 2015), this implies that oil palm expansion in the period 2009–2012 caused a more serious impact on biodiversity loss than the expansion in earlier years. Moreover, we also noticed LUC inside protected areas. Khlong Phanom national park was subject to encroachment by oil palm plantations. Tai Rom Yen National park was subject to, in particular, encroachment by rubber plantations. These encroachments involved several hundreds of hectares and strongly increased in the second period, based on a comparison of our maps with those of the Royal Forest Department (RFD 2016) indicating park boundaries.

3.5.3. Carbon storage service

Land use types differ in their capacities to store and accumulate carbon from the atmosphere. Details on carbon stock pools for each land use type are provided in Table A1.

Table 7 shows that stored carbon in biomass, dead organic matter and soil can be released in large quantities when peat swamp forests, peatlands or forests are converted and drained. Converting rubber to oil palm also releases carbon. On the other hand, converting annual crops to oil palm results in net negative carbon emissions (i.e. sequestration), in the order of 41–60 ton C/ha on average, as the carbon-storing capacity of oil palm is higher.

From 2000 to 2009, dLUC associated with expanding oil palm in the Tapi river basin resulted in about 7.2 million ton of carbon released into the atmosphere. However, iLUC led to the sequestration of carbon, with around 1.4 million ton of carbon, due to the conversion of annual cropland and unused lands to rubber plantations. The net effect therefore was a release of around 5.8 million ton of carbon. During the period 2009–2012, both dLUC and iLUC led to the release of carbon into the atmosphere. dLUC and iLUC led to emission of 0.3 million ton of carbon and 1.2 million ton of carbon, respectively. In this period, iLUC also led to carbon emissions since in this period a larger amount of forests were converted as part of iLUC. Note that the periods are of different length, i.e. 9 respectively 4 years. On an annual basis, carbon released into the atmosphere due to LUC amounted to 5.8/9 = 0.65 ton of carbon each year in the first period, and 1.5/4 = 0.38 ton of carbon each year in the second period. Note that the rate with which oil palm expanded in the first period is 12% per year, whereas in the second period this was only 2% per year. Hence, on a per hectare basis, these environmental impacts have strongly increased in recent years.

INTERNATIONAL JOURNAL OF BIODIVERSITY SCIENCE, ECOSYSTEM SERVICES & MANAGEMENT
4. Discussion

4.1. Data uncertainties

4.1.1. Uncertainties associated with input data and ESS modelling

There is a large uncertainty when modelling LUC. These uncertainties stem from both uncertainties in the input data set (Dendoncker et al. 2008) and in the model (Ray et al. 2012). For the input data set, we analysed land use change (dLUC and iLUC) based on available land use maps in 2000, 2009 and 2012 from the LDD, Ministry of Agriculture and Cooperatives, Royal Thai government. These land use data sets were developed based on both satellite images for land use classification and site survey for ground-checking and for producing attribute data (Chanroj 1999). According to a conversation with an LDD official, the uncertainty associated with the LDD land use maps is approximately 20%.

In our model, we quantify ESS based on available statistics and literature. To model food and non-food provisioning service, statistics on crop yields, crop prices and costs from Office of Agriculture Office (OAE 2009, 2011b, 2013) are used. The data represent an average value at provincial level. We then converted them from provincial to the basin level. This conversion leads to uncertainties. For the carbon storage service, we used carbon stocks data from the literature and there are uncertainties associated with assuming such values to be representative for the Tapi basin; however, we do not have local measurements. Hence, we are able to identify but not quantify the uncertainties in our model. We note that, in general, it seems to be difficult to analyse uncertainties in relation to ESS assessment, given the shortage of data required to model ESS and the need for additional, local data to verify the models.

4.1.2. Farmers’ survey

We interviewed in total 37 farmers from Thammarat and Thungyai districts in Nakhon-sithammarat. We acknowledged that our sample is relatively small and may not be a good representation for the entire Tapi river basin. Nevertheless, our results from farmer interviews fit very well with our model outputs as they indicate that rubber plantations were mainly replaced by oil palm, whereas there is also conversion of unused land and rice fields. In addition, the farmer interview...
4.1.3. Integrated analytical approach for land use change

We modelled land use change caused by oil palm expansion using ArcGIS 10.0 based on the available land use data sets from the LDD. The model output maps provide insights in the extent to which types of land use changed as a result of oil palm expansion in the Tapi river basin including dLUC and iLUC. We believe that it is important, however, that in particular iLUC is not only analysed on the basis of spatial information. There are multiple processes, actors and types of land use change, and a causal relation between dLUC and iLUC can in our view not be established on the basis of modelling alone but also requires an understanding of why and how local actors decide upon LUC (cf. IFPRI 2009).

4.1.4. Implication of land use change on hydrology services

We think that the most important ESS which could not be included in our analysis is the hydrological service provided by, in particular, forests (Gilfedder et al. 2012; Hughes et al. 2012; Mustafa et al. 2012). Babel et al. (2011) showed that the conversion of forests to oil palm plantations resulted in an increased surface runoff by about 13% and reduced base flow by about 7% in Thailand. In contrast, the conversion of orchards and rubber plantations to oil palm hardly decreased surface runoff and base flow. Babel’s study was carried out in the Klong Pho watershed, where the biological and hydrological characteristics of this basin are similar to that of the Tapi basin (Haii 2013). This means that, in particular, there is a risk that the conversion of forests to oil palm in, in particular, the second period has affected the hydrological service, potentially increasing flood risks in the basin. Further study is required, using hydrological modelling, to quantify these effects.

4.1.5. Implication of open burning on air pollution

Another main environmental issue, which is not adequately covered in the ESS framework, relates to externalities of ecosystem use. A main issue in the Tapi river basin is open burning, which is commonly applied by farmers to clear a new land before planting oil palm, leading to large emissions of air pollutants and GHGs (Kanabkaew & Kim Oanh 2011; Permadi & Kim Oanh 2012). We present a preliminary estimate of the annual emissions of burning residues after land conversion of rice to oil palm as an example. We used equations and emission factors from the study of Kanabkaew and Kim Oanh (2011) for annual emission rates. Our analysis shows that oil palm expansion in the period of 2000–2009 replaced 17,600 ha of rice fields. This conversion of rice to oil palm alone results in annual emissions of approximately 2900 ton CO₂, 24 ton CH₄, 0.45 ton SO₂, 6 ton NOx, 232 ton CO, 17 ton non methane volatile organic compounds and 23 ton particulate matter in the Tapi river basin. Hence, this is an important environmental effect of oil palm expansion, and it should be studied in more detail and considered in policymaking.

