Agricultural Transformation and Land-Use Change

Evidence on Causes and Impacts from Indonesia

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This thesis is dedicated to both of my sons Anton and Benno, who have made my life as happy as it is.

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1 Introduction[1]

'Yes, "it's globalization, stupid", but its effects on land use can be harnessed if land use is understood as being part of open and complex human-environment systems dominated by long distance flows of commodities, capital, and people.'

Eric F. Lambin and Patrick Meyfroidt

Human induced land-use change has direct economic and ecological consequences, which are felt the most in the poorest world regions. Therefore, the key question in land-use change research is how to protect and enhance the ecological functions of tropical landscapes while simultaneously improving human welfare. Addressing the complex links between the economic and ecological sphere, this thesis seeks to shed a light on the socio-economic drivers of land-use change in developing countries.

In tropical regions the transformation of previously forested landscapes for agricultural use and also the future settings of these transformed landscapes are highly interrelated to the conditions and structural changes within the agrarian sector, driven by globalizing markets. In the developing world South-East Asia is an outstanding example of the clash between the ecological and economic sphere: the region is facing ecological degradation driven through agricultural expansion, while its economies are increasingly following a path towards modernization, entailing rapid structural transformation within the agriculture sector. These transformation processes do not affect all households uniformly. For instance, even though many farm households have increasingly integrated their production into global markets and realized economic benefits, there is still substantial heterogeneity between them in terms of economic performance.

Taking Indonesia as an example, this dissertation will specifically focus on the determinants and impacts of land-use change that are relevant for income growth of farm households in developing economies. In a globalizing world with rapidly expanding and sometimes cross-scale interdependencies, it is essential to understand these determinants and impacts in order to overcome trade-offs between economic development

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[1] I wrote this dissertation within the context of two research projects at the GIGA German Institute of Global and Area Studies under the supervision of Prof. Dr. Jann Lay: the DFG-supported project 'Integrated modelling of land-use changes at rainforest margins in Indonesia' (03/2011-09/2012) and within the scope of the DFG-supported Collaborative Research Centre 990 (EFForTS – Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems, Indonesia), the B10 subproject 'Landscape-level assessment of ecological and socioeconomic functions of rainforest transformation systems in Sumatra' (09/2012-08/2016).

and ecological sustainability on the local and also global levels. This work attempts to disentangle further the reciprocal links and feedback mechanism of land-use change and the dynamics of households' land-use change decisions in the long term. In doing this, the analysis will also take into account the long-term interrelation between economic and ecological goals. As effects could also vary between the local, regional, and global scales, this thesis will consider the impacts of working transmission channels on the different scales looking specifically on cash crop specialization. Moreover, this work gives insights into the underlying causes of the productivity heterogeneity among smallholders, which could help to define the potential to reduce poverty and vulnerability to poverty of farm households in tropical regions.

The rest of this introduction embeds the topic of the thesis in the current and pertinent literature on the global effects of land-use change before explaining the relevance of studying this topic in Indonesia. Finally, it lays out the research questions and the individual contributions of the dissertation.

1.1 The global effects of land-use change

Around the world, human-induced land-use change has shaped two key parameters which are central to human life. The first parameter relates to the rapid conversion of tropical forests, which is exacerbating global climate change (Myers et al., 2000, Pimm and Raven, 2000, Lambin et al., 2003, Wardle et al., 2004). The world's agricultural production, forestry and fishing has emerged as one of the main sources of anthropogenic greenhouse gas (GHG) emissions, accounting for nearly 25 per cent of the world's GHG emissions in 2014 (Smith et al., 2014). These numbers are more than alarming considering that GHG emissions from the agricultural sector have nearly doubled over the past fifty years and are expected to increase by another 30 per cent by 2050 (Tubiello et al., 2014). At the same time, expedited land-use change has transformed a wide range of natural habitats around the globe, resulting in millions of ecosystems being perturbed or even irreversibly destroyed. Never before have the world's hotspots of biodiversity been so threatened by human actions on land as they are today (Sala et al., 2000). Currently, agricultural land accounts for 38 per cent of the earth's physical surface and even for a greater percentage across the tropics (Foley et al., 2011). Between 1980 – 2000, 55 per cent of new agricultural land in tropical regions came at the expense of intact forests (Gibbs et al., 2010). This change in land use has been accompanied by a rapid reduction in biodiversity in particular, a decrease in vertebrate and bird populations (Butchart et al., 2010). The current risk of extinction for species is an estimated 7.9 per cent; though this is expected to increase in the future (Urban, 2015).

The second parameter relates to the economic consequences of land-use change, especially those that have a greater impact on the poorest regions in the world. The amount of land being used for agricultural purposes has been extended and continues to be extended in areas mainly located in developing countries. Driven by the world's growing population and globalizing agricultural markets, the agricultural sector in developing countries is transforming from a subsistence agricultural sector into a more commercial sector integrated into the global market. Related land-use change is found to be especially acute in regions with rapid population growth and low income levels (Bawa and Dayanandan, 1997, Jha and Bawa, 2006). The commercialization of the agrarian sector bears enormous opportunities for economic growth, especially in those world regions where poverty requires reducing. Given this background, it is clear that the agricultural sector in the poorest areas of the world increasingly competes with the world's natural ecosystems.

Against the backdrop of expanding agricultural areas in poor world regions, Land-Change Scientists have discussed possible solutions to reconciling ecology and economics. One prominent approach is land sparing or land segregation that is focused on land zoning. This sees forest conservation sharply defined, on the one hand, and agricultural land intensified to reach higher production levels, on the other hand (Phalan et al., 2011). Land sparing approaches initially seemed to be a promising tool to preserve ecosystem functions and biodiversity and were employed in global polices such as the program for Reducing Emissions from Deforestation and Forest Degradation (REDD) and in national or local polices targeted at protecting the biosphere or forest reserves. However, acknowledging our interconnected world, Land-Change Science now increasingly elaborate the socio-economic problems associated with dividing land into protected and intensively farmed land – namely, that it can lead to ambiguous, cross-scale or cross-regional effects. In a world characterized by global-scale flows of factors, goods and information, local-scale polices are likely to have indirect effects on land-use change in other countries – for example, through price effects, changing demand for agricultural commodities or shifting consumption patterns (Lambin and Meyfroid, 2011, Eakin et al., 2014, Liu et al., 2013). Moreover, generating higher productivity levels through intensification might also offset land-saving effects by raising incentives for further agricultural expansion (Lambin and Meyfroid, 2011).

With these factors in mind, Land-Change Science has made serious efforts to develop scenarios that successfully reconcile ecological and economic goals and promote more sustainable forms of land use (Turner II et al., 2007). A widely discussed pathway is that which focuses on multifunctional landscapes, represented by the so-called land sharing approach (Phalan et al., 2011). Within multifunctional landscapes, research takes into account the causal and feedback relationships of coupled human and environmental systems (Lambin et al., 2003). Interestingly, far from calling for a purely ecological approach, ecologists do not solely insist on untouched habitat reserves. Although, for example, forest degradation often reduces ecological functions, different forms of land use within a multifunctional landscape can also generate high conservation values (Clough et al., 2011). Here, the land sharing concept draws on one key characteristics of ecosystem functions and biodiversity – namely, the non-linearity of effects and interactions within an ecosystem. Consequently, the ecological connectivity between different land types (e.g. between forest patches) is a parameter of great interest by which to maintain the conservation of ecological functions within a landscape mosaic (Tscharntke, 2005, Perfecto and Vandermeer, 2010, Broadbent et al., 2012). Thus, highly specialized agricultural areas (e.g. those consisting of tree orchards) could be integrated into these landscapes (Lusiana et al., 2012). In doing this, the creation of new spatial settings may allow for the reconciliation of ecological services and human welfare.

1.2 Agricultural transformation and land-use change in Indonesia

South-East Asia is of particular concern globally regarding ecological degradation. In recent decades, South-East-Asian countries have exhibited the highest rates of habitat destruction, with an projected loss of biodiversity for this century of up to 85 per cent in 2100 (Sodhi et al., 2010). Indonesia, specifically, is an epicentre of economic and ecological transformations. It boasts the world's third-largest area of tropical forest but also has one of the highest deforestation rates – measured at 5 per cent annually between 2000 and 2010 (Miettinen et al., 2011, The World Bank, 2006). Between 2001 and 2014, Indonesia's total loss of forested regions (defined as areas with a canopy density of >30%) was 18,507,771 hectares (ha), which accounts for around 10 per cent of the country's land (see Figure 1.1) (World Resources Institute, 2014). As a result of these land transformations, Indonesia has become one of the largest greenhouse gas (GHG) emitters and, in turn, one of the largest contributors to climate change. Land conversions, in particular, increase the emission of nitrous oxide (N_2O) (Butterbach-Bahl et al., 2013, Kroeze et al., 1999). In Indonesia land-use

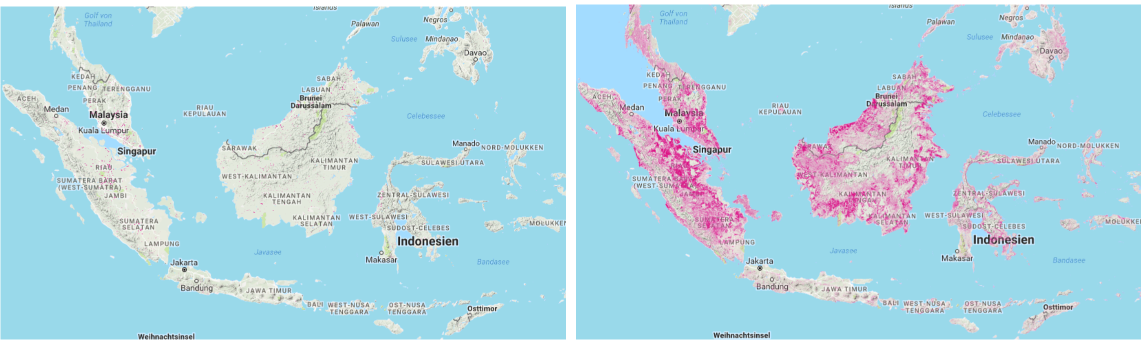

Figure 1.1: Land conversion in Indonesia between 2001-2014

Note: Areas are included with a canopy density of >30%. Losses (marked in red) between 2001-2014 make an area of 18,507,771 ha.

Source: World Resources Institute (2014).

change is responsible for 73 per cent of this form of GHG emission – an amount that makes Indonesia responsible for more land-use change GHG emissions (measured by the carbon loss from drained organic soils under cropland) than any other country in the world (The World Bank, 2009, FAOSTAT, 2016a). Between 1990 and 2014, the country's CO_2 emissions totalled 285,367 gigagrams, which is four times the amount produced by the United States, the second largest emitter in the world (see Figure 1.2) (FAOSTAT, 2016a). Furthermore, Indonesia is the second-largest producer of forest conversion emissions (see Figure 1.3) (FAOSTAT, 2016b). As an archipelago, the country is particularly vulnerable to the negative impacts of global climate change. The increasing frequency and intensity of extreme weather events (such as droughts, torrential rain, and strong winds) have negative impacts on the local population – especially for those living in lowland coastal cities, which contain approximately 60 per cent of Indonesia's population (UNFCCC, 2007, Measey, 2010).

At the same time, South-East Asian countries have been following a path towards industrialization. As part of this process, economies have been undergoing a continuous shift from predominantly agricultural sectors to manufacturing and service sectors. Consequently, the manufacturing and service sectors are moving up the value chain due to the increase in export-oriented manufacturing products and services (Martinez-Fernandez and Powell, 2009).[2] Despite being the least productive sector, nearly half of South-East Asia's total employment is engaged within the agriculture sector. In fact, the sector supports the livelihoods of about half of the total population (44.5 per

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[2] Nevertheless, the service sectors are still heterogeneous with both traditional and low-productivity services and modern, high-productivity services (ADB, 2013).

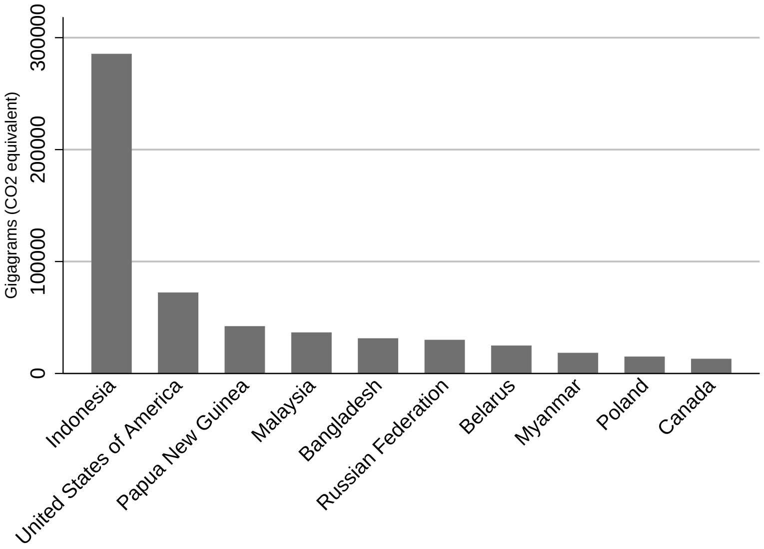

Figure 1.2: Top 10 emitting countries of greenhouse gas (GHG) emissions (CO_2 equivalent) from cropland organic soils between 1990 - 2014

Note: Annual average of net CO2 emissions, consisting of net carbon stock loss from drained histosols under cropland.

Source: Graphical representation based on FAOSTAT (2016a).

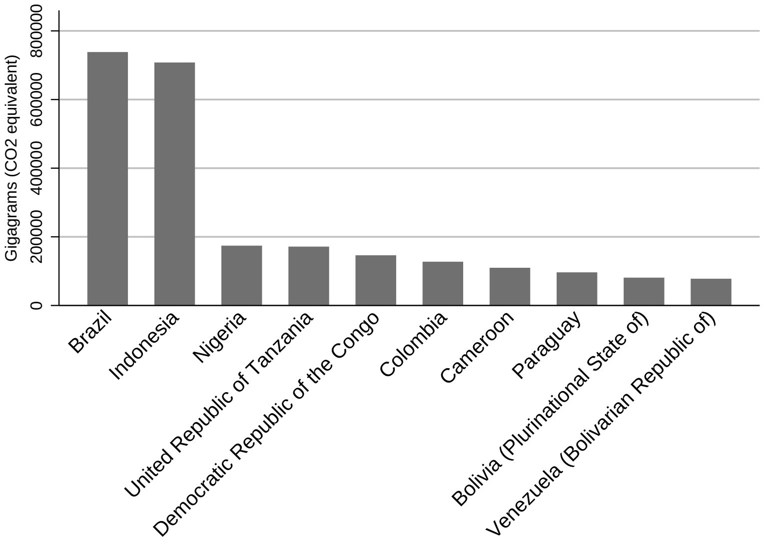

Figure 1.3: Top 10 emitting countries of greenhouse gas (GHG) emissions (CO_2 equivalent) from forest conversion between 1990 - 2015

Note: Annual average of net CO_2 emissions, consisting of net carbon stock loss in the living biomass pool (aboveground and belowground biomass) associated with forest and net forest conversion.

Source: Graphical representation based on FAOSTAT (2016b).

cent for the ASEAN countries in 2007) (Martinez-Fernandez and Powell, 2009). In Indonesia the agricultural sector made up 14 per cent of the gross domestic product (GDP) in 2015 and still employed around 35 per cent of the total population (in 2014) (The World Bank, 2016a).

Since the 1960s, Indonesia has experienced substantial economic growth, which has been driven by the interplay of a rising manufacturing sector with labour-intensive exports, increasing productivity within the agricultural sector (through enhanced technologies), and economic deregulation promoting exports and foreign direct investment (FDI) (Timmer, 2007). This economic growth has also been accompanied by conscious pro-poor policies, which has led to high investments in agricultural infrastructure (Suryahadi et al., 2009). The agricultural sector has been found to contribute to poverty reduction at the provincial level, where manufacturing exports have had a direct impact on only a few provinces located on the island of Java (Timmer, 2007). As a result of the Indonesian economy's increasing inclusiveness, poverty has been reduced in both absolute and relative terms (Timmer, 2007). For instance, a recent poverty headcount ratio revealed a decrease from 23.4 per cent in 1999 to 11.3 per cent in 2014 (see Figure 1.5).[3]

Since the 1970s, Indonesia's agricultural sector has diversified into tropical cash crops, leading to a sharp rise in the country's exports.[4] This process has been driven by (i) Indonesian policies which promote export crop production to raise exports especially from agricultural products (in contrast to oil and gas exports); (ii) increased global demand for food products; (iii) changing consumption patterns, such as an increase in the global demand for edible oils; and (iv) the global demand for biofuels (Barbier, 1989, Caroko et al., 2011). Globally, Indonesia is currently the largest producer and exporter of palm oil; together with Malaysia, it produces around 90 per cent of the world's palm oil. Hence, Indonesia's agriculture sector has been progressively transformed from slash-and-burn cropping systems into intensified monoculture plantations (Feintrenie et al., 2010b). Cash crops like oil palm, cocoa, and rubber – which are the most exported ones – have been extensively adopted by Indonesian small-scale farmers (Timmer, 2007, Suryahadi et al., 2009, Klasen et al., 2013). Indeed, the average annual growth rate of small-scale crude palm oil production was 11 per

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[3] The poverty headcount ratio measures the percentage of the population living below the national poverty line.