4.2. Policy recommendations

4.2.1. The policy setting

According to government statistics, market prices of both FFB and latex increased over the past decade (2000–2013). The annual average price of FFB increased from 24,100 THB/ha in 2000 to 72,500 THB/ha in 2013. Meanwhile, the annual average price of latex increased from 33,500 THB/ha in 2013 to 64,700 THB/ha in 2013. This increase in prices may be one of the main reasons for farmers to switch their rubber and rice areas to oil palm. The annual average price of latex increased from 33,500 THB/ha in 2013 to 64,700 THB/ha in 2013. This increase in prices may be one of the main reasons for farmers to switch their rubber and rice areas to oil palm.

Table 7. Effects of land use change (dLUC and iLUC) on carbon storage service.

| Land use type       | Area of LUC, ha | Carbon stock change by land conversion to oil palm (ton carbon/ha) | Carbon stock change (ton carbon/basin) |
|---------------------|----------------|------------------------------------------------------------------|---------------------------------------|
|                     | 2000–2009      | 2009–2012             | Biomass                              | Dead organic matter | Soil carbon | Balance   | 2000–2009     | 2009–2012             |
| Cropland            |                |                      | dLUC       | iLUC       | -         | -         | -         | dLUC       | iLUC       |
| Oil palm            | 69,355         | -5542                | -96.77     | -2.65      | 99        | -6,895,471| -550,989  | -          | -          |
| Rubber              | 3186           | 13,071               | 2151      | 3396       | 47.62     | 11.95     | 60        | 189,777    | 778,512    |
| Rice                | 3111           | 3433                 | 4961      | 41.39      | -0.020    | -41       | 41        | 128,699    | 142,025    |
| Orchards            | 5980           | 12,853               | 2675      | 2564       | 47.62     | 11.95     | 60        | 356,197    | 765,560    |
| Abandon rice⁴       | 3952           | 932                  | 9165      | -119.06    | -6.86     | -60.56    | -186      | -6,700,126 | 788,518    |
| Natural land        | 8               | 86                   | -69.92    | -6.35      | -76       | -597      | -6652     | -142,179   | -142,757   |
| Forest              | 844            | 291                  | 49        | 23         | -22.93    | -27.65    | -400.35   | -414,529   | -142,757   |
| Mangrove            | 11,777         | 3419                 | 43.66     | -0.15      | 25.55     | 18        | 211,421   | -61,379    | -          |
| Wetlands and peatland|               |                      |           |            |           |           |           |            |            |
| Unused land         |                |                      |           |            |           |           |           |            |            |

Notes: ‘−’ shows a releasing stored carbon to the atmosphere while ‘+’ shows a storing and accumulating carbon from the atmosphere.

⁴Assumed to be the same condition as rice field.
2000 to 119,100 THB/ha in 2013 (OAE 2009, 2013). However, the market price alone seems to be an insignificant driving force for oil palm expansion and land use change in the Tapi river basin – more important are the availability of government support for land use change (in particular, changing from rubber to oil palm), the interest of farmers to diversify and the lower labour requirements of oil palm. The interviewed farmers generally indicated that price changes, within the currently encountered price range, had a small influence on farmer’s decisions in changing either oil palm or rubber investment.

A national campaign to promote biodiesel production and consumption was initiated in 2005. However, at the initial stage the effects of this policy were insignificant. Later, in 2008, the Thai government adopted this policy requiring a replacement of all regular diesel with B2 biodiesel (a mixture of diesel with 2% biodiesel) (Kumar et al. 2013). Production of palm oil as biodiesel feedstock has been growing fast since then. The Thai government has continuously modified its policy and plans to increase the production and consumption of biodiesel. In 2012, the mandatory B5 rule (a mixture of diesel with 5% biodiesel) came into force. To achieve this goal, the Thai government promoted the expansion of oil palm area to a targeted 880,000 ha with targeted average yield at 20 ton/ha/year. (DEDE 2012; Preechajarn & Prasertsri 2012). The farmer interviews confirmed that the farmer support that resulted from these policies was a major driver for the land use change in the Tapi river basin.

The national policies were also reflected in the provincial development plans. We studied the 2000–2012 development plans of three provinces in the Tapi river basin. These development plans promoted rubber and oil palm development (Krabi Administrative 2014; Nakhon-Si-Thanmarat Administrative 2014; Suratthani Administrative 2014). Our farmer interviews show that the financial aid from Office of the Rubber Replanting Aid Fund, on average 100,000 THB/ha for a period of 5 years, had been granted to the farmers who switched their rubber plots to oil palm. This contributed to the rapid expansion of oil palm plantations in the Tapi river basin, confirming that government support is one of the main drivers for land use change.

Cultivation of oil palm has been increasing due to political interest in biofuels in Thailand. Currently, also second- and third-generation biofuels are being considered. These include new energy crops (i.e. jatropha and micro-algae) and technologies to convert from biomass to energy (i.e. pyrolysis) and bio hydrofined diesel (DEDE 2012). However, full commercialization of these is not likely to occur in at least a decade around the world (Kumar et al. 2013) and their implications for mitigating land use change in the Tapi basin are likely to be small, at least in the time frame of the coming 10–20 years.

4.2.2. Negative effects of oil palm expansion can be reduced by stopping the conversion of new lands and increasing productivity

Annual average productivity of oil palm was 16 ton/ha in the period 2000–2009 and 20 ton/ha in the period 2009–2012 (OAE 2009, 2013). Our analysis revealed that the annual expansion rate of oil palm was 12% for the period 2000–2009 and 2% for the period 2009–2012 (see Section 3.1). In principle, increased productivity could be met with a smaller area of oil palm plantations. However, higher productivity could also increase the motivation and financial means of the farmers to convert even more land to oil palm.

We note that the current practice of expanding oil palm areas into cropland and other land use types is not consistent with sustainable palm oil production because the available land in the Tapi river basin is limited and because the remaining forest resources are both limited and important for water regulation and other ESS. If the current trends continue in the coming years, the production of other food crops (i.e. rice and orchards) will be so low that food security might become an issue in the basin. People may have to import, for instance, fruits into the basin from other regions. Inevitably, this will increase the price of fruits, with potential consequences for low-income households. The drive for expanding oil palm production is also affecting national parks, with substantial encroachments of oil palm and rubber observed in two national parks in the Tapi basin (Khlong Phanom and Tai Rom Yen). We also note that, on a per hectare basis, the environmental impacts of converting land in the period 2009–2012 were much higher than in the period 2000–2009, meaning that further land conversion will increasingly bring negative environmental and economic effects. To minimize this risk, freezes on further land conversion, and promotion of the application of technologies and best practices that increase yields is recommended. Promoting the intensification of agricultural production should go hand in hand with environmental practices that minimize runoff of pesticides and fertilizers, such as reduced tillage and cover crops (Sharpley 2016).
5. Conclusion

The Thai government has been promoting biodiesel since 2005. To meet its target, palm oil production considerably increased and oil palm plantations rapidly expanded. Land use change effects that resulted from the oil palm expansion cause environmental problems and deteriorate ESS supply, especially when natural ecosystems are cleared. We analysed both direct and indirect land use change effects using spatial analysis in ArcGIS10.0 in combination with a farmer survey and then quantified subsequent effects on the supply of selected ESS (i.e. food and non-food provisioning service, carbon storage, biodiversity conservation). Our analysis focused on the Tapi river basin which is one of the main oil palm-producing areas of the country.

Our analysis indicates that the pattern of land use change changed over time. In the period 2000–2009, approximately 80% of new oil palm area replaced crop-land (i.e. rubber, rice, orchards, abandoned rice). Rubber was the main crop being replaced. In addition, natural ecosystems (i.e. forest, mangrove, wetland or peatland, unused land) were affected; this accounted for 16% of new oil palm area. iLUC in this period (as well as in the next) involved in particular the conversion of various land use types to rubber plantations. In the period 2009–2012, iLUC exceeded dLUC. Forests were cleared (39% of iLUC) to replace other crops (mainly rubber) that were converted to oil palm. Farmers’ motivations for changing land use to oil palm include higher profits, the availability of government subsidies and lower labour requirements compared to rubber.

Expanding oil palm plantations led to an increase in the annual average FFB production in the Tapi basin from 1,330,000 ton FFB/year in 2000 to 4,369,000 ton FFB/year in 2012. However, the production of a range of other crops (i.e. latex, rice and fruits) declined in the same period. Oil palm expansion also adversely affected carbon storage and biodiversity conservation in the Tapi basin and, in particular in the second period, is likely to have affected the hydrology of the Tapi river. The encroachment of oil palm and rubber in national parks in the basin stands out as environmental effect. Worryingly, the clearance of natural forest for oil palm and rubber production strongly increased in the second period compared to the first period. Between 2009 and 2012, some two-thirds of the LUC (including dLUC and iLUC) involved loss of natural forests. This reflects that there is very little additional arable land available for oil palm in much of the Tapi basin. We therefore strongly recommend the government to stop promoting the conversion of additional land to oil palm. Instead, the government should aim to increase productivity in existing plantations.

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Appendix

Table A1. Carbon stock pools taken from literature for modelling carbon storage service.

| Land use       | Carbon stock pool (ton C/ha) | Location                          | Age (year) | Soil depth (cm) | Source                                                                 |
|----------------|-----------------------------|-----------------------------------|------------|----------------|------------------------------------------------------------------------|
| Oil palm       |                             |                                   |            |                 |                                                                        |
| Above-ground   | 63.92                       | 43 Johor, Malaysia                | 23         | –              | Lab analysis by Khalid et al. (1999a)                                  |
| Below-ground   | n.a.                        | 7.95 Johor, Malaysia              | 23         | 0–100          | Lab analysis by Khalid et al. (1999b)                                  |
| Litter/dead    | –a                         | –                                 | –          | –              | IPCC guideline (2006)                                                  |
| organic matter|                             |                                   |            |                 |                                                                        |
| Soil organic   | 63.65                       | 118.70 Krabi, Thailand            | 13         | 0–30           | IPCC guideline (2006)                                                  |
| carbon         |                             |                                   |            |                 | Lab analysis by Siangjaeo et al. (2011)                                |
| Rubber          |                             |                                   |            |                 |                                                                        |
| Above-ground   | 83.66                       | 137.15 Songkhla, Thailand         | 26         | –              | Allometric equation by Chiarawipa et al. (2012)                         |
| Below-ground   | n.a.                        | 10.20                             | –          | –              |                                                                        |
| Litter/dead    | –a                         | 2.65                              | –          | –              |                                                                        |
| organic matter|                             |                                   |            |                 |                                                                        |
| Soil organic   | 63.65                       | 55.81                             | n.a.       | 0–50           |                                                                        |
| carbon         |                             |                                   |            |                 |                                                                        |
| Rice           |                             |                                   |            |                 |                                                                        |
| Above-ground   | 51.70                       | 67.98                             | n.a.       | 0–40           | IPCC guideline (2006)                                                  |
| Below-ground   | n.a.                        | 8.15 Nant, Thailand               | n.a.       | –              | Lab analysis by Pibumrung (2007)                                       |
| Litter/dead    | –a                         | 0.47                              | –          | –              |                                                                        |
| organic matter|                             |                                   | –          | –              |                                                                        |
| Soil organic   | 63.65                       | 67.98                             | n.a.       | 0–40           | IPCC guideline (2006)                                                  |
| carbon         |                             |                                   |            |                 |                                                                        |
| Orchards       |                             |                                   |            |                 |                                                                        |
| Above-ground   | 131.60                      | 150.07 National reserves forest, Nan, Thailand | n.a.       | –              | Lab analysis by Pibumrung (2007)                                       |
| Below-ground   | n.a.                        | 19.56                             | –          | –              |                                                                        |
| Litter/dead    | 5.20                        | 6.86                              | –          | –              |                                                                        |
| organic matter|                             |                                   | –          | –              |                                                                        |
| Soil organic   | 47.00                       | 124.21                            | n.a.       | 0–40           |                                                                        |
| carbon         |                             |                                   |            |                 |                                                                        |
| Mangrove       |                             |                                   |            |                 |                                                                        |
| Above-ground   | 47.00                       | 70 Samut Songkram, Thailand       | 12         | 0–100          | Lab analysis by Kridiborworn (2010)                                    |
| Below-ground   | n.a.                        | 44.91 Nakhon-Si-Thammarat, Thailand | n.a.     | –              | Lab analysis by Wantongchai et al. (2013)                              |
| Litter/dead    | 28.59                       | 27.65 Narathiwit, Thailand        | n.a.       | –              | Allometric equations by Verwer and Meer (2010)                          |
| organic matter|                             |                                   | –          | –              |                                                                        |
| Soil organic   | 82.00                       | 504 Thailand                      | 6          | 0–100          | Lab analysis by Buniyavechewin and Nuyim (1996)                         |
| carbon         |                             |                                   |            |                 |                                                                        |
| Wetlands and   |                             |                                   |            |                 |                                                                        |
| peatland       |                             |                                   |            |                 |                                                                        |
| Above-ground   | 8.00                        | 5.91 Nan, Thailand                | n.a.       | 0–100          | Review by Verwer and Meer (2010)                                       |
| Below-ground   | n.a.                        | 1.01                              | –          | –              |                                                                        |
| Litter/dead    | n.a.                        | 0.15                              | –          | –              |                                                                        |
| organic matter|                             |                                   | –          | –              |                                                                        |
| Soil organic   | 89.20                       | n.a.                             | 0–40       |                 |                                                                        |