[4] Cash crops (also called commercial or estate crops) are defined as food or non-food farm products which are grown primarily for marketing and which are sold predominantly in formal agricultural markets (Achterbosch et al., 2014, Barbier, 1989).

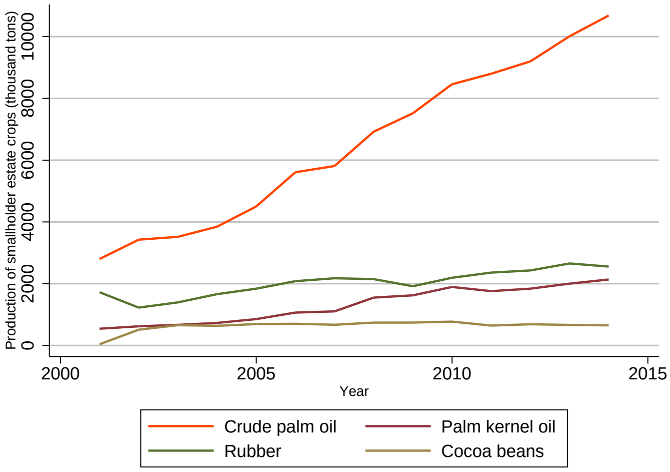

Figure 1.4: Production of smallholder estate crops (thousand tons), 2001-2014

Source: Graphical representation based on BPS Statistics Indonesia (2016c).

cent between 2001 and 2014 (see Figure 1.4). Although the size of the areas allocated for palm oil production on smallholder plantations remained fairly stable between 2001 and 2014 at around 3 million ha, the actual area size of agro-industrial oil palm plantations increased significantly from around 3 million ha in 2001 to 6.4 million ha in 2014 (BPS Statistics Indonesia, 2016b). The emerging literature on large-scale investments in developing countries suggests that large-scale oil palm estates increase agricultural wages and productivity, particularly those of smallholder producers tied to estates as outgrowers or contracted farmers (Herrmann, 2016).[5]

Many experts argue that the production of cash crops offers Indonesian small-scale farmers a way out of poverty (Suryahadi et al., 2009, Klasen et al., 2013, OECD, 2015). Therefore, policies that promote cash crop cultivation at the regional level are of particular benefit to households in Indonesia's rural areas (Feintrenie et al., 2010b). The economic returns which stem from the cultivation of cash crops increase investments in, for example, farm and human capital, and also create demand for non-tradable goods and services, which are sold on informal and local markets (ADB, 2013, Timmer, 2007).

While the economic status of small-scale farmers can be improved on average, and poverty reduced, we still have to examine the extent to which agricultural diversification into cash crops and related income growth have contributed to reducing farm

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[5] Tied farmers allocate a part of their land to a company and in return receive inputs and technical assistance for their own oil palm plantation. They also use the company's marketing structures – for example, they supply their products to the company's palm oil mill (IFC, 2013).

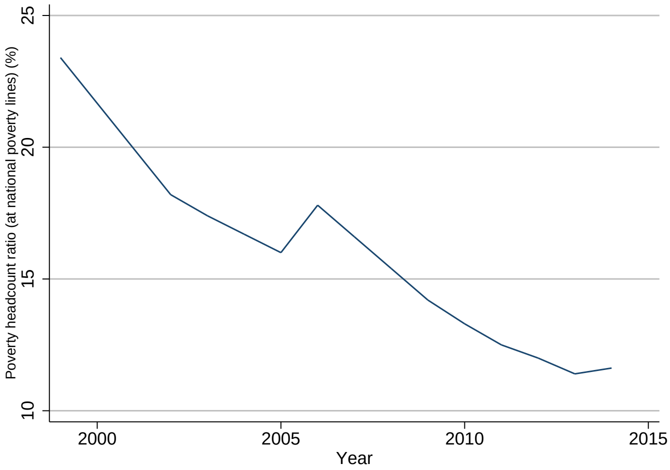

Figure 1.5: Poverty headcount ratio measured at national poverty lines from 1999-2014
Source: Graphical representation based on The World Bank (2016a).

households' vulnerability to poverty and chronic poverty. Many Indonesians still live just above the poverty line, and vulnerability afflicts half of the population – particularly in rural areas – which is why many Indonesians repeatedly slip back into poverty (Tsakok, 2011, p. 128). In 2013 about 28 million people (about ~ 11 per cent of the total population) lived in extreme poverty on less than USD 25 a month (The World Bank, 2016b). Hence, the question is still how to reduce poverty among Indonesian farm households in the long term to reach sustainable poverty reduction and inclusive growth. The related literature points to the need for substantial increases in productivity in the agriculture sector that are able to improve the income potential of poor farm households (Lee et al., 2014, Hasnah et al., 2004, ADB, 2013, Tittonell et al., 2007). Productivity should be raised, for example, through improved management practices and by enhancing transport infrastructure (Lee et al., 2014, OECD, 2015). Given the archipelagic geography of Indonesia, better transport infrastructure would significantly lower transport and production costs. Moreover, more partnership arrangements between large estates and smallholders, and/or the grouping of independent smallholders into cooperatives might improve marketing networks and technical services for Indonesian smallholders (OECD, 2015, 2016).

However, increasing agricultural productivity is just the first step towards reducing poverty. One has to consider that farm households also face new risks associated with cash crops through, for example, price shocks and risks linked to production (Wood et al., 2013, Rist et al., 2010, Sunderlin et al., 2001). Moreover, farmers are increasingly affected by environmental risks – especially by floods, droughts, earthquakes, landslides, and pests (Lassa, 2012, Clough et al., 2009). Given the combination of numerous risks and idiosyncratic constraints faced by farm households living in remote areas, smallholders' cash crop production displays a high degree of heterogeneity in terms of economic outcomes. Insights into the determinants of these differences would help to raise the production levels of households and would also contribute to the development of risk coping strategies for households. This, in turn, would go some way to bringing about a sustainable reduction in chronic poverty and poverty vulnerability among farm households in Indonesia.

1.3 Research questions and own contribution

This thesis is concerned with the main socio-economic determinants of land-use change across the tropics. It contributes to the debate on the causes and impacts of global land-use change by identifying the key land-use determinants of farm households, with a particular focus on smallholders' cash crop cultivation in developing countries. Accordingly, the parameters – and their impact – of farm households' land-use decisions will be evaluated (i) by employing a conceptual framework to conduct a meta-analysis of the current literature; (ii) by using a case study in Sulawesi, Indonesia, in order to empirically examine the welfare effects of smallholders' cash crop production, paying particular attention to heterogeneity among households' production outcomes; (iii) within a landscape model that captures the reciprocal links between the ecological system, small-scale production, and decisions on land-use change; and (iv) by running an analysis that complements the previous results, paying particular attention to broader-scale effects and the trade-offs between the specialization of farm households' cash crop production and related environmental consequences. A short summary on the main results of these analyses is presented below.

The first analysis within the ***second chapter***, titled ***'Drivers of households' land use decisions: A critical review of micro-level studies in tropical regions'***, uses a conceptual framework to comprehensively review the literature. More specifically it uses a meta-analysis to explore the underlying drivers of land-use change at the farm household level across the tropics. Since the emergence of Land-Change Science, a number of literature reviews and meta-analyses examining the causes of land-use change have been published (see Angelsen and Kaimowitz (1999), Geist and Lambin (2001), Rudel (2007)). However, the micro-level drivers of land-use change and related decision parameters of farm households are still underexplored in the literature. In reviewing 91 recent empirical and theoretical studies that analyse land-use change at the micro-level, this chapter identifies the key determinants of households' decisions on land-use change within the current literature. Moreover, the results of these studies are examined within a meta-analysis. The findings reveal that the conversion of forests into cultivated land or grassland, mainly for agriculture or ranching purposes, are the most frequently analysed. However, the analysis also reveals more subtle land-use changes into wildlife-friendly land uses, for example the transition of agriculture for fallow holdings and the conversion from agriculture into protected zones. Moreover, feed-back mechanisms between drivers and non-linearity of effects add to the complexity of land-use change processes. One example for an important non-linearity is the inverse U-shaped relationship between market access and agricultural expansion that has been shown in a number of studies. Integration into agricultural markets first leads to agricultural expansion, but, in a second stage, households start to invest in off-farm activities and might reduce the pressure on forests and thus ecological degradation. These interrelationships are conditioned by institutional changes, such as market-oriented reforms adopted by many developing countries in the 1980s and 1990s. The meta-analysis presents some methodological challenges, since many studies use small samples and face problems of internal validity. Nevertheless, the literature on micro-level drivers on land-use change points towards micro-level economic growth (e.g. in income and capital endowments) being a strong catalyst of human-induced land-use change. Moreover, the review suggests that there is substantial heterogeneity among farm households regarding these endowments, which is also significantly associated with households' land-use changes – including land-use changes towards agricultural use and land uses with high ecological value such as fallow holdings as well.

One central result within the first chapter is that household endowments are key for land-use decisions but might also be heterogeneous among farm households. This finding is analysed in greater detail in the ***third chapter*** with the title: ***'Cash crops as a sustainable pathway out of poverty? Panel data evidence on heterogeneity from cocoa farmers in Sulawesi, Indonesia'***, linking the income potential of cash crop production to the heterogeneity of smallholders' productivity. Since the resulting welfare effects of farm households might only be static, and productivity among households could differ significantly, it is not certain that poverty and vulnerability of smallholder households are reduced by cash crop cultivation in the long term. Instead, cash crop farmers, in particular those without proper farm management skills, may experience boom and bust cycles, caused by volatile world market prices, local weather shocks and pests. Empirical evidence on the long-term impact of commercial farming on economic sustainability remains scarce as such assessments require long-term panel data in order to control for household-specific effects, endogeneity, and initial conditions. Yet, few studies assess the long-term impact of cash crop cultivation on rural incomes, thus making it impossible to draw inferences about its potential as a sustainable pathway out of poverty.

To examine the long-term poverty impacts of cash crop agriculture, the analysis draws on a unique panel data set of smallholder farmers in Central Sulawesi, Indonesia, covering the years 2000, 2006, and 2013. In this region farmers have increasingly cultivated cocoa since the turn of the century. This chapter explores how cocoa cultivation contributes to poverty reduction and whether income gains from cash crops are more volatile. The results show that – over the analysed time horizon of more than 10 years – cocoa cultivation is associated with strong and sustainable poverty reduction. Cocoa farmers fare better than non-cocoa farmers and the welfare gains can mainly be attributed to increasing cocoa yields. Yet, yield gaps among cocoa smallholders remain large and are increasingly heterogeneous. We can trace back this productivity heterogeneity to farm management practices. Linking these findings to poverty transitions, we can show that better management practices – for the cocoa case a mixture of an input- and labour-based cultivation strategy – facilitate the transition out of poverty and shield against income losses. Hence, trainings of smallholders bear the chance not only to narrow yield gaps but also to add ecological value through, for example, improved and accurate application of chemical inputs.

Having gained insights into households' potential of cash crop cultivation, the ***fourth chapter***, titled ***'Towards an integrated ecological-economic land-use change model'*** presents a dynamic ecological-economic model of land-use change. The model explores the potential of landscapes with different land-use patterns to balance ecological and socio-economic goals. In recent years, research on socio-economic and eco-economic modelling has been increasingly used to analyse a variety of specific real-world situations (Holdo et al., 2010, Le et al., 2008, 2010). However, the eco-economic potential of landscapes with different land-use patterns is an underexplored issue. The model presented serves as an integrated, exploratory tool with which to tackle the question of the kind of landscape mosaic that can improve the ensemble of ecosystem functioning, biodiversity, and economic benefit. Often, integrated models lack available data for all aspects of such complex systems, particularly data that link the relevant socio-economic and ecological functions. This model incorporates such data by building on a detailed household survey from Jambi, Indonesia, and matching context-specific data on ecological functions.

Within the economic submodel, smallholders' decisions on land use and land management – evaluating specifically the cash crop production of palm oil and rubber – are simulated. Smallholders' land use and management decisions are based on a profit maximization assumption bounded by the available wealth of that household. Household's financial resources are implemented as the most restrictive decision-making parameter considering the fact that access to capital markets are often limited for small-scale farmers in rural areas of developing countries. This model enables a dynamic analysis: In each year each household determines factor inputs for all its fields and decides about land use and potential land-use change. Households' land decisions are directly linked to the ecological submodel, which includes a simple account of carbon sequestration in aboveground and belowground vegetation.

Initialized with realistic or artificial land-use maps, the ecological-economic model serves as a basis for the future testing of different scenarios – for example, how 'external' effects (e.g. policies or price shocks) or 'internal' effects (e.g. heterogeneity in technology and production among farm households) advance the understanding of the mechanisms underlying the trade-offs and synergies of ecological and economic functions in tropical landscapes. Moreover, first simulations show that the relationships between carbon accumulation/storage and economic benefit might not be completely straightforward. Extending this basic model, it can serve to test, for example, a combination of wildlife-friendly and land sparing farming practices in order to assess the effectiveness of this approach to identify the landscape mosaic balancing economic and ecological goals.

The ***fifth*** chapter with the title: ***'Economic and ecological trade-offs of agricultural specialization at different spatial scales'*** complements the previous chapters' focus on the micro-level determinants of land-use change by concentrating on the broader scale effects (from the household to the village, region, or above), particularly on the trade-offs between economic gains and the loss of ecosystem functions achieved through the agricultural specialization within transformed landscapes. Agricultural specialization can result in substantial ecological costs (e.g. reduced ecosystem functions and services), especially if it emerges at the village or regional levels. The temporal scale also matters in the event that there is a mismatch between the ecological and economic systems. For instance, in the short term the progressive loss of ecosystem functions and associated services may only have a small impact on the profitability of specialized monocultures; however, in the longer term the sharp reduction or entire disappearance of important functions could undermine the profitability of monocultures on broader spatial scales.

The chapter starts with a conceptual framework in which economic gains can be maximized when production activities are specialized on increasingly broader scales, particularly when markets for outputs and inputs function well. The analysis takes Jambi province, Indonesia, a current hotspot of rubber and oil palm monoculture, as a case study to illustrate these issues. It empirically shows that the level of specialization differs across scales, with higher specialization occurring at the household and village levels, and higher diversification towards the provincial level. Findings further suggest that there are gains from specialization at the farm level but that this specialization does not necessarily lead to a consolidation of smallholder farms to ever-larger units. This result can be set in the context of a conciliating landscape design within multi-functional landscapes, where land use patches of highly specialized smallholders are intermingled with areas characterized with high levels of ecosystem services. This would be one possible way to resolve trade-offs between economic gains and ecological costs on the landscape level, supported by policies targeting on ecosystem functions, on the one hand and economic benefit, on the other.

2 Drivers of households' land use decisions: A critical review of micro-level studies in tropical regions[1]

2.1 Introduction

Global change is the aggregate result of billions of individual decisions and understanding the determinants of these decisions is crucial for its analysis. This is particularly true in the case of land-use change as one important component of global change. Land-use change has impacts on biodiversity, food security as well as on the levels of of greenhouse gas (GHG) emissions. Governments, policies as well as global and domestic markets set the conditions, under which micro-agents, i.e. households, firms, and farms, eventually take and implement decisions on land use. This process is accelerated by interlinked and interacting economic systems as well as the digital proximity of social systems in a globalizing world (Liu et al., 2014, 2013, Eakin et al., 2014).

Studying the patterns, causes, and consequences of land-use change requires the integration of natural sciences with social and geographical information (Rindfuss et al., 2004). Geographers and natural scientists utilize spatially explicit models at highly disaggregated scales while social scientists mostly rely on models that include human behavioural components to understand the determinants of land-use change (Irwin and Geoghegan, 2001). Based on these approaches, Land System Science (LSS) has evolved from a science that solely addressed the patterns and causes of deforestation to a science that is now capable of analysing more subtle land-cover changes through the use of intricate models that conceptualize the causal and feedback relationships within coupled human and environmental dynamics (Turner II et al., 2007, Lambin et al., 2003). The data fed into these models has become more sophisticated in recent years and now includes high-resolution satellite imagery, the use of geographic information systems as well as detailed socio-economic and geophysical data that model the human-environment interactions driving land-use change (Vance and Geoghegan, 2004). Given the theory of coupled human and environmental systems, Land System Science extends its scope to the linkages and feedback mechanism between integrated coupled systems over geographically and socially large distances (Eakin et al., 2014,

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[1] This chapter is a slightly updated version of Elisabeth Hettig, Jann Lay and Kacana Sipangule (2016): 'Drivers of households' land use decisions: A critical review of micro-level studies in tropical regions', in: *LAND*, 5(6), 32.

Liu et al., 2014). These so-called telecoupled interactions include socio-economic and environmental effects, which might be non-linear and multidirectional and lead to intended or unintended, direct and/or indirect changes of different orders in the affected system (Eakin et al., 2014).

Since the emergence of Land-Change Science, a number of literature reviews and meta-analyses that analyse the causes of land-use change have been published, in particular Angelsen and Kaimowitz (1999) and Geist and Lambin (2001). The reviews are based on the first wave of land-use change studies that analysed the causes of deforestation in tropical regions in the early 1990's. These literature reviews called for more micro-level case studies that enable a better understanding of the causes and the mechanisms of land-use change (Geist and Lambin, 2001, Angelsen and Kaimowitz, 1999). Since then, a large empirical literature of micro studies has emerged and first meta-analyses of these studies are included in Keys and McConnell (2005) and Rudel (2007).

This paper aims to analyse and review the land-use change drivers that influence households' land-use change decisions. For this, we systematically review 91 micro-level studies and conduct a meta-analysis to understand the importance of specific determinants of households' land-use decisions. Similar to Keys and McConnell (2005), our focus is on tropical regions as they have experienced dramatic land-use change in the last decades. Hence, the studies that consist of both empirical and theoretical multidisciplinary works were conducted in tropical regions and published between the years 2000 and 2015. The studies must analyse land-use change at the village- or household level and the drivers of change have to include household characteristics. Two important contributions of our review stand out: first, we depart from the conventional practice in earlier reviews to focus on the conversion of forest lands by including a discussion on the conversion of agricultural/ranching lands, protected forests and wetlands. Secondly, by placing an emphasis on the micro-level studies, we can provide a more detailed assessment of household-level drivers than earlier reviews (with Keys and McConnell (2005) being the exception) that stressed the role of more aggregate drivers such as population growth and market developments. This allows us to demonstrate not only the importance of household factors for land-use change, but also the heterogeneity in the relationship between land-use change and growth-associated micro-level drivers, which is caused by the complex interactions among these drivers, in particular income and technology, and the role of context-conditions, in particular institutions, policies, and market conditions. These results imply that land-use policies will have to take into account this heterogeneity and avoid one-size-fits-all approaches. In fact, this may explain why global fairly uniform approaches targeted at influencing land use change, for example Reducing Emissions from Deforestation and Forest Degradation (REDD, and REDD+) have not been overly successful (Angelsen et al. 2012).

The remainder of this paper is structured as follows: We first introduce a conceptual framework adapted from Angelsen and Kaimowitz' scheme (Angelsen and Kaimowitz, 1999). This is followed by a systematic meta-analysis of the micro-level studies reviewed. We then provide a detailed and comprehensive literature review and close with a summary, conclusions, and some reflections on future research.

2.2 Conceptual framework of land-use change

To conceptualize the multiform and complex dynamics of human-environmental systems systems and land-use change, we build on a concept on the causes of deforestation proposed by Angelsen and Kaimowitz (1999). This simple framework that provides a stepwise distinction of the causes of deforestation has been widely cited in the both deforestation and land use literature (for instance, Geist and Lambin (2001)). It includes a three-stage-process of underlying causes (macro-economic variables), immediate causes (decision parameters) and sources of deforestation (agents' actions). While we find that this model is a good starting point for a more detailed analysis of the drivers of land-use change, we identify three major limitations of the framework. First, it neglects the role played by household endowments and characteristics in driving land-use change. Second, it does not explicitly consider interlinkages and feedback mechanisms within coupled human and environmental systems and between different systems. Within a system, there could be feedback mechanisms between the different stages, for example between agents' choices and underlying causes of deforestation. For instance, agents may influence policies, which again affect land-use decisions. Further, interlinkages between the decision parameters are need consideration. For example, technology and infrastructure are likely to be linked. Further, there could be multidirectional interactions of one system towards other socially and geographically remote human-environmental systems, so-called telecoupling interactions (Eakin et al., 2014, Liu et al., 2013).

We draw on this standardized model of deforestation but modify it to suit our purposes in the following ways. First, rather than analysing all actors of land-use change we only focus on the land-use decision parameters of farm-households and small-scale farms. Second, deforestation is obviously only one form of land-use change and we include other categories, such as reforestation or the conversion of wetlands to agriculture. Third, we expand the range of micro-level drivers (institutions, infrastructure, markets and technology) to include household characteristics and endowments (for instance, physical capital and family workforce) and key policies (for example, forest conservation policies, institutional reforms of land rights, or agricultural policies). Forth, we present more precise elaborations of the feedback mechanisms between and within the hierarchical components of land-use change within a specific human-environmental system. Fifth, we link the dynamics of one system to others capturing the potential interacting and feedback processes between two or more systems (see Figure 2.1). Our concept thus integrates the determinants and outcomes of land-use change in a human-environment system both vertically, i.e. between underlying causes, micro-level drivers and outcomes, as well as horizontally, i.e. between specific micro-level drivers. Embedded in a telecoupled world, it is further linked to at least one other but distant land systems by telecoupling interactions and feedbacks. Figure 2.1 shows our framework. It illustrates the decision-making process of micro-level agents and how the underlying causes of land-use change (macro-economic variables) are linked to the micro-level drivers and to the final land-use change outcomes, which we define as non-used forest, forestry, protected forest, logging, fallow, agroforestry, agriculture, ranching, or wetland cultivation. Underlying causes include policies, population growth, and global markets. It further sets the dynamics of land-use change in one system in the context of telecoupling processes with other human-environmental systems. To keep it simple, we do not illustrate the potential and/or cross-scale links between specific elements of the system A to elements of the system B (and possibly further systems, which are described by the third white arrow).

Focusing on the land-use change dynamics of micro-level agents, we refer to the central causalities between macro-economic variables and micro-level drivers of land-use change. The impact of underlying policies on land-use decision making is dependent on two relevant aspects: first, on the institutional framework of land-use rights and the (non-)existence of land tenure security and second, on key policies for land use. Individual land-use decisions highly depend on the respective land governance and on the ways in which land-use rights can be transmitted and guaranteed. Likewise, land-specific key policies such as settlement programs, public schemes for highway expansion, or land extension services, influence and alter all other land-use decision parameters of agents. To illustrate how population growth affects agents' land-use decision, our concept focalize primarily on local population pressure via immigration. Immigration is either triggered by key polices and/or by price signals of developing

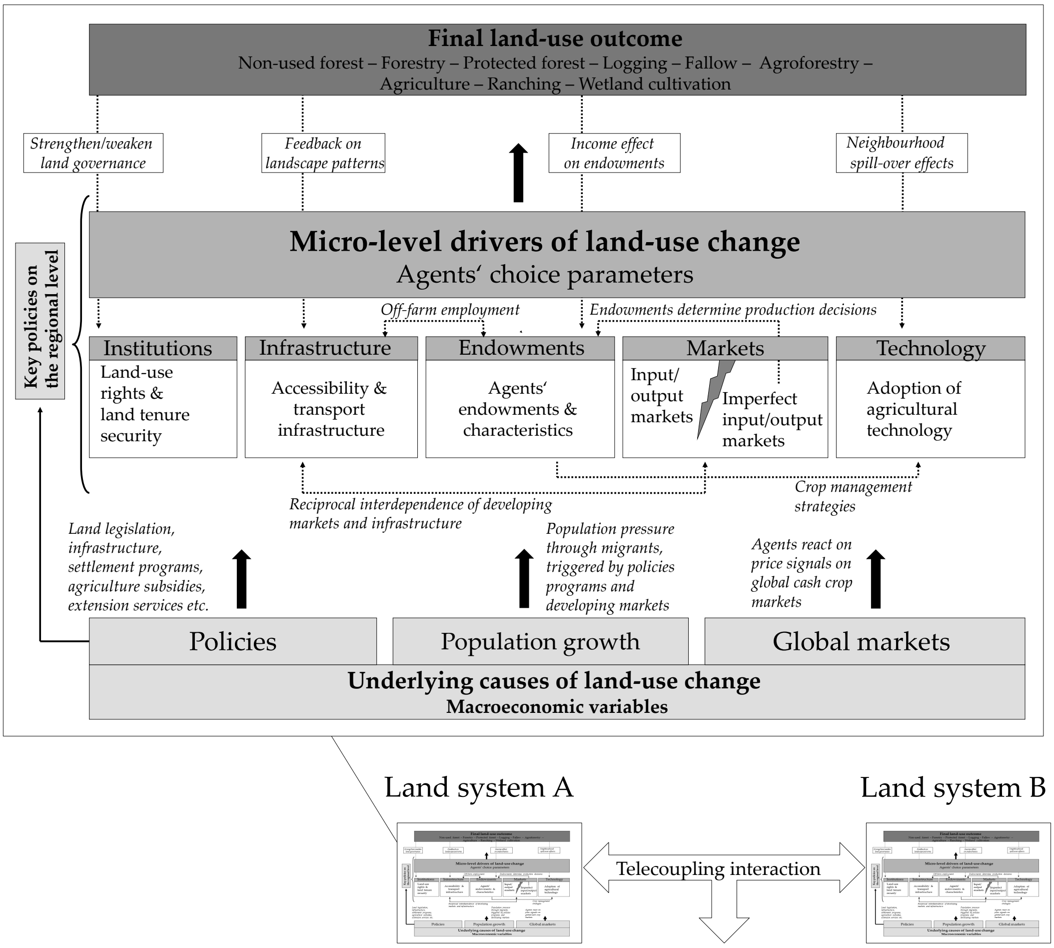

Figure 2.1: Concept of the micro-level drivers of land-use change

Source: Authors' concept based on Angelsen and Kaimowitz (1999).

markets. Finally, we include the impact of global markets and focus on global cash crop markets, which create incentives for agents to switch their land use towards cash crop cultivation and thus might raise households' incomes. Income growth in turn may alter crop consumption patterns and hence crop demand on the regional and global scale.

The micro-level drivers consist of five choice parameters of households, which are institutions, infrastructure, agents' endowments and characteristics, markets and technology (Figure 2.1). Introducing institutions, we show that local land-use rights, such as formal property rights or informal (customary) rights drive land-use change. Taking these contrary systems as an example, agents may react differently regarding their decision on land extension or cash crop cultivation. The degree of tenure security, implemented through legal titling or local agreements, determines the reliability of these land rights. As second decision parameter, the accessibility to public services/markets centres and transport infrastructure, influences agents' land-use decisions by enabling rural households to improve their access to agricultural inputs and/or to sell their products. Thirdly, the agent's characteristics and endowments that include the culture/ethnicity of a household and for example its physical capital, labour or social capital are key parameters for agent's land-use decision making. To illustrate, a higher level of wealth enables a household to invest in a more capital intensive land use such as pasture. These individual effects are reinforced if access to capital (or other factor) markets is limited. Hence, introducing the fourth choice parameter, the quality of input and output markets plays a fundamental role for agents' land-use change. Households' land use differs if markets for labour and agricultural inputs are limited or even non-existent. For example, cash crop adoption and/or agricultural expansion – and thus the systematic forest conversion – is more restricted for households in areas with fragmented markets. Finally, land-use decisions are determined by the respective agricultural technology available for and adopted by households.

Furthermore, our framework on land-use change identifies four relationships between the micro-level drivers within one human-environmental system that are depicted by the dotted lines in Figure 2.1. First, there is a reciprocal link between the accessibility to infrastructure and developing markets. On the one hand, public improvements in transportation networks reduce costs and facilitate economic activity, which in turn promotes the emergence of input and output markets in remote areas. On the other hand, evolving markets trigger infrastructure development. Both dynamics are interdependent and mutually reinforcing. Second, household endowments and characteristics affect the adoption of technologies and agents' crop management strategies. For example, the adoption of a more labour-intensive technology depends on either household's capital available for hiring labour or on family workforce. Third, access to infrastructure and public services influences agents' options of off-farm employment and vice versa. Lastly, market conditions determine the production decisions of households. If input and/or output markets are limited or non-existent, households have to fall back on family workforce and capital endowments. Thus, the decision on land-use change depends on the households' own shadow price for family labour, leisure and assets and is not determined by external factor market prices.

Feedback loops also operate from the final land-use outcomes to the micro-level drivers through the mechanisms depicted by the small boxes above the micro-level drivers of land-use change. Certain land-use changes could strengthen or weaken land rights. This is especially the case if land is weakly governed and/or there are additional informal rules of land rights. Since the conversion of non-used forests in tropical regions goes along with the introduction of property rights, longer fallow periods could attract other agents to encroach and convert foreign land for their own purposes. In addition, different land uses and the corresponding landscape changes may influence infrastructure requiring a different set-up such as those necessary for plantation cultivation. At the household level, land-use choices go along with specific income effects, for example, cash constraints could be relieved allowing the household to accumulate physical capital for new investments. This in turn determines production decisions, especially so under imperfect factor markets. Finally, land-use outcomes induce neighbourhood spill-over effects, for example via copying or knowledge transfer in informal networks. Across systems, telecoupling interactions include socio-economic-environmental effects, which might be governed and intended, for example global policy programs including the global program for sustainable forest management called Reducing Emissions from Deforestation and Degradation (REDD and REDD+). An example for unintended, ungoverned impacts across systems is the recent phenomenon of large-scale land acquisitions in developing countries – sometimes referred to as 'land grabbing'. These acquisitions, often by foreign investors are driven by the increased global demand for agricultural products and have repercussions, sometimes land right conflicts, in very remote places (Anseeuw et al., 2012). That conflicts in such places reach the attention of a worldwide audience and influence global discourses through the campaigns of NGOs shows that – in a globalized world – agents might not only cross distance, but also scale and hierarchical contexts (Eakin et al., 2014), thereby linking not only the elements of within but also between different systems.

2.3 Meta-analysis

Following the concepts of Cooper (1982) our review adopts the elements of an *integrative research review*. As is common with integrative research reviews our study collects and compares the results of primary studies on micro-level land-use change to represent the current state-of-the-art and to point at research gaps within the relevant literature. As part of this, we apply a meta-analysis to synthesize the results of the reviewed studies systematically. Specifically, we code the qualitative information across studies according to a questionnaire (see Appendix A, Table A.1). We further extend the existing theory building on the concept presented above and examine carefully the potential threats to validity of the reviewed studies on micro-level land-use change. The studies reviewed in this paper were collected during the period from

March 2011 to September 2015. They were sourced from academic databases and search engines such as Google Scholar, Scirus, Repec, Mendeley, AgEcon Search as well as from cross references of cited papers. Key words and search items included 'land-use change' and 'household' or 'village', restricted to studies published between 2000 and 2015.[2]

Our initial search resulted in a total number of approximately 180 studies. These studies were carefully read by two of three authors and only included in the sample of studies if they met the following key criteria. First, the data analysed in the studies must include information collected at the household or village level. In addition, the studies must analyse land-use change at the village- or household level and the drivers of change have to include household characteristics.[3] Second, the papers had to be published in peer-reviewed journals between 2000 and 2015. We took 2000 as the base year because the last comprehensive meta-analyses and empirical reviews were published in the early 2000s. Third, we restricted our sample to studies that were conducted in tropical regions as these regions experienced the highest rate of land-use change during our study period. Once papers that fulfilled all three criteria were selected, they were further screened for the methodological rigour. If the authors concluded that – despite having undergone a peer review process – a paper still failed to properly identify the drivers of land-use change at the household level it was excluded from the literature review. In the event that the same author published a set of accompanying papers using the same dataset and identifying the same drivers of land-use change, only one paper was included in the review. These restrictions resulted in a subset of 91 studies that were included in the review.

After the 91 papers were selected, the authors underwent a rigorous reading and coding process based on a self-developed questionnaire (see Appendix A, Table A.1). The questionnaire was designed to collect information such as the academic backgrounds and present affiliations of the authors of the reviewed studies, the year of publication, and applied methods. The main results of the papers, i.e. the type of land-use change and land-cover change, the land-use change drivers suggested in the paper as well as the region and country of study were also systematically recorded. Each paper was read and coded by two of the three authors to allow for a stringent cross-verification

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[2] Selection of articles published in peer reviewed journals and the omission of grey literature may result in a publication bias; however, we assume that acceptance for publication in a peer reviewed journal is indicative of the quality of the paper.

[3] In village-level studies, these household characteristics will typically be collected at the village level, for example as the share or number of households with certain characteristics.

of all entries.

Our classification of the drivers of land-use change is based on the conceptual framework introduced in the preceding section. In addition to the five main drivers identified by Angelsen and Kaimowitz (1999) we include two new drivers of land-use change, i.e., household characteristics/endowments and key policies (see Appendix A, Table A.2). Overall, 330 proxy variables for specific drivers are reported as having a significant impact on land-use change in the 91 studies.