Notes: n.a.: data are not available. 

*In IPCC Guidelines for National Greenhouse Gas Inventories – Tier 1, the dead wood and litter stocks are not present in the cropland.
Table A2. The iLUC effects of (a) rice and (b) orchard expansion during the periods 2000–2009 and 2009–2012.

| LUC (as a consequence of | Converted to rice | Converted to rice | Converted to rice | Converted to rice | Converted to rice | Converted to rice |
|--------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                          | (gross) a, in ha  | (net) b, in ha    | (gross) a, in ha  | (net) b, in ha    | (gross) a, in ha  | (net) b, in ha    |
| Cropland                 |                   |                   |                   |                   |                   |                   |
| Oil palm                 | 51                | -3186             | -                 | 102               | -2131             | -                 |
| Rubber                   | 2380              | -11,535           | -                 | 150               | -3387             | -                 |
| Orchards                 | 396               | -1535             | -                 | -                 | -9                | -                 |
| Abandon rice             | 2043              | 287               | 287               | 78                | -189              | -                 |
| Subtotal                 | 4871              | 287               | 287               | 330               | -                 | -                 |
| Natural and unused land |                   |                   |                   |                   |                   |                   |
| Forest                   | 29                | -43               | -                 | 1                 | 1                 | 1                 |
| Mangrove                 | -                 | -                 | -                 | -                 | -                 | -                 |
| Wetlands and peat land   | 13                | 13                | 13                | -                 | -                 | -                 |
| Unused land              | 177               | -782              | -                 | -                 | -65               | -                 |
| Subtotal                 | 218               | 13                | 1                 | 1                 | 1                 | 1                 |
| Other                    |                   |                   |                   |                   |                   |                   |
| Water                    | 15                | -220              | -                 | -                 | -6                | -                 |
| Built-up area            | 428               | -1202             | -                 | -                 | -22               | -                 |
| Other agriculture land   | 701               | 591               | 591               | -                 | -36               | -                 |
| Subtotal                 | 1144              | 591               | 591               | -                 | -                 | -                 |
| Total                    | 6233              | 890               | 331               | 1                 |                   |                   |

Notes: *Gross = area converted to rice. The gross values are taken from the spatial analysis by ArcGIS 10.0.

*Net = area converted to rice (gross) minus area of rice converted to other types of land use. Positive values of this net change are considered ‘the indirect land use change (iLUC)’. A negative net indicates that area of rice replaced by other land use types exceeds the area converted to rice.

(b) Orchards

| LUC (as a consequence of | Converted to orchards (gross) a, in ha | Converted to orchards (net) b, in ha | Converted to orchards (gross) a, in ha | Converted to orchards (net) b, in ha | Converted to orchards (gross) a, in ha | Converted to orchards (net) b, in ha | Converted to orchards (gross) a, in ha | Converted to orchards (net) b, in ha | Converted to orchards (gross) a, in ha | Converted to orchards (net) b, in ha |
|--------------------------|----------------------------------------|--------------------------------------|----------------------------------------|--------------------------------------|----------------------------------------|--------------------------------------|----------------------------------------|--------------------------------------|----------------------------------------|--------------------------------------|
|                          |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |
| Cropland                 |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |
| Oil palm                 | 943                                    | -3111                                | -                                      | 107                                  | -3433                                  | -                                    |
| Rice                     | 1931                                   | 1535                                 | 1535                                   | 9                                    | 9                                      | 9                                    |
| Rubber                   | 22,187                                 | 5211                                 | 5211                                   | 758                                  | -4961                                  | -                                    |
| Abandon rice             | 1025                                   | 519                                  | 519                                    | 13                                    | 13                                     | 13                                   |
| Subtotal                 | 26,086                                 | 7265                                 | 7265                                   | 887                                  | 22                                     |                                      |
| Natural and unused land  |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |
| Forest                   | 1710                                   | -419                                 | -                                      | 16                                    | 14                                     | 14                                   |
| Mangrove                 | -                                      | -133                                 | -                                      | -1                                    | -                                      | -                                    |
| Wetlands and peat land   | 52                                     | 22                                   | 22                                     | -                                    | -                                      | -                                    |
| Unused land              | 787                                    | -1386                                | -                                      | 149                                  | -111                                   | -                                    |
| Subtotal                 | 2549                                   | 22                                   | 22                                     | 165                                  | 14                                     |                                      |
| Other                    |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |                                        |                                      |
| Water                    | 1311                                   | -224                                 | -                                      | 9                                     | -10                                    | -                                    |
| Built-up area            | 1356                                   | -2646                                | -                                      | 1198                                 | 899                                    | 899                                  |
| Other agriculture land   | 680                                    | -132                                 | -                                      | 129                                  | -24                                    | -                                    |
| Subtotal                 | 3346                                   | -1337                                | -                                      | 2390                                 | 934                                    |                                      |
| Total                    | 31,981                                 | 7287                                 | 2390                                   | 934                                  | 1                                      |                                      |