2.3.1 Land-use (and -cover) change

The literature on micro-level land-use change often defines land-use change rather implicitly or vaguely and does not use an uniform definition of *land-use change*. Additionally, some studies do not make a clear distinction between *land use* and *land cover*. However, to synthesize the results of the 91 studies, a precise distinction between land use and land cover is required, as suggested by Lambin and Geist (2006) and Fisher and Unwin (2005). A widely used definition describes land cover as the observable (bio-)physical qualities of the earth's land surface (Di Gregorio and Jansen, 2000). In contrast, classifying land use always demands a socio-economic perspective on land (Fisher and Unwin, 2005). Consistent with this approach, Lambin and Geist (2006, p.4) refer to land use as the 'purposes for which humans exploit land cover. It involves both the manner in which biophysical attributes of the land are manipulated and the intent underlying that manipulation'. Hence, land use is always determined by the 'arrangements, activities and inputs people undertake on a certain land-cover type to produce, change or maintain it' (Di Gregorio and Jansen, 2000). Following these definitions, a change in land use does not lead necessarily to a change in land cover, for example in the case of intensification. Moreover, the terms land cover and land use follow a many-to-many relation (Fisher and Unwin, 2005). For example, land covered by *forest* could be land used for forestry or conservation. In addition, the land use *agriculture* can occur on land cover classified as grassland, woodland or wetland. Inconsistencies in the use of these terms render the systematic comparison of study results difficult, especially if evidence is based on remote sensing data, which need the interpretation of aerial information (Fisher and Unwin, 2005, Rindfuss et al., 2004).

In our systematic analysis of land-use change across the reviewed case studies, we are able to capture more subtle land-use change scenarios, which have not yet been classified in literature reviews. Moreover, we illustrate that it is indeed useful and instructive to distinguish between land-cover (change) and land-use (change) clearly.

We identify the initial land uses (LU) and land covers (LC) and the final LU and LC for each study in our sample using a one-to-many relationship between LC and LU categories (see Table 2.1). Considering the variety of research objectives and applied methodologies, we only include land uses and land covers, which are central for each study. For those cases that do not provide direct information about the initial and final land covers/land uses, we derive the categories from study site description and central statements or conclusions provided by the respective study. Since most studies analyse several land-use change scenarios, we allow for more than one land-use change scenario per study. We finally identify 184 land-use change scenarios that fall into 33 different categories of land-use change.

Due to the variety in land-cover information across studies and disciplines (and sometimes the lack of precise information), our cover categorization follows a broader definition than other, more detailed categorizations, for example, the Land Cover Classification System (LCCS) by Di Gregorio and Jansen (2000). We classify land cover (LC) into *forest*, *cultivated land*, *grassland*, *shrubland*, *desert* and *wetland* (see Table 2.1). Under *forest* we include land cover such as natural forest, primary forest, old-growth forest, mature forest, secondary forest, residual forest or woodland. We define *cultivated land* as areas used for agricultural purposes (including orchards and plantations). The land-cover categories *grassland*, *shrubland* and *desert* denote land cover described as pasture land, arable land, savannah, bushland, or non-forest vegetation. Since one of the studies reviewed analyses land-use change at desert fringes, we also include *desert* as land cover referring to dune landscapes. *Wetland* indicates land covered, for example, by swamps.

Under these LC categories we further classify 12 different land uses (LU) (Table 2.1). We assign the following forest uses: *non-used forest* that captures natural forests; *forestry*, which refers to resource extraction[4]; *protected forest* that includes forest reservation; *logging* for commercial reasons; and *fallow*, which is land left for regeneration – mostly within a cultivation cycle of shifting cultivation. Cultivated land could be used for *agroforestry* or *agriculture*, whereby *agriculture* as a broader term encompasses mono and mixed-cultivation (including plantations) and is mostly used for cash crop cultivation. *Agroforestry* describes woody perennials and agricultural crops planted in agroforestry systems as well as shifting cultivation (Nair, 1993, Raintree and Warner, 1986). Grasslands, shrublands and dune landscapes are mainly used for *ranching*; this includes livestock farming, cattle ranching or agro-pastoralism. To capture the use of natural grasslands, shrublands and deserts, we include the terms

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[4] Resource extraction comprises, for example, firewood collection and hunting.

non-used grassland/non-used shrubland/non-used desert. Similarly under wetland, we subsume *non-used wetland*, that captures natural wetlands, and *wetland cultivation*, that includes landscapes, for example, with rice fields.

Overall, 77 per cent of all scenarios analysed in the reviewed studies concern land covered initially by forests (see Table 2.1). Within this subsample, the conversion of non-used forest and forestry receives most attention. Looking at final land uses, land is predominantly changed towards agricultural usage (52 per cent) followed by ranching (22 per cent) and some minor categories, like fallow (9 per cent) and forestry (5 per cent). Hence, as expected, the most analysed scenario is the conversion of non-used forests or forestry for agricultural purposes, together these make up 62 cases (34 per cent of all land-use changes in reviewed studies). The second largest share (35 cases or 19 per cent) is accounted for by studies that analyse the conversion of non-used forests or forestry towards ranching. Hence, deforestation – represented by the land-cover change of forests into cultivated land or grassland/shrubland – is still the main focus of studies analysing land-use change on the micro level.

Table 2.1 also reveals other important land-use change scenarios, for example the change of land use for agriculture/ranching towards fallow holding, which is covered by 14 cases in the scenario sample. In contrast, we identify only 8 cases of converted fallow holdings for agricultural purposes and one for ranching. There are also an important number of cases (14) that analyse the transformation of protected forest. Very few studies (5) in our sample delve into the reverse process, i.e. land-use change scenarios towards protected forest (or other protected zones). While these transformations may indeed be less frequent, this relatively low number of studies at the micro-level — at least when our inclusion criteria are applied – is surprising. Furthermore, the small number of cases focusing on the conversion of wetlands for agricultural purposes reveals the lack of research on, amongst others, the conversion of mangrove forests, which decline similar or faster than adjacent inland forests (Duke et al., 2007). Additionally, only three cases consider land-use transitions from non-used forests/forestry to logging. The low number of studies examining logged forests maybe explained by the fact that logging is predominantly carried out on large-scale concessions (Sodhi et al., 2004). Further, we could not find any studies that analyse the contribution of micro-level agents to systematic logging. This could be because logging activities carried out by households, might be illegal and thus less likely to be reported in household surveys (Sodhi et al., 2010).

Table 2.1: Land use and land cover (change) of micro-level case studies

Final LC and LU		**Forest**					**Cultivated Land**		**G/S/D**		**Wetland**		**Total**
Initial LC and LU		*Non-used forest*	*Forestry*	*Protected forest*	*Logging*	*Fallow*	*Agroforestry*	*Agriculture*	*Ranching*	*Non-used G/S/D*	*Wetland cultivation*	*Non-used wetland*	
Forest	*Non-used forest*		6		2	1	2	36	18				65
	Forestry	1			1			26	17				45
	Protected forest		3					7	4				14
	Logging			1				3	2				6
	Fallow	3					1	8					12
Cultivated land	*Agroforestry*					1		4	1				6
	Agriculture			3		12		4	1	1			21
G/S/D	*Ranching*			1		2		1					4
	Non-used G/S/D							6	2				8
Wetland	*Wetland cultivation*												
	Non-used wetland										3		3
Total		4	9	5	3	16	3	95	45	1	3		N=184

Notes: G/S/D refers to Grassland/Shrubland/Desert.

2.3.2 Geographical coverage

South America accounts for the largest share of studies in our sample (41 per cent) and together with Central America it contributes to 63 per cent of all the studies reviewed (see Table 2.2). This result is in line with the earlier review by Geist and Lambin (2001) who find that the majority of case studies come from Latin America. The studies in our sample were carried out in 29 (sub)tropical countries (see Figure 2.2). This large share can be attributed to the high deforestation rates in Central and South America, which hold the major share of earth's primary forest cover and stocks in forest biomass (FAO, 2015, Laurance et al., 2001). The high number of studies in this region could also be a result of regional preferences by research groups and the related availability of land-use data. Land-use change studies on African countries account for 20 per cent of all reviewed case studies; however, the bulk of these studies (N=13) are conducted after 2010 – pointing at the rising importance of land-use change in African countries (Chidumayo and Kwibisa, 2003). Only 15 per cent of the case studies analyse land-use change in Asian countries. The limited number of Asian case studies is surprising, since evidence hints at high deforestation rates in South-East Asia due to logging activities and plantation agriculture (Miettinen et al., 2011, Sodhi et al., 2004). As noted above with regard to the lack of studies on logging, firms that operate such logging or large-scale agricultural activities appear to remain beyond the scope of micro-level studies of land-use change determinants.

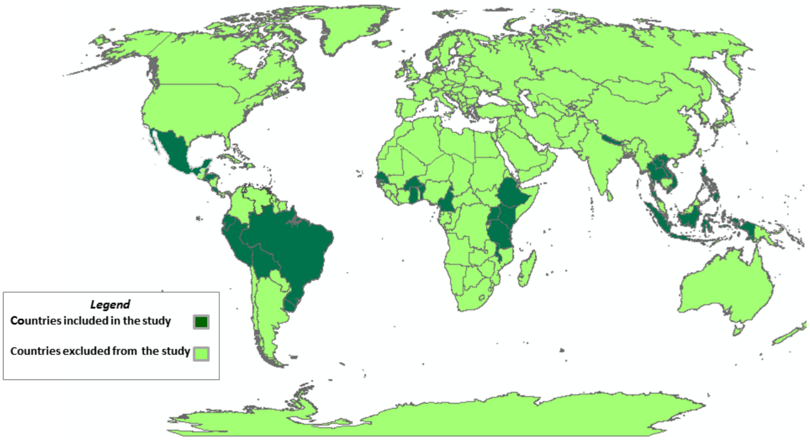

Figure 2.2: Geographical coverage of micro-level case studies on land-use change across tropical regions in the period 2000-2015

Note: We have also included one single case study from Uruguay located in the subtropics, because the country is a prime example of rapid land-use change from free cattle ranching to estate plantations Vihervaara et al. (2012).

Table 2.2: Regional coverage of micro-level case studies on land-use change across (sub)tropical regions in the period 2000-2015

Region	*Central America*	*South America*	*Africa*	*Asia*	*Total*
No. of case studies	20	37	20	14	91
Per cent	22	41	22	15	100

2.3.3 (Inter)disciplinarity

Ideally, Land-Change Science integrates natural, social and geographical sciences to understand patterns of land-use change (Rindfuss et al., 2004). We examine which disciplines are most actively involved in land-use change research and to which extent these disciplines collaborate. This is done by scrutinizing the authors' educational qualifications and their current research interests.

Table 2.3: Scientific disciplines in micro-level land-use change case studies

Disciplines	**Subdiscipline**	**Contribution (%)**
Economics	Agricultural Economics, Forest Economics, Environmental Economics, and Resource Economics	41
Geography	Spatial Analysis and Spatial Planners	29
Ecology	Environmental Sciences, Ecology, Biology, Botanic, Forestry, Biogeochemistry, Agricultural Science, Oceanography, Biostatistics, Entomology, and Soil Science	25
Anthropology	Anthropology	10
Social Science	Sociology, Political Science, Development Studies, Public Policy	2
Demographic Science	Demography, Population Science	3

Table 2.3 provides a summary of the disciplines that are involved in land-use change research according to the studies reviewed. Within all case studies, most research is done by economists and geographers, followed by ecologists. Moreover, about half of the studies are multidisciplinary (N=47) and this share remains relatively constant over the period from 2001-2015.

2.3.4 Methods and data

The methods applied in reviewed studies differ considerably. We aggregate all methods used into five categories that comprise regression analysis (including choice models), multivariate analysis, descriptive statistical analysis, theoretical models, and (data-based) simulation techniques. Some studies use multiple methods, which results in 106 methods applied in 91 studies.

Table 2.4: Methodological approach in micro-level land-use change studies

Methods	**Per cent**	**N**
Regression analysis	59	62
Multivariate analysis	9	10
Theoretical model	6	6
Descriptive analysis	16	17
Simulation techniques	10	11
Total	100	106

Table 2.4 shows that regression analyses account for 70 per cent of the methods used. In addition, a few studies (9 per cent) rely on multivariate analysis (for example ANOVA, Hazard models) or on simple descriptive techniques, such as correlation analysis. 10 per cent of all applied methods are simulation techniques and out of these, half of the studies use agent-based modelling systems. We do not find that the disciplinary background of the authors determines the choice of methods used.

In regression analyses, typical left-hand-side, explained or dependent variables are represented by discrete choices, for example pixels related to specific land-use types. When analysing continuous changes, the models often explain total area deforested by households, total cropped area of households, or fallow length of plots. The regression models are chosen accordingly, with binary or multinomial choice models, OLS, or system estimations being most common. In addition, a few studies (N=10) rely on multivariate analysis (for example ANOVA, Hazard models) or on simple descriptive techniques, such as correlation analysis. Most studies analyse land-use change using household and/or village data, relying often on relatively small samples of 100-200 observations (see Figure 2.3). Moreover, 48 per cent of all studies integrate socio-economic data and information from satellite images (N=45). Only a few studies (explicitly) include qualitative data, such as results from focus group discussion or expert interviews (N=4). Though most studies explore between-household variation, i.e. household-level data, 8 per cent (N=7) of all studies are based on village-level data. Some studies use also more than one database, which leads to a total number

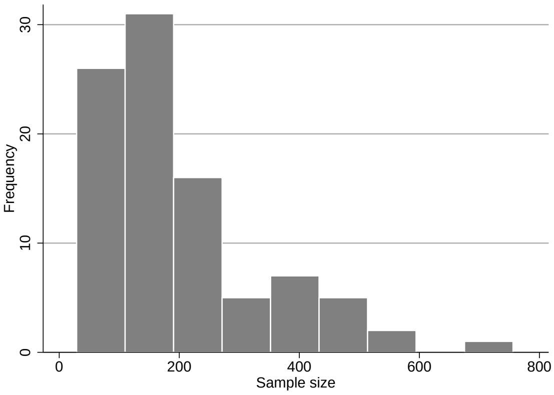

Figure 2.3: Sample size of household data in reviewed case studies

Note: For the graph one study by Ali et al. (2014) with a sample size of 3554 households, has been excluded.

Table 2.5: Variance of micro-level land-use change studies over spatial and time dimension

Spatial level	**Cross-section analysis**	**Panel analysis (t=2)**	**Panel analysis (t>2)**	**N**
Household or farm level	51	15	8	74
Village level	5	0	2	7
Regional level	5	1	2	8
N	61	16	12	89

of databases of 93. In terms of temporal dimension, many studies are based on cross-sectional data, and only 16 studies use panel data with typically two rounds of observation (see Table 2.5). Beyond that, some studies rely on retrospective data (N=6) although this approach is prone to measurement errors, for example through recall biases, which especially increase for longer periods (Bernard et al., 1984).

2.3.5 Internal and external validity

Before providing some meta-analytical insights on the results of the studies, we briefly discuss some of the methodological challenges one is likely to encounter in the analysis of the micro-level drivers of land-use change and then explain how the studies reviewed have dealt with them. One of the key empirical challenges is revealing a truly causal relationship between a specific driver and the dependent variable. While some studies do their best to address the challenges of causal inference, other studies face problems of internal validity because of endogeneity (simultaneity and reverse causality) and omitted variable bias. If these possible sources of bias are not accounted for, a correlation between land-use change and changes in a specific driver (or rather a proxy of it) is mistaken as a causal effect of the latter on the former.

In a number of studies, these empirical (econometric) problems are not adequately addressed. When estimating the causal effects of household-level variables (agents' endowments, off-farm employment) on land use, the results may often be biased because of reverse causality and simultaneity, i.e. not only is the driver influencing land-use change, but also vice versa. For instance, if household wealth (or income) and a particular land use, such as cash cropping or ranching, are found to be correlated, this does not necessarily imply that wealthy households are more likely to be engaged in these land uses. Such a correlation is also likely to reflect that engaging in these commercial activities may have turned households wealthy in the first place. A similar argument can be made for off-farm employment – a variable that is often used as an explanatory variable in land-use change regressions. Here, reverse causality stems from the fact that the proceeds from cash crop farming enable otherwise liquidity-constrained households to invest in off-farm activities. More generally, both theory and evidence suggest that rural households that are constrained on important factor markets – most notably labour and credit markets – decide simultaneously on agricultural and non-agricultural production as well as on consumption. This simultaneity is formalized in so-called 'agricultural household models'.[5]

At the household level, another potential source of bias – often ignored in empirical land-use change studies – is the so-called 'unobserved heterogeneity'. In particular, regression analyses of technology adoption or market participation, i.e. cash crop adoption and land-use change, suffer from omitted-variable bias. Households may have unobserved characteristics, such as their intrinsic motivation or entrepreneurship skills, engagement in rent-seeking behaviour, or risk attitudes that directly explain their patterns of land-use change. Such unobserved characteristics tend to be correlated with some of the typical household or farmer characteristics included in regression analysis, for example education, income, and wealth. If unobserved characteristics are omitted from the estimation equation, the effects of these variables are likely to be biased.

Omitted variable bias is not only a problem at the household level. A particular challenge of empirical studies at the micro level regards disentangling the effects of policies that tend to affect all studied households and individual (household-level) effects. Large-scale land-use change is often the result of deliberate planning policies, in particular agricultural and settlement policies. These policies establish infrastruc-

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[5] See Taylor and Adelman (2003) for an accessible overview.

ture and create markets. Households react to these policies and incentives by moving to the agricultural frontier, and engaging in cash crop farming (sometimes through contract farming). This implies that empirical studies in such contexts need to account for the fact that there is a policy that simultaneously causes roads to be built, migrants to move into a certain area and to engage in a specific land use. It is obvious, that the correlation between roads and deforestation that will be observed in such a context cannot be interpreted as a causal effect. Finally, another very severe problem of reverse causality often arises, when the effect of institutions on land-use change is analysed. Property rights at the agricultural frontier are often obtained directly by deforestation. This implies that a correlation between insecure property rights (acquired by deforestation) and land-use change cannot be taken as a sign of a causal relationship from weak institutions to deforestation.

All these challenges pose serious threats to the internal validity of micro-level land-use change studies, i.e. to correctly attributing causality to specific drivers of land-use change. These challenges are addressed in only 17 of the 57 regression analyses by using Instrumental Variable (IV) techniques or Fixed Effects (FE) estimations. This includes the studies by Shively and Pagiola (2004), Maertens et al. (2006) and Chibwana et al. (2011). The application of these techniques is taken as a proxy that the study has made an explicit effort to reflect upon issues of endogeneity. We acknowledge that this is not to say that these issues have been addressed convincingly by the respective study. In principle, these empirical problems do not apply to simulation and theoretical models (with the exception of regression-based simulations). Here, assumptions, functional forms, rules, and parameters have to be put under scrutiny. Very few studies, however, rely on very stylized optimization models (N=2).

Studies dealing with land-use change on the micro level may also face difficulties of external validity. Since micro-level studies have per definition a small geographical coverage, they have to be clear in their contextualization also referring to the representativeness of their results. However, some studies fail to differentiate between the mechanisms specific to the study area and possibly generalizable results. For example, the insights on the impact of a particular set of communal rights on land may only be relevant in the respective context. This holds in particular for drivers related to institutional and policy change.

2.3.6 Overview of covered drivers

In this section, we present some first generalizations on the drivers of households' land-use decisions analysed by the reviewed case studies over space and time. This

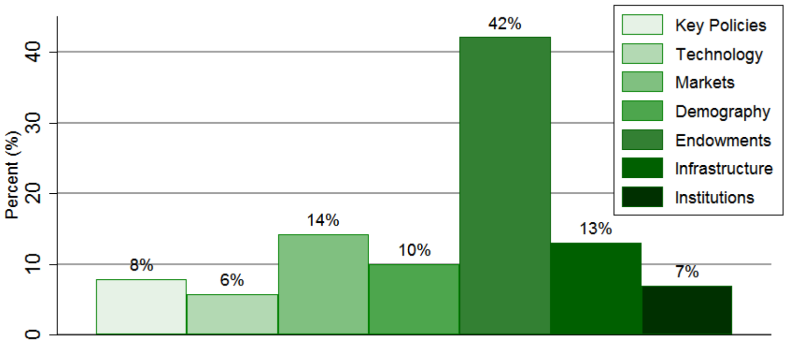

Figure 2.4: Micro-level drivers of land-use change

indicative analysis is based on the frequency of a reported driver that is found to have a significant effect on land-use change. Since many studies are not using regression models, our interpretation of significance does not only refer to statistical significance, but also classifies as significant those drivers that are stressed most by authors within their results or conclusions. Overall, 330 proxy variables for specific drivers are reported as having a significant impact on land-use change in the 91 studies. We classify the 330 variables into seven main categories of drivers (institutions, infrastructure, endowments and characteristics, markets, technology, key policies, and demography referring to population and migration) (see Appendix A, Table A.2).[6] This is done by first listing all 330 drivers and then categorizing them. For example, if a study reported that land property rights or land tenure significantly affect land-use change, institutions are recorded as the main driver. Similarly, when agricultural prices or access credit were denoted to be the key drivers, we code these results as markets.

Our findings reveal that household endowments and characteristics account for 42 per cent of all identified drivers (see Figure 2.4). This is followed by markets and infrastructure, representing 14 per cent and 13 per cent of the drivers reported in the studies; demography, technology, key polices, and institutions play a minor role in driving land-use change in the studies reviewed. Since household endowments and characteristics emerge as the most prominent driver, we further disaggregate this driver into physical-, human- and social capital and labour.[7] Among the household endowments, physical capital is often found to be significantly associated with land-

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[6] The seven categories for the land-use change drivers are derived from the conceptual framework, consisting of the five micro-level drivers and additionally, key polices and demography (population/migration) as underlying causes, that are directly linked to the households' decision-making processes on land.

[7] See Appendix A, Table A.3 for the respective coding of the endowments.

Table 2.6: Decomposition of the micro-level driver: household endowments and characteristics

Household endowments and characteristics	**Physical capital**	**Labour**	**Human capital**	**Social capital**	***Total***
Per cent	50	33	14	3	*100*

use change. In addition, labour and human capital also receives considerable attention (see Table 2.6).

These meta-analytical findings need to be interpreted with caution. They cannot be directly taken as evidence that household characteristics and endowments are the most important driver of land-use change. For their interpretation, it is important to understand that the findings reflect the level of variation between households. In micro-level studies, households tend to be exposed to the same socio-economic and ecological environment; be it with regard to prices, other market conditions or institutions. Detecting land-use change in response to changes in the households' environment typically requires variation and data over time; and as seen above, less than half of the studies have such data. That scale matters for the results, becomes apparent when we disaggregate the studies into different scales distinguishing between data collected on the household, village or regional level. Then it turns out that demography is the most important driver of land-use change on the village level. This finding points at the importance of migration for land-use change since demographic variation between villages is mainly driven by migration, not by natural demographic forces. Once the caveats to the above aggregation exercise of drivers are understood, the meta-analytical findings first tell us that there is indeed substantial household heterogeneity, not only in terms of household-level characteristics, but also of observed land-use choices. Second, the household heterogeneity, in particular in terms of income and endowments, is significantly associated with land-use change. It is important to note that this is not necessarily the case, as one may expect household-level land-use change to be driven mainly by external forces with all households reacting more or less the same. In contrast, the detailed review of selected studies below will illustrate how household-level factors condition households' reaction to these external forces. Third, in addition to this general insight regarding the heterogeneity in household characteristics and reactions, the results of Figure 2.4 and Table 2.6 can be taken as a first indication that economic growth is an important aggregate force that drives land-use change. This is because the micro-level determinants of economic growth, in particular physical capital, often turn out to be associated with households' land-use decisions.

However, the relationship between land-use change and these growth-associated micro-level drivers is not simple. As the subsequent literature review will show, there are complex interactions between these micro-level determinants, for example in the use of capital and labour, the application of technologies, and context-conditions, in particular institutions, policies and the conditions on factor markets.

2.4 Drivers, studies and cases of households' land use decisions

We organized the review below according to the grouping of seven drivers suggested above. In addition to the factors that have been considered in earlier reviews, we carefully review household endowments/characteristics as well as key policies addressing land-use change. The many examples and case studies illustrate the complex interrelationships between land-use change and its supposed drivers. Different transmission channels with varying importance in different contexts are at work, often simultaneously. Empirical ambiguities do not only arise from different context conditions, but also because of the existence of non-linearity's in the relationship between a specific driver and land-use change.

2.4.1 Property rights and institutions

In a setting where households draw their sustenance from agricultural activities, the rules and institutions that govern the ownership and utilisation of land play a key role in determining households' behaviour and decisions. A significant number of the households analysed in the studies reviewed are faced with weakly defined and insecure property rights (Etongo et al., 2015, Adams et al., 2013, Newby et al., 2012, Muriuki et al., 2011, Dolisca et al., 2007, Mena et al., 2006b, Pan et al., 2004, Murphy, 2001, Otsuka et al., 2001).

In the absence of well-defined property rights and tenure security households often gain de facto land rights through deforestation and land clearing (Etongo et al., 2015, Damnyag et al., 2012, Dolisca et al., 2007, Otsuka et al., 2001, Cattaneo, 2001). Cattaneo's (2001) simulation model-based analysis of deforestation in the Brazilian Amazon assumes that deforestation enables the acquisition of property rights to 'unclaimed' land. He further argues that this adds a speculative value of informal tenure rights to the potential returns from agriculture. These relationships imply an ambiguous effect of tenure security on deforestation or other forms of land-use change. In general, households or farmers in environments with relatively insecure rights may tend to use land conversion or possession of 'unclaimed' land as a way of establishing informal land-use rights. In line with this argument, Dolisca et al. (2007) find that illegal occupants are more likely to convert forest into cultivable land than farmers with titled land in Haiti. Such behaviour is reinforced by regulations that foresee titling through adverse possession; that is, farmers acquire titles after physically living on a piece of land for a 20-year period. Yet, the authors also point at evidence for the same country that shows that titling programs have equally caused more deforestation, as more land is then cleared because of an increased value of the property rights established by clearing. This is very much in line with Cattaneo's (2001) argument above. Generally, households will deforest or clear land up to the point where the marginal benefits of clearing (including both the value of potential agricultural production and of tenure rights) exceed or match the marginal costs of doing so (including the direct costs of clearing, for example labour costs, and of violating laws).

Beyond these 'direct' effects of establishing property rights through land conversion, the presence of insecure tenure has important effects on agricultural management practices, profits to be earned from agricultural activities, and, hence, investment decisions. It is well established that insecure property rights have an inverse relation with household's planning horizons (Besley and Ghatak, 2010, Goldstein and Udry, 2008). With shorter planning horizons, farmers are more likely to apply less sustainable agricultural management practices; in particular, they may invest less in soil conservation measures and leave too little land fallow. In line with this argument, Damnyag et al. (2012) show that farm households in Ghana are more likely to invest in shade grown cocoa and other perennial crops when they have a secure land title.[8] One should note that these decisions might still be optimal for the individual household under the constraints faced. Less sustainable agricultural practices may eventually lead to land degradation and to possibly higher rates of conversion of non-cultivated to cultivate land again.

In household surveys, the common practice in collecting information on land tenure and property rights is to include questions that either specify the characteristics of land tenure arrangement (customary or freehold, titled, rented or leasehold, share cropped) or to ask about the land acquisition process (inheritance, leasehold, purchase or illegal use) (Damnyag et al., 2012, Dolisca et al., 2007). In cases where land titles are absent (or no information is available), property rights may be proxied

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[8] Such behaviour is confirmed by Ali et al. (2014), who evaluate a pilot land regularization program in Rwanda. Their results suggest that the program was significantly associated with the higher investment in soil conservation.

through the duration of residence Dolisca et al. (2007). These measures and proxies are typically used as explanatory variables in equations that explain land-use change. This procedure is not without problems, as it neglects the possibility that causality may be reverse: for instance, it assumes that land-use decisions are determined by property rights and not vice versa. However, the act of forest clearing may be observed because this decision gives rise to some kind of property right. The feedback between land rights and land-use change is illustrated in a study by Otsuka et al. (2001) who use data from Sumatra, Indonesia. They show that customary land rights respond to changing context conditions, in particular higher population pressure, by giving higher tenure security to households that invest more, specifically through planting trees, into land acquired by clearing communal forests.

2.4.2 Market accessibility and infrastructure

Households' land-use choices highly depend on access to infrastructure and markets. Infrastructure networks and market integration determine households' production decisions. This is because they influence economic structures beyond agriculture, i.e. income-generation opportunities in non-agricultural sectors with possible repercussions on land-use change. Hence, on a gradient of market integration, the production costs of agricultural commodities, the marketing networks, and the opportunity costs of engaging in agriculture differ and so will households' land uses. The interrelation between developing markets and infrastructure extension is twofold: First, infrastructure can be triggered by developing markets, cash crop adoption and economic growth – possibly reinforced by spontaneous in-migration. Secondly, infrastructure extension can be a component of rural development and settlement policies and exogenously drives market integration. In reality, this process will often be iterative and both channels will reinforce each other.

Similar to earlier reviews (Geist and Lambin, 2001, Angelsen and Kaimowitz, 1999), recent empirical findings confirm a strong impact of changing market integration on households' land-use decisions (Kaminski and Thomas, 2011, Vadez et al., 2008, Caviglia-Harris, 2004). Better access to markets is found to be positively correlated with the extension of agricultural areas, especially for cash crop cultivation (Adams et al., 2013, Ellis et al., 2010, Klepeis and Vance, 2003, Vance and Geoghegan, 2002). Accordingly, a number of studies find a negative relation between distance to market centres and deforestation (Caviglia-Harris and Harris, 2011, de Souza Soler and Verburg, 2010, Wyman and Stein, 2010, Pan et al., 2007, Geoghegan et al., 2004, Sunderlin et al., 2001).

Most studies capture the effect of accessibility to markets on land-use change by controlling for infrastructure variables, such as distance to markets (Müller and Zeller, 2002) or distance to all-year roads (Maertens et al., 2006). As outlined above, interpreting the correlations between these variables and land-use change decisions as causal may be problematic. This is because neither the establishment of infrastructure nor the development of markets (the latter even much less) can always be considered to be exogenous to the household's decisions. Instead, both land-use change decisions as well as the establishment of rural infrastructure may be driven by the same – unobserved or omitted – factors, for example a rural development policy aimed at cash crop expansion. Furthermore, capturing market accessibility via distance variables is prone to ignore underlying variables, for example failing output and input markets. Some studies provide very instructive insights on the relationship between infrastructure/markets and land-use change. Cattaneo (2001), for example, uses a dynamic computable general equilibrium model to analyse the impact of infrastructure extension on deforestation in the Amazon. He explicitly considers the response of commodity markets and finds that a 20 per cent reduction in transportation costs for all agricultural products leads to an increase in deforested land between 21-39 per cent. Other studies, however, suggest a more complex relationship between market access and land-use change. Using cross-sectional village-level data combined with GIS-data from Central Sulawesi, Indonesia, Maertens et al. (2006) analyse how improved technologies in the lowlands affect agricultural expansion and deforestation in the uplands. In doing this, the authors also control for market access of households. Their findings suggest an inverse U-shaped relation between market access and agricultural expansion and argue that improved market access and declining transaction costs lead households to expand their land for agricultural production. However, at a later stage, households start to invest in off-farm activities, which in turn reduce the pressure on the forest. Müller and Zeller (2002) combine satellite imagery and survey data from Vietnam to analyse the land-use dynamics in the central highlands of Vietnam econometrically. They find that a period of land-intensive agricultural expansion (at the expense of forest) was followed by a second period of labour and capital intensive agricultural growth. This pattern of agricultural growth without further land expansion was mainly driven by increased market integration that eased constraints on agricultural input and output markets.

2.4.3 Household characteristics, income and wealth

Household characteristics and endowments are crucial determinants of households' behaviour and are often included as control variables in regressions even when they are not the main motivation behind the study. Education levels, income, wealth/assets, gender and age of the household head are commonly controlled for in regression analyses of land-use change. Furthermore, households' endowments with land, physical capital, and (family) labour are important determinants of land-use change decisions, but these will be discussed in the subsequent section.

The conceptual framework above clearly shows the rationale for including education and income as explanatory variables into land-use change regressions. Yet, most studies could be more explicit about the reduced-form character of this type of exercise. In addition, endogeneity issues remain largely unaddressed in most studies. Education, gender and age, for example, affect the productivity and opportunity costs of most economic activities (in off-farm activities often more than in farming). At the same time, they affect values and attitudes of all kinds, for example the valuation of work as a farmer or consumption aspirations. Hence, the effects observed in a regression of land-use change on education (or age) will always reflect a combined (reduced-form) effect of these different transmission channels. Instead of acknowledging this, most studies tend to present an eclectic interpretation of the relationship between a specific household characteristic and land-use change. For example, Codjoe and Bilsborrow (2011) and Dolisca et al. (2007), point at a possible effect of education through increased consumption aspirations. Busch and Geoghegan (2010) stress the importance of education for the profitability of off-farm and/or non-agricultural opportunities at higher levels of education. While the hypothesized effects are likely to be at work in the respective cases, there may be other relevant transmission channels of education to land-use change. In addition, most studies fail to note that formal education is typically correlated with unobserved abilities (of different kinds, for example logical reasoning), which again tend to bias the measured effects.

In particular in the absence of functioning labour markets, the availability of household labour, i.e. the composition of households in terms of age and gender, will affect agricultural production decisions and thus land-use change. Perz et al. (2006), for example, find that the number of both old and young household members is correlated with the cultivation of annuals and perennials, no such correlation can be detected for pasture.

The relationship between income and land-use change is the most important and interesting, but empirically most challenging one. It is common for empirical micro-level land-use change studies to find a positive correlation between income and bringing land under cultivation (Godoy et al., 2009, Schmook and Vance, 2009). We have already pointed at the obvious problem of reverse causality in this relationship above, i.e. income determines the household's current land use and, at the same time, this land use also influences income levels. Yet, very few studies make an attempt to address this problem. One exception is Caviglia-Harris and Harris (2008) who use lagged variables of income – instead of current income – in their analysis of cattle ranching expansion in the Brazilian Amazon. They could find a positive correlation between income and pasture but not for cropland.