Notes: *Gross = area converted to orchards. The gross values are taken from the spatial analysis by ArcGIS 10.0.

*Net = area converted to orchards (gross) minus the area of orchards converted to other types of land use. Positive values of this net change are considered ‘the indirect land use change (iLUC)’. A negative net indicates that the area of orchards replaced by other land use types exceeds the area converted to orchards.
### Table A3. Interview results for farmers who recently started oil palm cultivation.

| Description                              | Number of farmers (N = 14) | Relative share (%) |
|------------------------------------------|----------------------------|--------------------|
| **Area (ha)**                            |                            |                    |
| <8 (smallholder)                         | 12                         | 86                 |
| ≥8 (large-scale)                         | 2                          | 14                 |
| **Oil palm age (years)**                 |                            |                    |
| 0–2                                      | 1                          | 7                  |
| 3–15                                     | 12                         | 86                 |
| >15                                      | 1                          | 7                  |
| **Oil palm variety**                     |                            |                    |
| Complex                                  | 1                          | 7                  |
| Tenera                                   | 2                          | 15                 |
| Do not know                              | 11                         | 79                 |
| **Source of seedlings**                  |                            |                    |
| Government                               | 2                          | 14                 |
| Private sector                           | 11                         | 79                 |
| Self-breeding                            | 1                          | 7                  |
| **In case of planting other crops besides oil palm, how do the farmers manage other crops after planting oil palm?** | 14                         | 100                |
| No change                                |                            |                    |
| **Reasons for planting oil palm – can answer more than one choice** |                            |                    |
| Expect higher income than a previous crop | 2                          | 14                 |
| Regular income                           | 2                          | 14                 |
| Easy to manage/less labour work          | 1                          | 7                  |
| Neighbour’s suggestion                   | 5                          | 36                 |
| Government campaign                      | 2                          | 14                 |
| A grant from the Office of the Rubber Replanting Aid Fund (ORRAF) with 100,000 THB/ha for 5 years | 2                          | 14                 |
| Suitable land for oil palm               | 10                         | 71                 |
| Other                                    | 2                          | 14                 |
| **Trial**                                | 2                          | 100                |
| **Reasons for planting oil palm – can answer more than one choice (1 = most important, 6 = least important)** |                            |                    |
| 1. Suitable land for oil palm            |                            |                    |
| 2. Neighbour’s suggestion                |                            |                    |
| 3. Regular income                        |                            |                    |
| 4. Expected higher income than a previous crop |                      |                    |
| 5. Government campaign                   |                            |                    |
| 6. Easy to manage/less labour work       |                            |                    |
| **Satisfaction after planting oil palm**  |                            |                    |
| Satisfied because                        | 8                          | 57                 |
| Easy to manage                           | 6                          | 75                 |
| Gaining a higher income                  | 2                          | 25                 |
| Unsatisfied                              | 6                          | 43                 |
| Unstable (decreasing) price              | 2                          | 33                 |
| Difficult farm management                | 1                          | 17                 |
| Low productivity                         | 3                          | 50                 |
| **Land ownership**                       |                            |                    |
| Heritage                                 | 6                          | 43                 |
| Buy a new land                           | 6                          | 43                 |
| Land reforms by government               | 2                          | 14                 |
| Other                                    | -                          | -                  |
| **Previous land use before planting oil palm** |                        |                    |
| Rubber                                   | 4                          | 29                 |
| Betel nut                                | 1                          | 7                  |
| Rice                                     | 3                          | 21                 |
| Abandon rice                             | 1                          | 7                  |
| Unused land                              | 3                          | 21                 |
| Degraded forest (land reform)            | 2                          | 14                 |
| **Land clearing method**                 |                            |                    |
| Burning and tillage                      | 8                          | 57                 |
| Tillage                                  | 3                          | 21                 |
| Manual cutting                           | 3                          | 21                 |
| Other                                    | 1                          | 7                  |
| **Main problems when planting oil palm (can answer more than one choice)** |                            |                    |
| Flood/drought                            | 7                          | 50                 |
| Decreasing price                         | 3                          | 21                 |
| Low productivity                         | 3                          | 21                 |
| Rodent problem                           | 1                          | 7                  |
| **Expanding oil palm in the future**     |                            |                    |
| Expanding oil palm because               | 8                          | 57                 |
| Expectation of increasing price in the future | 1                      | 12.5               |
| Available land for planting oil palm     | 1                          | 12.5               |
| Easy to manage                           | 2                          | 25                 |
| Increase investment in oil palm to earn more income | 4                      | 30                 |
| No expansion of oil palm because         | 6                          | 43                 |
| No land available                        | 5                          | 38                 |
| Difficult farm management                | 1                          | 7                  |

(Continued)
Table A3. (Continued).

| Description | Number of farmers (N = 14) | Relative share (%) |
|-------------|---------------------------|--------------------|
| Willingness to replant oil palm | | |
| Willing to replant because | 10 | 71 |
| Easy to manage | 3 | 21 |
| Suitable land for oil palm | 5 | 36 |
| Higher income than previous crop | 2 | 14 |
| Prefer to change to other crops | 2 | 14 |
| Rubber | 2 | 14 |
| Other | 2 | 14 |
| Heritage for daughter/son | 1 | 14 |
| Changing to residential/commercial building | 1 | 14 |