Off-farm income is often explicitly considered in analyses of land-use change as an important component of income of many rural households. It can reduce households' dependency on agriculture and, as an important alternative income generation strategy, determines the opportunity costs of engaging in agriculture (Broadbent et al., 2012, Kaminski and Thomas, 2011). At the same time, off-farm activities may provide the liquidity required to invest in certain agricultural activities that need some initial investment, for example livestock or certain cash crops. Most studies do not make an attempt to disentangle these effects, but they confirm a net reduction in deforestation due to increased off-farm income. As the income portfolio and hence income, are simultaneously determined (by the same factors), the empirical caveats in terms of a causal relationship between income and land-use change mentioned above, also apply to off-farm income.

Setting these concerns aside, the Mexican case study from the southern Yucatán, by Geoghegan et al. (2001), finds that households' income generated through off-farm employment is found to be negatively correlated with forest clearance. In one of the few panel data studies, Rodríguez-Meza et al. (2004) empirically analyse the determinants of households' land use in El Salvador. Controlling for household fixed effects, they also find that households' engagement in income diversification through non-farm activities reduces land clearance. Pender et al. (2004) examine the determinants of land management in Uganda using village-level data. The results suggest six different development pathways where one is related to increasing non-farm activities. The study points at another interesting effect of higher opportunity costs for labour: the pathway of increased off-farm opportunities seems to enhance soil degradation since less household labour is available for more sustainable practices. Similarly, the pressure on (local) labour markets by better-paying off-farm opportunities may encourage switching to less labour-intensive crops. For example, Newby et al. (2012), mainly attribute the increase of smallholder teak plantations in northern Laos to such an effect.

Access to and the availability of capital may also considerably raise households' income levels. Access to capital may not only be required to finance investment costs, for example to set-up a rubber or oil palm plantation, but also to finance fertilizer and other inputs. These are two important related – but yet separate – transmission channels that would probably result in ambiguous dynamic effects of access to capital – facilitating agricultural expansions initially and saving land later. To date, however, the literature has little to say on these possible dynamic ambiguities, which are also difficult to assess empirically. This is, for example, because capital incorporated in established farming activity is often not easy to measure. This may explain why the reviewed studies typically hypothesize a positive correlation of the availability of physical capital with agricultural land use. This conceptual weakness is reinforced by the fact that the problems of endogeneity and attribution of causality, which are similar to those with regard to income, are often not addressed. While some studies directly use capital endowments to explain land-use change, others recur to access to capital. It should be noted that the estimates of the effects of the latter variable are also prone to suffer from endogeneity biases, as access to capital is typically determined by the same unobserved factors that determine land-use change, for example entrepreneurial or farming ability.

Despite these shortcomings, the fact that capital (or access to it) is often found to be correlated with land-use change has some empirical content and points at the important role of capital. A number of studies suggest that capital is an important driver of deforestation for ranching and agriculture purposes (Busch and Geoghegan, 2010, Wyman and Stein, 2010, Schmook and Vance, 2009, Perz et al., 2006, Vance and Iovanna, 2006, Vance and Geoghegan, 2004, Klepeis and Vance, 2003, Vance and Geoghegan, 2002). The 'effect' of capital on land-use change can be very large. For example, using data on 132 households from Uruará County in eastern Brazil, Caldas et al. (2007) find that households with some capital (measured as durable goods available to the household upon arrival on the property) deforest between 20-30 hectares more of forest than poorer households without any capital (the mean farm size in the study is 23 hectares).

In addition, access to capital is also found to be associated with the adoption of longer term and higher yielding activities such as the cultivation of perennial cash crops and adoption of pasture in a number of studies (VanWey et al., 2011, Vanwambeke et al., 2007, Perz et al., 2006). Kaminski and Thomas (2011) investigate the impact of institutional reforms within the cotton sector on households' land uses in Burkina Faso, Africa. The authors combine a structural framework with cross-sectional regression analyses to show that the increase in cotton cultivation can be linked to both the enhanced access to credits and improved credit conditions after institutional reforms. While education, income, capital accessibility and wealth are certainly among the fundamental drivers of land-use change towards agricultural use, they are often reinforced (or mitigated) by social networks and other forms of social capital that are likely to play an important role, particularly in the diffusion of certain crops or agricultural technologies. They facilitate learning by observation and provide farmers with local knowledge of soil quality, suitable agricultural technologies and crop marketing when extension services and other forms of formal institutions are absent. Busch and Vance (2011), for example, develop a theoretical model that focuses on the role of information spill-overs in spurring the diffusion of pasture in the southern Yucatán for groups of households originating from the same villages. They find that increases in village networks raise cattle adoption at a decreasing rate. Similarly, Vanwambeke et al. (2007) find that belonging to a social network is positively correlated with a household's increased use of inputs (intensification) in irrigated areas in northern Thailand. They also use village membership as a proxy for membership in a social network. Their analysis is limited to short-term effects and they do not find evidence for the decreasing positive impact of social capital reported in Busch and Vance (2011).

2.4.4 Input and output markets

In developing countries, rural smallholders typically face considerable constraints on input and output markets. While constraints on output markets generally hamper agricultural expansion, imperfections on capital, labour and other input markets may have ambiguous effects. On the one hand, they may also simply constrain expansion; on the other hand, input factor and input market imperfections may lead to substitution of these factors for land and thus promote land-intensive agricultural strategies. This mechanism is shown by Busch and Geoghegan (2010) who analyse land-use choices of rural households in the southern Yucatán region in Mexico. Using a cross-sectional survey, the authors show that labour scarcity drives households' expansion in cattle ranching, which is more intensive in land and capital than in labour. However, intensification of one sector can alter returns to factors and thus reduce pressure on land. In his case study on Philippine farm households at rainforest margins, Shively (2001) illustrates the effect of agricultural intensification in a context of a dichotomous lowland-upland economy. He estimates a theoretical model of lowland agricultural production with a model of labour allocation on a representative upland farm. The author find that upland forest clearing and hillside farming are reduced by agricultural intensification in the lowlands (in this case, the introduction of irrigation). Higher labour productivity in the lowlands increases demand for labour from the uplands and creates a small but significant reduction in the rate of forest clearing.

A typical finding of micro-level studies with regard to labour is the correlation between deforestation and agricultural extension and the use of hired labour (Caviglia-Harris and Harris, 2008, Mena et al., 2006a, Walker et al., 2002, 2000), particularly for commercial agriculture (Walker et al., 2002). Unfortunately, these studies do not take into account that hired labour is endogenous to land-use change. Labour use, be it family or hired labour or a combination, is always determined by the production technology (determined by input and output markets) and labour market conditions, i.e. wages and the availability of labour for hire – rather than vice versa.

Kaminski and Thomas (2011) theoretically analyse the role of price fluctuations and the role of marketing risk for household's crop choices; hence looking at product markets. To account for the importance of price fluctuations, the authors include the relative variability of crop prices as a proxy. They find that optimal land use is also determined by the relative risk-profitability of households' crop portfolios, which are a function of households' technologies and input and output prices. This study illustrates the important role of output markets as a central driver of households' production decision and land-use change, as does another study by Caviglia-Harris and Harris (2011) on the impact of settlement design in the Brazilian Amazon. Based on panel data of Brazilian households, who are predominantly small-scale farmers, the authors find a short- and a long-term impact of fluctuating milk prices on deforestation: first, increasing milk prices translate directly in higher income and encourage agents to intensify agricultural production. Then, labour is drawn away from forest clearing. In the longer term, increasing milk prices however raise incentives to extend the production, which leads to further forest clearance to support larger cattle herds.

The effect of new markets has received surprisingly little attention in the literature. One exception is Hought et al. (2012) who examine land-use change in Banteay Meanchay Province, Cambodia. The study that combines remote sensing data with field interviews suggests that a sharp increase in (regional) demand for biofuel feedstock has been associated with a rapid expansion of cassava production at the expense of forests. While energy demand drives land-use change in this case, an important secondary effect of cattle ranching is pointed at by Lusiana et al. (2012). Using a spatially explicit ecological-economic model, they consider the twofold land-use change of cattle ranching, on the one hand, and the associated cultivation of feed resources and fodder, on the other.

Finally, recent analyses of land markets stress the role of speculation. For example, Takasaki (2007) uses a theoretical model to show that, if labour and land markets exist, increasing land prices may promote forest clearing for speculative land holding. The case study of Carrero and Fearnside (2011) provides the corresponding empirical evidence for the role of speculation in land holding: in their analysis of land-use strategies of households in one of Brazil's deforestation hotspots along the Transamazon Highway, the authors suggest that at least 30 per cent of surveyed farmers acquire land for speculative reasons.

2.4.5 Adoption of agricultural technology

The availability of and the capacity (and willingness) to adopt agricultural technologies is a key driver of land-use change. Once a technology is chosen, it will determine smallholders' factor use and the respective output level. Hence, the technology applied by households determines land uses and may induce land-use change depending on the specific characteristics of the technology. These technological characteristics that include the level of substitutability between input factors, interact with household endowments, such as the availability of family labour, and prevailing factor market conditions, for example the availability and price for hired labour. Once new agricultural technologies are adopted, they may lead to technological spill-over effects within villages and communities.

Recent studies on the impact of technology on agriculture examine technology as a land-saving or land-consuming driver of land-use change. Empirically, these studies focus on the use of chemical inputs (Caviglia-Harris and Sills, 2005, Rodríguez-Meza et al., 2004), irrigation systems (Shively and Pagiola, 2004), or mechanical tools (Codjoe and Bilsborrow, 2011). The results are ambiguous: some studies observe a negative link between the adoption of a new technology and deforestation or agricultural expansion (Vanwambeke et al., 2007, Pender et al., 2004, Mertens et al., 2000). However, other studies find evidence for land extensification that is driven by technological improvements (Rodríguez-Meza et al., 2004, Sankhayan and Hofstad, 2001). In this context, the effects of farm input subsidy programs to encourage the use of fertilizer may also be instructive. Chibwana et al. (2011) analyse the effect of the nationwide Farm Input Subsidy Program (FISP) in Malawi. The authors draw on a household survey of 380 households and apply a two-step regression strategy to control for endogenous selection into the program. They find an increased use of inputs for households participating in the FISP and an increase in the area of land planted with maize and tobacco. Furthermore, results suggest that subsidies reduce crop diversity and promote specialization in maize production.

Although these studies show a correlation between land conversion and technology adoption, some of them fail to take the respective market conditions into account, particularly on input markets, as an underlying driving force. Especially in rural regions, area extension due to technical improvements may be induced through relaxed access to formerly constrained input markets. We have already referred to Kaminski and Thomas' study (2011) on institutional reforms as the main driver of cotton expansion in Burkina Faso above. These reforms improved access to input markets and to technical advice.

Underlying driving factors would need to be factored in not only conceptually, but also in the empirical analysis. The correlation between the use of a technology, for example chemical inputs or mechanical tools, and land conversion may often be traced back to underlying driving forces, such as access to capital or degraded soils. Moreover, the ambiguity of the findings on the impacts of technological change can be due to differences in elasticities of demand for agricultural products. As has been argued by Villoria et al. (2013) and Hertel (2012), a productivity improvement can be land-consuming when this demand elasticity is high, as it would be, when innovation happens at regional scale and the product is substitutable. However, on the global level, demand for agricultural products is likely to be rather inelastic – close to the demand elasticity for food – and the response to technological change then land-saving (Hertel, 2012).

Only a few studies discuss the net effects of new technologies on land use once the technology's impacts on factor use (substitution), factor prices and possibly resulting spill-over effects between regions and sectors are taken into account. In South-East Asia, rural areas are often characterized by an upland-lowland dichotomy. Shively's study (2001) of such a context in the Philippines suggests that the adoption of a more labour-intensive technology (irrigation) in the lowlands promotes employment and reduces pressure on forests in both regions: with higher productivity, the factor returns in the lowland increase and lowland wages rise. As a consequence, upland households, who are now employed in the lowlands, pursue an intensification strategy on their own land, which in turn leads to a decrease in forest clearing and hillside farming. Within the same country context, Shively and Pagiola (2004) confirm these results using panel data with a focus on the impact of intensification on deforestation. With irrigation development in the lowlands, wages and employment rise and the authors show a positive correlation between the shadow value of lowland labour and the days of hired labour in the uplands. This indicates that upland households employed in the lowlands replace family labour with hired labour on their own farms. The wage-induced increase in labour productivity in the uplands reduces forest clearing and leads to intensification.

Müller and Zeller (2002) use cross-sectional regression analysis to investigate the possible land-saving effects of intensification in the Central Highlands of Vietnam. They show that intensification indeed triggers land-saving effects; however, this result is only observed if technological change is accompanied by enhanced market integration and simultaneously enforced forest protection policies. These results are in contrast to those obtained by Maertens et al. (2006) who use cross-sectional village-level data combined with GIS-data to analyse the land-use implications of the introduction of hand-tractors in the rice sector in Central Sulawesi, Indonesia. They show that the improved technology for rice cultivation induces a shift of labour into the forested uplands and thus increases agricultural extension and deforestation. The contradicting effects found in these two studies illustrate the importance of context specific conditions, here in particular the labour market conditions, in shaping the effects of technological change.

With regard to the processes of technology adoption, a couple of recent studies have investigated the role of household interaction with the diffusion of technologies. Mena et al. (2011) use an agent-based model fed with empirical data. In this study, the authors assume that households transfer information and knowledge through imitation of neighbours' cultivation strategies. Vanwambeke et al. (2007) analyse the emergence of cash crop markets and the industrialization of rural households in northern Thailand. Based on cross-sectional household data and remote sensing data, the authors apply a choice model to examine the impact of social-networks on new land-use strategies. The authors show that social networks defined by the number of other adopters in the village lead to intensified land use through information via sharing or observing.

2.4.6 Population and migration

There is a consensus in the literature that population pressure is an important driver of land-use change (Mekasha et al., 2014, Garedew et al., 2012, Ellis et al., 2010, Mena et al., 2006a) and that it also triggers technological change in agriculture technologies (Maertens et al., 2006). Since population pressure can only be partially reflected at the household level, micro-level studies on land-use change often incorporate census data into their analysis (see for instance, Garedew et al. (2012), Ellis et al. (2010), Walsh et al. (2008), Maertens et al. (2006), Mena et al. (2006b), Geoghegan et al. (2004), Cattaneo (2001)). More precisely, population growth – often accelerated by migration – can either result in extensive (if uncultivated lands are available) or intensive land use (if uncultivated lands are not available). As many of the areas within the studies reviewed were previously forestland before they were converted to settlements or agricultural land, the opening of this land has been accompanied by migration into the previous forestland.

In fact, migration has received considerable attention in the land-use change literature and migration status has in many micro-level studies been hypothesized to affect households' land-use decisions. First, migrants are expected to follow intensive and unsustainable agricultural practices that lead to the encroachment of the forest frontier because they have shorter planning horizons, which cause them to be more destructive than host populations. Second, migrants are assumed to use unsustainable agricultural practices due to their limited knowledge of the local agro-ecological conditions of their new region. Codjoe and Bilsborrow (2011) find weak empirical support for these hypotheses for migrant farmers in central Ghana, as they tend to have less fallow years than non-migrants. In a study on colonist farm incomes in the Ecuadorian Amazon, Murphy (2001) finds that new migrants earn less because they have less experience about the regional conditions. While this supports the claims made above that new migrants are not familiar with the agro-ecological conditions of their new residence it does not provide any evidence on their land-use patterns. Other studies that show that duration of residence matters for land-use change include Dolisca et al. (2007) who find that the longer households have lived in the Forêt des Pins Reserve in Haiti the less likely they are to clear forests.

Using data from southern Yucatán in Mexico, Schmook and Radel (2008) find that households with migrants that have migrated to the US have more pasture than non-migrant households. This is because the establishment of pasture is initially labour intensive but requires very low levels of labour inputs once established which makes it ideal for households with members that have migrated to the US.

2.4.7 Key policies

To analyse the impacts of policies, inter-temporal data (that captures the conditions before and after the policy) or data from a counterfactual group (that consists of households with the same characteristics that have not been exposed to the policy change) is necessary (Schmook and Vance, 2009). However, since policies are often experienced uniformly within a region, such data are not usually available for most of the studies reviewed in this paper. Therefore, the analyses are sometimes made with retrospective data based on surveys, which question households on their experiences before the policy change.