Motives for changing the investment decision if prices of FFB decrease

| In case of investment change | 2 | 14 |
| Planting rubber | 2 | 14 |
| In case of no investment change | 12 | 86 |
| Trial plot | 1 | 8 |
| No available land | 1 | 8 |
| Have to wait until end of lifetime | 10 | 83 |

Motives for changing the investment decision if prices of FFB increase

| In case of investment change | 5 | 36 |
| Expanding oil palm area because farmers want to gain more income | 4 | 80 |
| Change to rubber | 1 | 20 |
| In case of no investment change | 9 | 64 |
| Trial plot | 1 | 11 |
| Lack of budget | 1 | 11 |
| Have to wait until end of lifetime | 7 | 78 |

Impact of rapid and large expansion of oil palm

| No impact | 4 | 29 |
| Decreasing prices of FFB | 8 | 57 |
| Drought/flood | 2 | 14 |

Table A4. Interview result for farmers who recently started rubber cultivation.

| Description | Number of farmers (N = 13) | Relative share (%) |
|-------------|-----------------------------|--------------------|
| Area (ha) | | |
| <8 (smallholder) | 9 | 69 |
| ≥8 (large-scale) | 4 | 31 |
| Rubber age (years) (can answer more than one choice if have many rubber plots) | | |
| 0–7 | 1 | 8 |
| 8–20 | 9 | 69 |
| >20 | 5 | 38 |
| Rubber variety | | |
| PRIM 600 | 12 | 92 |
| Do not know | 1 | 8 |
| Source of seedlings | | |
| Government | 4 | 31 |
| Private sector | 8 | 62 |
| Do not know | 1 | 8 |
| In case of planting other crops besides rubber, how do the farmers manage other crops after planting rubber? | | |
| No change | 13 | 100 |
| Reasons for planting rubber – can answer more than one choice | | |
| Expect higher income than a previous crop | 4 | 31 |
| Regular income | 3 | 23 |
| Easy to manage/less labour work | 1 | 8 |
| Neighbour's suggestion | 2 | 15 |
| Government campaign | 3 | 23 |
| A grant from the Office of the Rubber Replanting Aid Fund (ORRAF) with 100,000 THB/ha for 5 years | | |
| Suitable land for rubber | 8 | 62 |
| Reasons for planting rubber – can answer more than one choice (1 = most important, 6 = least important) | | |
| (1) Suitable land for rubber | | |
| (2) Expected higher income than a previous crop | | |
| (3) Regular income | | |
| (4) Government campaign | | |
| (5) Neighbour's suggestion | | |
| (6) Easy to manage/less labour work | | |

Satisfaction after planting rubber

| Satisfied because | 10 | 77 |
| Gain a higher income than previous crop | 4 | 40 |
| High productivity | 3 | 30 |
| Easy to manage | 1 | 10 |

(Continued)
| Description                                                                 | Number of farmers (N = 13) | Relative share (%) |
|-----------------------------------------------------------------------------|----------------------------|--------------------|
| **Skilful at planting rubber**                                             | 1                          | 10                 |
| **Unsatisfied**                                                            | 3                          | 23                 |
| **Unstable (decreasing) prices of latex**                                  | 3                          | 100                |
| **Land ownership**                                                         |                            |                    |
| Heritage                                                                    | 6                          | 46                 |
| Buy a new land                                                             | 5                          | 38                 |
| Land reforms by government                                                 | 2                          | 15                 |
| **Other**                                                                  |                            |                    |
| **Previous land use before planting rubber**                               |                            |                    |
| Rice                                                                        | 5                          | 38                 |
| Abandon rice                                                               | 1                          | 8                  |
| Unused land                                                                | 4                          | 31                 |
| Land reforms                                                               | 2                          | 15                 |
| Orphans                                                                     | 1                          | 8                  |
| **Land clearing method**                                                   |                            |                    |
| Burning and tillage                                                        | 10                         | 77                 |
| Tillage                                                                    | 3                          | 23                 |
| **Main problems when planting rubber (can answer more than one choice)**   |                            |                    |
| Fungi disease                                                              | 10                         | 77                 |
| Flood                                                                      | 2                          | 15                 |
| Decreasing price                                                           | 1                          | 8                  |
| Low soil quality                                                           | 1                          | 8                  |
| **Expanding rubber in the future**                                         |                            |                    |
| Expanding rubber because                                                   | 5                          | 38                 |
| Increase investment in rubber to earn more income                          | 4                          | 80                 |
| Easy to manage                                                             | 1                          | 20                 |
| No expansion of rubber because                                             | 8                          | 62                 |
| Lack of budget and labour                                                  | 4                          | 50                 |
| Change to other crops                                                       | 1                          | 12.5               |
| Change to commercial/residential buildings                                 | 1                          | 12.5               |
| Planted area is big enough                                                 | 1                          | 12.5               |
| Drought                                                                    | 1                          | 12.5               |
| **Willingness to replant rubber**                                          |                            |                    |
| Willing to replant because                                                 | 9                          | 69                 |
| Skilful at planting rubber                                                 | 4                          | 44                 |
| Suitable land for rubber                                                   | 3                          | 33                 |
| Easy to manage                                                             | 1                          | 11                 |
| Higher income than previous crop                                           | 1                          | 11                 |
| Prefer to change to other crops                                            | 4                          | 31                 |
| Oil palm                                                                   | 3                          | 75                 |
| Vegetables                                                                 | 1                          | 25                 |
| **Motives for changing the investment decision if prices of latex decrease**|                            |                    |
| In case of investment change                                               | 4                          | 31                 |
| Change to oil palm                                                         | 3                          | 75                 |
| Change to vegetables                                                       | 1                          | 25                 |
| In case of no investment change                                            | 9                          | 69                 |
| Skilful at planting rubber                                                 | 6                          | 67                 |
| Lack of (family) labour                                                    | 3                          | 33                 |
| **Motives for changing the investment decision if prices of latex increase**|                            |                    |
| In case of investment change                                               | 5                          | 38                 |
| Expanding rubber area because farmers want to gain more income             | 3                          | 60                 |
| Change to oil palm                                                         | 1                          | 20                 |
| Change to vegetables                                                       | 1                          | 20                 |
| In case of no investment change                                            | 8                          | 62                 |
| Lack of land                                                               | 5                          | 62.5               |
| Lack of budget and labour                                                  | 3                          | 37.5               |
Table A5.1. Interview result for farmers who recently started both oil palm and rubber cultivation, and switched in some plots of rubber to oil palm.