Market-oriented reforms adopted by many developing countries in the 1980s and 1990s played an important role in altering land use in many of the countries covered by the reviewed studies. One of the most extensively studied policies with respect to its land-use change implications is the Programa de Apoyo Directo al Campo (PROCAMPO). PROCAMPO is a cash transfer program introduced in 1994 in Mexico to mitigate the possible adverse effects of the North American Free Trade Agreement (NAFTA) on rural populations (Schmook and Vance, 2009, Klepeis and Vance, 2003). Klepeis and Vance (2003) were the first to clearly establish a link between the receipt of PROCAMPO cash transfers and the subsequent land-use decisions made by farm households. Using a panel data set with individual farm-level data that spans an eleven year period from the southern Yucatán peninsula in Mexico, the authors show that PROCAMPO payments are responsible for nearly 38 per cent of deforestation that occurred in the study region between 1994 and 1997. They relate this finding to the eligibility conditions of PROCAMPO that are at odds with fallow regeneration and cause households to clear more forests in order to maintain the cultivation of crops in rich soils.[9]

A later study, by Schmook and Vance (2009), uses a seemingly unrelated regression to compare the effects of PROCAMPO and another agricultural support program – called Alianza Para el Campo – on the households in the same region. PROCAMPO puts no restrictions on how the transfer should be spent, but attaches conditions on how land should be used. Instead, transfers from Alianza are tied to specific agricultural activities that have to be implemented by households. In line with Klepeis and Vance (2003), they find that PROCAMPO is significantly correlated with a reduction in forest area and with increases in area under pasture and cultivation. In a similar vein, Alianza is found to significantly influence land use, in particular in favour of pasture.

Using recall plot data from 1970-2009 in combination with aerial photographs, Ribeiro Palacios et al. (2013) examine the broader impact of economic reforms on land-use change in Mexico. Looking at the region of southern Huasteca, the authors stress that

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[9] Other studies that analyse the impacts of PROCAMPO such as Busch and Geoghegan (2010) and Vance and Geoghegan (2002) find similar results. Yet, Busch and Vance (2011) and Chowdhury (2006) find opposite effects on area under cultivation and fallow, respectively.

market-oriented policies such as the promotion of agribusinesses are a key driver of a reinforced land conversion for cash crops, especially for citrus orchards. This typically occurs at the expense of food crop agriculture and secondary forests. The finding that market-oriented reforms increased deforestation and expanded areas devoted to agriculture is not unique to south-eastern Mexico. Another example is the above mentioned case of the reform of the Burkinabé cotton sector analysed by Kaminski and Thomas (2011) that included the privatisation of the parastatal firm SOFITEX (National Cotton Fibre Company).

Going back to Mexico, Barsimantov and Antezana (2012) discuss how the adoption of the 1992 Forestry Law and the 1992 Reform of the Mexican Constitution that were part of a set of free market and regulation policies increased deforestation and later led to an increase in the production of avocados. The authors show that forest cover was reduced considerably because of these policy changes, particularly in the non-forestry communities that had relatively less forest cover to begin with.

Other policies that have played a key role in driving the land-use decisions made by households in the reviewed studies include policies targeted at infrastructure development (Pender et al., 2004, Müller and Zeller, 2002) and settlement policies (Caviglia--Harris and Harris, 2011). Caviglia-Harris and Harris (2011) show that even when policy makers take extra precautions in designing alternative new settlement policies to ensure that they meet both environmental and social objectives, in the long term the design does not influence land cover choices and that land clearing is extensive in all agricultural lots. After a ten-year period, they find that very little forest remains in the radial lots that are introduced by the new alternative settlement policy.

Prominent examples of land-related policies include the Payments for Ecosystem Services (PES) and Reducing Emissions from Deforestation and Forest Degradation (REDD and REDD+).[10] These policies directly address households' decisions to deforest by altering the pay-offs to different land uses. Therefore, their effects on land-use change depend on the farmers' livelihood and crop options and the related opportunity costs of altering land uses (Chavez and Perz, 2012). This is confirmed by Newton et al. (2012)'s evaluation of the impact of Bolsa Floresta, a PES scheme with an undifferentiated reward structure in the Brazilian Amazon. They emphasize

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[10] PES is a policy that compensates land owners and resource managers for the provision of ecosystem services (Jack et al., 2008). Providing income to resource managers for ecosystem services encourages sustainable land-use practices. REDD is based on a similar monetary incentive mechanism in compensating developing countries with payments that are equivalent to the amount of carbon emissions reduced if their national deforestation levels decrease (Damnyag et al., 2012).

the heterogeneity among farmers' livelihood strategies that results in a strongly heterogeneous impact of the program on the decision of deforesting. In addition, the schemes' impact also depend on possible differences in farmers' valuations of ecosystem services (Vihervaara et al., 2012). Mello and Hildebrand (2012) who analyse the potential effects of carbon trade on land-use decision and farm income of small-scale farmers in the eastern Brazilian Amazon illustrate the importance of sufficient compensation. The authors stress that carbon prices have to be high enough to cover transition costs to adopt land-saving technologies.

2.5 Conclusion

For this paper, we have reviewed 91 recent empirical and theoretical studies that analyse land-use change at the farm-household level. The review builds on a conceptual framework of a human-environmental system focusing on micro-level agents and resulting land-use change drivers. This concept extends previous work by Angelsen and Kaimowitz (1999). The framework considers feedback mechanisms between the different stages of the land-use change process, for example between the actions of agents and macroeconomic variables, and between specific causes within a stage, for example between different decision parameters such as the interlink between technology options and accessibility of infrastructure. Considering telecoupling interactions, the concept allows for multidirectional interactions of the whole system towards other socially and geographically remote human-environmental systems. Furthermore, our framework explicitly considers the role of household endowments and characteristics as drivers of land-use change.

We first conduct a meta-analysis of the 91 studies. We find that the most frequently analysed scenario is the conversion of non-used forests or forestry into land used for agricultural purposes – about a third of all scenarios. The second largest share is accounted for by studies that look into the conversion of non-used forests or forested areas into ranching. Most studies analyse land-use change using household and/or village data and, in doing so, often rely on relatively small samples of 100-200 observations. There is a clear regional concentration of studies on Central and South America and some studies on African countries, while only 11 per cent analyse land-use change in Asian countries. The limited number of Asian case studies is surprising, since evidence hints at high deforestation rates in South-East Asia due to logging activities and plantation agriculture. In our view, this may be explained by the literature's focus on household farms. Yet, the omission of firms that operate logging and large-scale farming activities implies that a key (micro-level) actor's behaviour remains unexplored. We find that a number of studies face problems of internal validity because of endogeneity (simultaneity and reverse causality) and omitted variable bias that are not adequately addressed.

When we aggregate the variables identified as drivers in the micro-level studies into stylized categories, we find that household-level heterogeneity and the resulting differences in land-use decisions can be considered a key driver of land-use change. This is less trivial than it may appear, as it is also conceivable that forces external to households, in particular, policies and market signals, are strong enough to dwarf the effects of household-level differences. Among the household-level characteristics, the literature points at micro-level determinants of economic growth, in particular in physical capital, as a catalyst of human induced land-use change.

However, as our detailed literature review shows, the relationship between land-use change and these growth-associated micro-level drivers is complex, in particular because of the interactions between these drivers, for example the use of capital and labour and the applied technologies, and also context-conditions, in particular institutions, policies and the conditions on factor markets. These complexities and interactions cause the above mentioned important challenges in the empirical study of land-use change.

Land governance systems make a good case for the complexities and interactions discussed above. It is well established that the absence of well-defined property rights and tenure security often leads households to gain de facto land rights through deforestation and land clearing. In addition, insecure tenure shortens farmers' planning horizons, which, in turn, makes them more likely to apply less sustainable agricultural management practices. When the impacts of tenure security on land use and management practices are empirically analysed reverse causality issues, i.e. the fact that tenure security is influenced by land-use and management, receive too little attention in the literature. Reverse causality is also an often-unresolved issue in a fundamental relationship of micro-level land-use change studies: the relationship between income and land use. Income determines the household's current land use and, at the same time, this land use also influences income levels. Similarly, empirical problems often remain unaddressed in the analysis of the effects of infrastructure development and increasing market integration that some studies also deem to be an important driver of land-use change. More and better infrastructure can be the result of increasing demand caused by cash crop adoption and economic growth, but it can also exogenously drive market integration. The literature too often assumes a one-directional causal relationship and ignores that infrastructure development may well be driven by the same rural development policy, for example one aimed at cash crop expansion. Complex causal relationships hence complicate the empirical analyses and so do non-linear relationships as well as interactions between different drivers that are also frequently observed. One example for an important non-linearity is the inverse U-shaped relationship between market access and agricultural expansion that has been shown in a number of studies. Improved market access first leads to agricultural expansion, but, in a second stage, households start to invest in off-farm activities and reduce the pressure on forests. Important interactions are at work between factor (land, labour and capital) markets and household characteristics. Factor markets in developing countries tend to be imperfect, which implies that households' initial factor endowments, for example initial wealth or household labour, may play an important role in explaining land-use and management choices. Factor market imperfection and/or limited household endowments may then simply constrain expansion. However, as the same market imperfections may lead to substitution effects, they may also promote land-intensive agricultural strategies. In the case of capital, these ambiguities are reinforced by the fact that capital does not only finance initial investment costs but also current costs for fertilizer and other inputs. This implies that access to capital may facilitate agricultural expansions initially and saving land later. These mechanisms are similar for technology adoption. New technologies, for example the introduction of a new crop, are often found to lead to agricultural expansion. Yet, they may also lead to land savings, conditional on the substitutability between input factors and possible interaction with household endowments and factor market conditions. In terms of household-level determinants of technology adoption, the literature has often stressed that migrant status tend to be associated with the application of intensive and unsustainable agricultural practices.

In sum, the rich empirical literature that has been reviewed in this study, illustrates the complexity of micro-level land-use change processes, in particular the interrelationships between household-level characteristics, factor market conditions, and land-use change. These are conditioned by institutions and policies. The review suggests that market-oriented reforms adopted by many developing countries in the 1980s and 1990s have had an important role in altering land use. However, the empirical designs of many reviewed studies do not account for the complexity of the land-use change processes properly. While the studies have explored some key facets of household-level drivers of land-use change, future research would greatly benefit from methodological rigour. Further, more care should be taken when results are interpreted as causal relationships. Yet, does it matter if an empirical analysis does not pay attention to the fact that income is also determined by land-use change and not only vice versa? Yes, it does since the conclusion to be drawn from either finding differs dramatically. If income growth causes deforestation, there are good reasons to worry since most rural households at forest frontiers are still way below income levels that they would consider desirable – and are probably likely to achieve income growth at some point in the future. If incomes, however, have in the past grown for reasons related to land-use change, for example because of growing a cash crop on converted forest land, they might in the future grow for different reasons, for example because growing economies tend to become more diversified and people engage more in non-agricultural activities.

We want to close by reflecting briefly on some further implications of this review for the way forward. To generate evidence from local to global levels, the telecoupling framework is a simple but general and common approach to describe the interactions different between human-environmental-systems in a globalizing world. It helps to capture synergies and trade-offs across different scales and systems and facilitate global policies to meet relevant socio-economic and environmental challenges. The telecoupling framework demands research on integrated systems, and more empirical studies building on this concept are desirable. Approaches may include both statistical and model-based analyses that combine data from a variety of sources, of course still including survey-based information. This should also enable researchers to extend the sample sizes and increase the external validity of the findings. External validity could also be improved by paying due attention to case selection and some more reflection on whether results should be regarded as context-specific or generalizable.

Recently, the wider literature on land-use change has shifted from exploring the determinants of direct human-induced land-use change towards assessing how households (and other agents) can cope with the consequences of global environmental change; thus land-use change indirectly caused by human activity. There are of course important lessons to be drawn from our review for this emerging literature, as the reviewed land-use change determinants are closely related to a household's or farmer's capacity to cope with climate change. Moreover, recent studies often extend their analysis to examine also the implications of land-use change on livelihoods. The latter trend shows that it is increasingly acknowledged that land-use change and household welfare are simultaneously determined.

Most of the studies focusing on land-specific policies combine satellite images with descriptive statistics of field data, which allow first snapshots on economic-ecological consequences of land-use change on broader scales. However, whether these policies are effective over time in actually influencing land-use change decisions is still under-researched. A dynamic analysis using panel data on the plot or household level would be necessary to assess these policies more rigorously. Also impacts of more recent policies, like PES or REDD+, have to be further explored.

Finally, while our review focused on household-level studies, we were surprised to find virtually no study that would have analysed – at the micro-level – the decisions by firms that operate logging and large-scale farming activities. This implies that a key (micro-level) actor's behaviour remains unexplored and this omission partly explains the lack of studies in Asian contexts, where these players are probably more important.

3 Cash crops as a sustainable pathway out of poverty? Panel data evidence on heterogeneity from cocoa farmers in Sulawesi, Indonesia[1]

3.1 Introduction

In the developing world, growth originating in the agricultural sector has long been identified as an essential pathway out of poverty. Since 70 per cent of world's poor live in rural areas, diversification in cash crops for global food markets has been widely discussed as a prospective route for agricultural growth and poverty reduction (Klasen et al., 2013, Feintrenie et al., 2010a, The World Bank, 2007). The cultivation of commercial crops has also been found to foster rural infrastructure and public services which both entail positive effects on broader levels (Vanwambeke et al., 2007, Walker et al., 2002). Hence, increased commercialization within the agriculture sector might be a key driver to transform a semi-subsistence agrarian society to a more diversified economy including off-farm industries and higher levels of welfare (Achterbosch et al., 2014). Living standards of cash cropping smallholders can be, on average, higher and the long-term income improvements depend highly on the respective technological skills of individual households, in particular agronomic practices (Tittonell and Giller, 2013).

However, a successful integration into global crop markets requires the individual ability of poor households to mitigate or cope with the risks associated with cash crop production. These are, among other factors, price shocks as well as marketing and production risks (Wood et al., 2013, Rist et al., 2010, Sunderlin et al., 2001, Barbier, 1989). The exposure to production and marketing risks faced by smallholders are, to an important extent, determined by the specific conditions of input and output markets. These conditions combined with the idiosyncratic capacities and constraints determine the crop choices and production technology chosen by smallholders and, in turn, their risk exposure, in particular to environmental shocks, such as floods, droughts or plant diseases (Chuku and Okoye, 2009). Changing the crop portfolio from subsistence cultivation to intensified cash crop cultivation might increase this risk exposure since it adds the hazards of mono-cropping that can promote and accelerate the incidence of pests (Steffan-Dewenter et al., 2007).The capacity to deal

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[1] This paper has been written in co-authorship with Katharina van Treeck, Martin Bruness, Jann Lay, Dewi Nur Asih and Nunung Nuryartono.

with these hazards depends in particular on farmers' management practices including the timing of operations, the accurate application and composition of chemical inputs and plantation maintenance (Schreinemachers et al., 2015, Chuku and Okoye, 2009, Sabatier et al., 2013).

It is well known that the capacity of smallholders to apply optimal management practices is limited, as are other means to cope with shocks, for example through credit markets (Harvey et al., 2016, OECD, 2015). As a result, the income gains of cash crop farming may be volatile and the long-term benefits smaller than the well-documented short-term gains (Klasen et al., 2013, Carletto et al., 2009, Tittonell et al., 2007). Empirical evidence, however, on the long-term impact of cash crop farming remains scarce, in particular since such assessments require long-term panel data. This paper addresses this gap by examining the long-term welfare impacts of smallholder cocoa farming. Our analysis draws on a unique three-wave panel data set of smallholder cocoa farmers in Central Sulawesi, Indonesia, which spans a period of 13 years. We first analyse income dynamics and poverty changes over this period comparing cocoa- and non-cocoa farmers. As cocoa yield improvements, as the key driver of increasing cocoa incomes, were accompanied by a higher variation in yields, we then look at the determinants of cocoa yields. This analysis allows us to distinguish between smallholders according to their management practices; a distinction that we, in a final step, use to assess whether well-managing farmers are faring better than those who fail to do so.

The paper is structured accordingly. We first provide a literature review on the welfare impacts of cash crop cultivation. After providing some background information on Indonesia, its cocoa sector and the study region, we describe the data. Our empirical analysis then looks into welfare changes, determinants of cocoa yields, and the influence of management skills on welfare trajectories. We close with summarizing our main results and suggestions for future research.

3.2 Literature review and research questions

In the transition from a low productivity, semi-subsistence agriculture to a high productivity, commercialized agriculture, cash crops can serve as a potential route for agricultural growth and thus poverty reduction in bringing substantial productivity increases and employment opportunities to the rural economy (Timmer, 1988). Transforming sectors can stimulate agricultural innovation by raising capital for agricultural investment and accelerating the build-up of institutions that enable further commercialization (Achterbosch et al., 2014).

For cash crops to be also a successful driver of poverty reduction, the transition from subsistence to commercial agriculture significantly depends on the participation of smallholder farmers who typically farm less than two hectares in developing countries (The World Bank, 2007). Feintrenie et al. (2010a) find that cash crops with low labour requirements and the absence of seasonality are most lucrative for traditional smallholder farmers. Then, cash crops can be easily integrated into the already prevailing farming systems through, for example, the planting of agroforests or the intercropping of new cash crops with previously cultivated crops. Moreover, fragmented markets let smallholders' choices to be non-separable for production and consumption. Decisions on cash- and food crops are thus interlinked and agricultural commercialization has therefore been found to have positive spill-over effects on households' food production (Govereh and Jayne, 2003). In turn, many farm households mitigate production risks of cash crops and vulnerability to price variability through diverse livelihoods relying also on food crop production or non-farm income (Eriksen et al., 2005). However, once markets for labour and inputs develop, intercropped areas are often converted into more intensified, productive land-use systems, possibly increasing farmers' exposure to shocks.