| Description                                                                 | Number of farmers (N = 10) | Relative share (%) |
|----------------------------------------------------------------------------|-----------------------------|--------------------|
| **Area (ha)**                                                              |                             |                    |
| <8 (smallholder)                                                           | 2                           | 17                 |
| ≥8 (large-scale)                                                           | 8                           | 67                 |
| **Oil palm age (years) (can answer more than one choice if have many oil palm plots)** |                             |                    |
| 0–2                                                                        | 11                          | 73                 |
| 3–15                                                                      | 4                           | 27                 |
| >15                                                                        |                             |                    |
| **Oil palm variety**                                                       |                             |                    |
| Surat 2                                                                     | 4                            | 40                 |
| Surat 7                                                                     | 1                            | 10                 |
| Complex ratera                                                             | 2                            | 20                 |
| DxP                                                                        | 2                            | 20                 |
| Do not know                                                                 | 1                            | 10                 |
| **Source of seedlings**                                                    |                             |                    |
| Government                                                                  | 4                            | 33                 |
| Private sector                                                              | 8                            | 67                 |
| **Rubber age (years) (can answer more than one choice if have many oil palm plots)** |                             |                    |
| 0–7                                                                        | 2                            | 17                 |
| 8–20                                                                       | 8                            | 67                 |
| >20                                                                        | 2                            | 17                 |
| **Rubber variety**                                                         |                             |                    |
| PRIM 600                                                                   | 6                            | 60                 |
| PRIM 235                                                                   | 1                            | 10                 |
| Do not know                                                                 | 3                            | 30                 |
| **Source of seedlings**                                                    |                             |                    |
| Government                                                                  | 2                            | 20                 |
| Private sector                                                              | 8                            | 80                 |
| **After switching in some plots of rubber to oil palm, how do the farmers manage remaining area?** |                             |                    |
| No change                                                                   | 9                            | 90                 |
| Continue change 2 ha of rubber plots to oil palm after planting oil palm for 7 years because of fungi disease | 1                            | 10                 |
| **Reasons for planting oil palm – can answer more than one choice**         |                             |                    |
| Expected higher income than a previous crop                               | 4                            | 19                 |
| Regular income                                                             | 3                            | 14                 |
| Easy to manage/less labour work                                            | 3                            | 14                 |
| Neighbour’s suggestion                                                     | 1                            | 5                  |
| Government campaign                                                        | 4                            | 19                 |
| **A grant from the Office of the Rubber Replanting Aid Fund (ORRAF) with 100,000 THB/ha for 5 years suitable land for oil palm** | 6                            | 29                 |
| **Reasons for planting oil palm – can answer more than one choice (1 = most important, 6 = least important)** |                             |                    |
| (1) Suitable land for oil palm                                             |                             |                    |
| (2) Expected higher income than a previous crop                            |                             |                    |
| (3) Government campaign                                                     |                             |                    |
| (4) Regular income                                                         |                             |                    |
| (5) Easy to manage/less labour work                                        |                             |                    |
| (6) Neighbour’s suggestion                                                  |                             |                    |
| **Satisfaction after planting oil palm**                                    |                             |                    |
| Satisfied because                                                          | 9                            | 57                 |
| Easy to manage                                                             | 5                            | 56                 |
| Gaining a higher income                                                    | 3                            | 33                 |
| Regular income                                                             | 2                            | 22                 |
| Can plant in seasonal flood area                                           | 1                            | 11                 |
| Unsatisfied                                                                | 1                            | 10                 |
| Rubber price is higher than oil palm price                                 | 1                            | 100                |
| **Land ownership for oil palm – can answer more than one choice**          |                             |                    |
| Heritage                                                                   | 8                            | 73                 |
| Buy a new land                                                              | 2                            | 18                 |
| Land reforms by government                                                  | 1                            | 9                  |
| **Land ownership for rubber – can answer more than one choice**            |                             |                    |
| Heritage                                                                   | 7                            | 64                 |
| Buy a new land                                                              | 3                            | 27                 |
| Land reforms by government                                                  | 1                            | 9                  |
| **Previous land use before planting oil palm – can answer more than one choice in case of having many oil palm plots** |                             |                    |
| Rubber                                                                     | 9                            | 60                 |
| Rice                                                                       | 2                            | 13                 |
| Unused land                                                                | 1                            | 7                  |
| Degraded forest (land reforms)                                             | 3                            | 20                 |
| **Previous land use before planting rubber – can answer more than one choice in case of having many rubber plots** |                             |                    |
| Rubber                                                                     | 5                            | 45                 |
| Coffee                                                                     | 1                            | 9                  |
| Rice                                                                       | 1                            | 9                  |
| Unused land                                                                | 1                            | 9                  |
| Degraded forest (land reforms)                                             | 3                            | 27                 |
| **Land clearing method**                                                    |                             |                    |
| Burning and tillage                                                        | 7                            | 70                 |

(Continued)
Table A5.1. (Continued).

| Description                                                                 | Number of farmers | Relative share (%)
|----------------------------------------------------------------------------|------------------|---------------------|
| Tillage                                                                    | 2                | 20                  |
| Natural decompose                                                          | 1                | 10                  |
| **Main problems when planting oil palm (can answer more than one choice)**  |                  |                     |
| No problem                                                                 | 5                | 50                  |
| Flood/drought                                                              | 2                | 20                  |
| Rodent problem                                                             | 2                | 20                  |
| Low productivity                                                           | 1                | 10                  |
| **Main problems when planting rubber (can answer more than one choice)**    |                  |                     |
| No problem                                                                 | 1                | 10                  |
| Fungi disease                                                              | 8                | 80                  |
| Flood/drought                                                              | 1                | 10                  |
| **Expanding oil palm in the future**                                       |                  |                     |
| Expanding oil palm because                                                 | 7                | 70                  |
| Easy to manage                                                             | 3                | 43                  |
| Increase investment in oil palm to earn more income by acquiring land from unused land or land reforms | 4                | 57                  |
| No expansion of oil palm because                                           | 3                | 30                  |
| Lack of (family) labour                                                     | 2                | 67                  |
| Prefer to expand rubber area                                                | 1                | 33                  |
| **Expanding rubber in the future**                                         |                  |                     |
| Expanding rubber because                                                   | 7                | 70                  |
| Rubber tree can be sold after the end of lifetime                          | 4                | 57                  |
| Increase in rubber investment to earn more income by acquiring land from unused land or land reforms | 3                | 43                  |
| No expansion of rubber because                                             | 3                | 30                  |
| Lack of (family) labour                                                     | 3                | 100                 |
| **Willingness to replant oil palm**                                        |                  |                     |
| Willing to replant because                                                 | 9                | 90                  |
| Easy to manage                                                             | 2                | 22                  |
| Suitable land for oil palm                                                | 1                | 11                  |
| Regular income                                                             | 2                | 22                  |
| Skilful at planting oil palm                                               | 4                | 44                  |
| Prefer to change to other crops                                            | 1                | 10                  |
| Rubber                                                                     | 1                | 100                 |
| **Willingness to replant rubber**                                          |                  |                     |
| Willing to replant because                                                 | 7                | 70                  |
| Rubber tree can be sold after the end of lifetime                          | 3                | 43                  |
| Skilful at planting oil palm                                               | 4                | 57                  |
| Prefer to change to other crops                                            | 3                | 30                  |
| Oil palm because easy to manage and regular income                          | 3                | 100                 |
| **Motives for changing the investment decision in oil palm if prices of FFB decrease** |                  |                     |
| In case of investment change                                               | 3                | 30                  |
| Multi-crops plantations                                                    | 1                | 33                  |
| Change to rubber                                                           | 2                | 67                  |
| In case of no investment change                                            | 7                | 70                  |
| Waiting until the oil palm reach end of lifetime                           | 2                | 29                  |
| Expectation of increasing price in the future                             | 3                | 43                  |
| Difficult to find a suitable land                                          | 1                | 14                  |
| Lack of labour                                                             | 1                | 14                  |
| **Motives for changing the investment decision in oil palm if prices of FFB increase** |                  |                     |
| In case of investment change                                               | 3                | 30                  |
| Expanding oil palm area by buying a new land                              | 3                | 100                 |
| In case of no investment change                                            | 7                | 70                  |
| Lack of labour                                                             | 1                | 14                  |
| Difficult to find a suitable land                                          | 2                | 29                  |
| Waiting until the oil palm reach end of lifetime                           | 3                | 43                  |
| Heritage for next generation                                               | 1                | 14                  |
| **Motives for changing the investment decision in rubber if prices of Latex decrease** |                  |                     |
| In case of investment change                                               | 4                | 40                  |
| Planting oil palm because easy to manage                                   | 2                | 50                  |
| Changing rubber variety                                                    | 1                | 25                  |
| Multi-crops plantations                                                    | 1                | 25                  |
| In case of no investment change                                            | 6                | 60                  |
| Waiting until rubber reach end of lifetime                                 | 2                | 33                  |
| Expectation of increasing price in the future                             | 2                | 33                  |
| Difficult to find a suitable land                                          | 1                | 17                  |
| Lack of labour                                                             | 1                | 17                  |
| **Motives for changing the investment decision in rubber if prices of Latex increase** |                  |                     |
| In case of investment change                                               | 5                | 50                  |
| Expanding rubber area to earn more income by buying a new land             | 5                | 100                 |
| In case of no investment change                                            | 5                | 50                  |
| Suitable land for oil palm                                                | 1                | 20                  |
| Lack of labour                                                             | 3                | 60                  |
| Keep the area for next generation (heritage)                               | 1                | 20                  |
| **Impact of rapid and widely expansion of oil palm**                       |                  |                     |
| No impact                                                                  | 4                | 40                  |
| Decreasing prices of FFB                                                  | 4                | 40                  |
| Drought/Flood                                                              | 2                | 20                  |
Table A5.2. Results of farmer interviews concerning annual cost–income comparison between oil palm and rubber (unit: THB/rai).

| Description                                      | Rubber Mean±SD | Sample (N = 10) | Oil palm Mean±SD | Sample (N = 10) |
|--------------------------------------------------|----------------|-----------------|------------------|-----------------|
| Fertilizers cost                                 | 1003 ± 446     | 10              | 1451 ± 930       | 10              |
| Labour cost for fertilizing                      | 183 ± 76       | 3               | 280 ± 311        | 2               |
| Herbicides cost                                  | 132 ± 84       | 4               | 455 ± 531        | 3               |
| Labour cost for cutting weeds/spraying herbicides| 182 ± 115      | 5               | 167 ± 58         | 3               |
| Labour cost for harvesting                       | 8450 ± 1626    | 2               | 1901 ± 1190      | 6               |
| Land cost                                        | 43,485 ± 638   | 3               | 10,000 ± 0       | 2               |
| Seedling cost                                    | 1483 ± 638     | 8               | 3073 ± 2055      | 10              |
| Fuel cost                                        | 142 ± 69       | 4               | 104 ± 77         | 4               |
| Income                                           | 22,858 ± 8151  | 8               | 20,246 ± 14,013  | 7               |

Net profit*                                       | 11,284         |                 | 12,816           |                 |

Note: * Land cost is not included in the net profit calculation.

Figure A1. Area of land (ha) converted to rubber plantations for the periods 2000–2009 and 2009–2012.

Figure A2. Slope levels of rubber and oil palm plantations from 2009 to 2012 in the Tapi river basin.