The benefits from cash crop farming have been shown, for example, by Bussolo et al. (2007) for the case of Uganda. They find that – in the 1990s – coffee market liberalization followed by a price boom was associated with substantial reductions in poverty that could be sustained when prices went down again. Cash crop cultivation has also been found to be poverty reducing by Klasen et al. (2013). Based on a shorter panel of the same households used in this paper (2001, 2004 and 2006), they show that households cultivating cocoa were on average able to achieve about 14 per cent higher income levels compared to cultivating other crops. The authors suggest that the switch to cocoa might be a strategy to raise income especially for the poorer segments of rural populations. In contrast, Carletto et al. (2009) present evidence on negative long-term welfare effects of agricultural commercialization. The authors focus on households' adoption of a non-traditional, agricultural export crop (snow pea) in the Central Highlands of Guatemala and use panel data between 1985 and 2005. Applying difference-in-differences estimation, the results suggest that while consumption levels have improved for all households in the surveyed communities, long-term cash crop adopters show on average lower gains with higher benefits only in the beginning. The authors point at agronomic problems – in addition to marketing and institutional problems – leading to decreasing profitability in snow pea production.

Weak management practices, combined with input and output market failures, are the the main cause behind such deficits and the considerable yield gaps of smallholder production in many cash crops around the world (Mueller et al., 2012, Neumann et al., 2010, Tittonell et al., 2007, Tittonell and Giller, 2013). The relationship between practices and yields, however, will depend on the specific crop and region and might be non-linear across scales. On the global level, Mueller et al. (2012) assess the link between yield variability and agricultural management using input-yield models. They postulate as key causes for worldwide yield gaps irrigation techniques, fertilizer application and climate condition – together the three factors explain 60-80 per cent of global yield variability for most of the major global crops. Complementary to this, studies on the regional and local level give insights into more subtle drivers of crop yield-gaps. For example, Neumann et al. (2010) estimate regional frontier yields to compute frontier production and inefficiencies in wheat, maize and rice cultivation. For Indonesia, they find that the variance in efficiency comes mostly from differences in market accessibility and availability of agricultural labour. Examining a more detailed case, Tittonell et al. (2007) explore maize yield gaps on the field level, analysing within-farm differences of smallholder farms in Kenya. They show that variability of yields stems from soil and climate conditions, the land use change history of fields, and also from the operational management, such as planting time and density or timing of weeding. For selected African countries, Tittonell and Giller (2013) analyse yield-gaps of smallholder farming systems. They conclude that the lack of inputs such as machinery, labour and capital are the main sources of production inefficiencies. However, the authors suggest that – even in the absence of inputs like fertilizer – proper agronomic management, such as cultivars, plant spacing and weeding, is able to narrow yield gaps.

The brief literature review illustrates that the long-term implications of cash crop production and the link to productivity heterogeneity remain underexplored. Using a panel sample of smallholders in a cocoa-growing region in Sulawesi, Indonesia, we therefore examine how cocoa farmers fare vis-à-vis other farmers over a longer time horizon. We also explore the determinants of cocoa yield and investigate whether bad or improved management practices are associated to the sustainability of the benefits of cash crop cultivation.

3.3 Cocoa in Indonesia and the study region

In the last decades, Indonesia has emerged as a key exporter of agricultural products on global markets. Since the late 1960s, Indonesia experienced high and sustained economic growth, partly driven by the development of its agricultural sector – specifically promoting export oriented agricultural production (Feintrenie et al., 2010a, Timmer, 2007, Mundlak et al., 2002). The vast expansion of the agricultural area, the adoption of subsidized technologies, such as irrigation, fertilizer, pesticides and improved seeds, were important drivers of this development that shifted cropping patterns towards the cultivation of cash crops and pushed commercialization (Maertens et al., 2006, Mundlak et al., 2002). The country's agricultural sector thus experienced a transformation from traditional cultivation systems (slash- and burn cropping systems and agroforestry) towards intensified monoculture plantations with cash crops such as coffee, cocoa, coconut, oil palm, and rubber (Feintrenie et al., 2010a). In 2014, the agricultural sector contributed about 35 per cent to national employment (The World Bank, 2016a).

One of the main agricultural exports of Indonesia are cocoa products, after palm oil and rubber, representing an exported value of 450 million USD in 2013 (BPS Statistics Indonesia, 2016b). Indonesia, which started to produce cocoa in the 1980s, now is the third largest producer and exporter of cocoa beans in the world, after the Ivory Coast and Ghana (ICCO, 2012). The country's total production of cocoa beans makes 709,330 tons for 2014 and smallholder farms contribute most to national cocoa production covering in total 1,198,962 hectares for cocoa plantations in the same year (BPS Statistics Indonesia, 2016c). The main locations of cocoa production in Indonesia are Sulawesi, North-Sumatra, West Java, Papua, and East Kalimantan. In Sulawesi, smallholder farmers have started to cultivate cocoa beans extensively in the early 1990s (Akiyama and Nishio, 1997). Sulawesi contributes today with a production of over 386,130 tons (2014) the biggest part to the national cocoa production (BPS Statistics Indonesia, 2016c). Our study focuses on the Lore Lindu region, which is part of the province Central Sulawesi and located south of Palu, the capital of this province. The region is predominantly rural and characterized by a high degree of diversity with respect to its geographical and climate conditions (Maertens et al., 2006). The region's centrally located Lore Lindu National Park forms one of the last and largest mountainous rainforests of Sulawesi.

Although cocoa beans are still one of the main exported cash crops, Indonesia's cocoa productivity started to decline in 2005. This decline is mainly attributable to the ageing of cocoa trees and the increasing prevalence of cocoa pests and diseases which smallholder farmers who account for the majority of plantations often cannot handle due to the lack of plot management expertise (Nuryartono and Khumaida, 2016). The most common pest in Sulawesi is the Cocoa Pod Borer, which already spread in the early 2000s (Neilson, 2007). In 2007, farmers of the Lore Lindu region report a yield loss of on average 24.3 per cent due to the Cocoa Pod Borer and also 20.5 per cent due to the black pod disease (Juhrbandt et al., 2010). By the mid-2000s, decreasing cocoa yields – reinforced by ageing plantations – had been perceived as a crisis in the sector (Clough et al., 2009). In this context, the application of intensification techniques – originally intended to raise yield levels – have been discussed to increase the susceptibility of cocoa trees to pests and diseases: Clough et al. (2009) discuss that specifically full-sun plantations and the corresponding removal of shading trees raise the physiological stress of the trees and make them more susceptible to the Cocoa Pod Borer and the black pod disease.

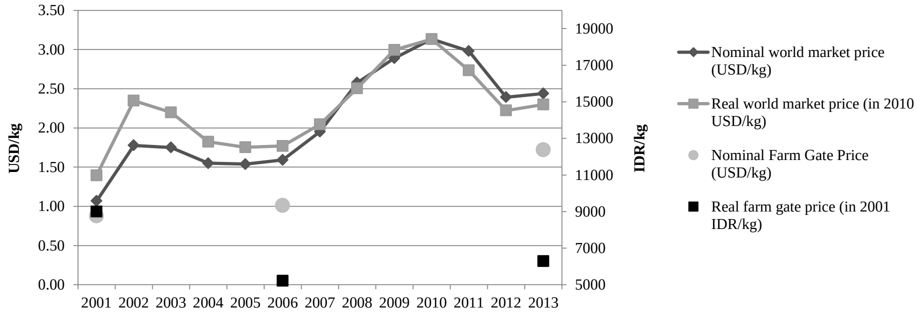

Figure 3.1: World market and farm gate prices for cocoa (in USD/KG and IDR/KG)

Note: Nominal farm gate prices are calculated as the median value of village prices. Village prices on cocoa are in turn derived as median values from the household-level output prices for cocoa. Real farm gate prices are in 2001 IDR prices, based on inflation data for Palu from BPS Statistics Indonesia (2016a). Nominal and real world market prices are drawn from The World Bank (2016c). *Source*: The World Bank (2016c) and authors' calculation and graphical representation based on STORMA and EFForTS data.

In light of these developments, the cocoa sector in Sulawesi has been considered to follow a 'boom and bust cycle' (Ruf and Yoddang, 2004, Clough et al., 2009).[1] This

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[1] This concept describes the process, when firstly young cocoa trees are planted within the tropical rainforest, which provides ideal conditions such as fertile soils, shade trees, and low weed pressure (Clough et al., 2009, Rice and Greenberg, 2000). Due to low investment costs economic gains can be realized once the tree matured at the age of 3 to 5 years and continues to produce cocoa until the age of 20-25 years (Wood and Lass, 2001). During the boom phase, other local farmers might be attracted by promising benefits and start to adapt cocoa cultivation. Then, in-migration is triggered to the rainforest frontiers and primarily agroforests are more and more transformed to mono-cropping

is also reflected in official statistics: cocoa yields in Central Sulawesi have decreased from about 1 ton in 2002 to 0.7 tons per hectare in 2014 (BPS Provinsi Sulawesi Tengah, 2005, 2010, 2015). The Indonesian government has reacted to these developments with a plan to raise productivity setting itself a target of one million tons of cocoa beans per year by 2013-2014. In particular, the plan intended to address the problems of ageing of trees, insufficient planting material, and the lack of knowledge on plantation maintenance (Ministry of Industry, Indonesia, 2016). As one policy, the government started the national program 'GERNAS' in 2009 to boost cocoa production through intensification, rehabilitation and rejuvenation activities of around 450,000 hectares (BKMP, 2010). However, actual total production in 2014 was only 70.9 per cent of the set target. Indonesia's efforts to revive cocoa production thus obviously failed in reaching the achievable yields.[2]

These developments in the cocoa sector took place in a period of relatively favourable world market prices that showed a slight upward trend between 2000 and 2013 (see Figure 3.1). After 2000, world market prices for cocoa increased and remained – after the food price hike in 2009 – on a level of around 2500 USD per ton, i.e. 2.5 USD per kg. Farm gate prices, derived from the survey data, increase correspondingly and are 30 to 70 US-Cents below the world market prices. Because of unfavourable exchange rate movements, this trend did not translate into rising farm gate prices. Real farm gate prices (below in 2001 Indonesian Rupiah (IDR)) fell between 2001 and 2006 and only slightly recovered until 2013.

3.4 Data and sampling

In the context of two collaborative research centres (STORMA – Stability of Rainforest Margins in Indonesia, and EFForTS – Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems, Indonesia), household panel data have been collected in 2001, 2006 and 2013 in the Lore Lindu region. The surveys include information on socio-demographics, land holdings, agricultural as well as non-agricultural activities, and endowments. Each survey represents a random sample of 13 villages, which were randomly chosen in 2001 out of official village census data with 115 villages (Zeller et al., 2002). Households are then randomly drawn,

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systems. This process stagnates, when pest and diseases increasingly spread and trees start to age (Clough et al., 2009).

[2] Nuryartono and Khumaida (2016) discuss various reasons for the failure of the government program, such as institutional barriers and inadequate assistance of smallholders.

with the number proportional to village size. In 2006 and 2013, households that split off from their original households and formed a new one within the Lore Lindu region were additionally interviewed and added to the respective sample. In total, the sample includes 316 households in 2001, 380 in 2006 and 387 households in 2013. We include all households into our analysis that could be interviewed more than once, which gives 300, 338 and 322 observations in 2001, 2006 and 2013 respectively. As cocoa farmer we classify all farmers with a cocoa plantation of at least 0.25 hectare.

3.5 Cocoa income and poverty dynamics

In the Lore Lindu region, income from crop agriculture is the main livelihood and it has increased significantly in recent years (see Figure 3.2(a)). Per capita household income from crop agriculture has risen from 644,590 Indonesian Rupiah (IDR) in 2001 to 1,605,030 IDR in 2013, implying an annual growth rate of 7.9 per cent over these 12 years.[3] Hence, household income per capita drawn from crop agriculture more than doubles in this period to around 170 USD in 2013 (see Figure 3.2(a)). Cocoa is the central source of income for many smallholder households in the Lore Lindu region, as it is also discussed by van Edig and Schwarze (2011) and Klasen et al. (2013). Figure 3.2(b) shows a large increase in cocoa income over time with an annual growth of on average 11.6 per cent in per capita terms.[4]

Agricultural growth and cocoa expansion has been a driving force of poverty reduction in the study region. Table 3.1 shows the poverty headcount ratio and poverty gap for all farm households, for cocoa and non-cocoa farmers, as well as separately for households that earn at least one third of their income from off-farm employment. The poverty headcount ratio declined from 62.33 per cent to 32.61 per cent for all households over the whole period. Especially notable is the stark decline between 2006 and 2013. The poverty gap, which estimates the depth of poverty and indicates the resources needed to lift the poor out of poverty by perfectly targeted transfers, decreased substantially from 36.30 per cent to 17.66 per cent from 2001 to 2013.

These significant improvements mainly arise from the poverty reduction among cocoa farmers. Table 3.1 show that poverty levels among cocoa farmers are lower and

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[3] Agricultural wage employment only represents a marginal source of income for our sample households. In addition to crop agriculture, non-farm activities also play an increasingly important role for rural incomes.

[4] Rice, the second most important crop, also increased substantially but only generates less than half of the income generated by cocoa cultivation All others crops display only minor income changes in relative terms and did not contribute significantly to increases in income.

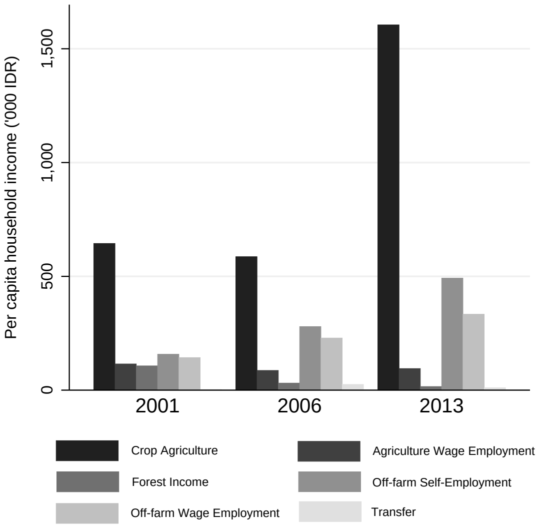
Table 3.1: Comparison of poverty measures for USD 1/day PPP poverty line from 2001-2013

	Poverty headcount ratio			**Poverty gap**			**Observations**		
	2001	2006	2013	2001	2006	2013	2001	2006	2013
All households	62.33	53.60	32.61	36.30	23.38	17.66	300	338	322
Cocoa farmers	54.55	46.35	24.36	31.30	19.30	13.18	176	233	234
- with at least 1/3 off-farm income	33.33	21.15	13.89	10.37	3.90	7.64	30	52	36
Non-cocoa farmers	73.39	69.52	54.55	43.43	32.56	29.55	124	105	88
- with at least 1/3 off-farm income	54.55	52.63	35.71	23.59	23.37	16.54	33	38	42

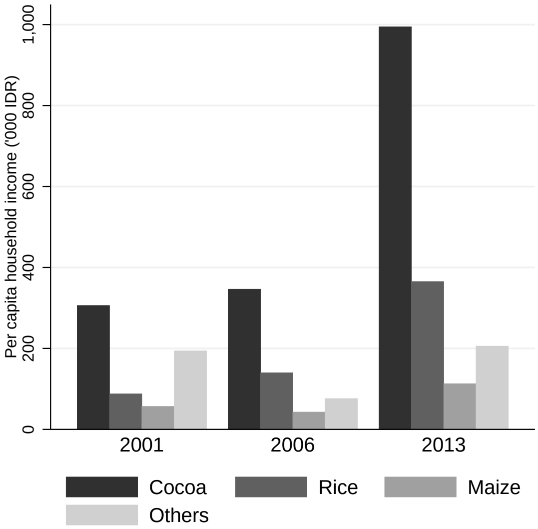
Notes: Currency conversion based on the World Bank PPP (Purchasing Power Parity) conversion factor for private consumption (Local Currency Unit (LCU) per international $). Households with a cocoa plantation of at least 0.25 hectare are classified as cocoa farmers.
Source: Authors' calculation based on STORMA and EFForTS data.

poverty reduction much stronger compared to non-cocoa farmers. Sampled households in the Lore Lindu region primarily shifted towards cocoa cultivation between 2001 and 2006, which is around 10 years later than the farmers in the South and South-West of Sulawesi. While in 2001, 176 out of 300 sampled households grew at least 0.25 hectare of cocoa, the share went up to 233 out of 338 households in 2006. The poverty depth decreased from 31.30 to 19.3 per cent during this time while the poverty incidence among cocoa farmers fell from 54.55 per cent to 46.35 per cent. This underpins the findings of Klasen et al. (2013) that the shift of households towards cocoa did not have a very strong immediate effect on the poverty incidence as cocoa trees had not yet reached their full maturity by 2006. Thus, poor cocoa farmers could increase their incomes and close the poverty gap but were not able to jump out of poverty. Between 2006 and 2013, the shift to cocoa turns out to be highly rewarding, when the cocoa trees developed their full productive potential. During this time, the poverty headcount ratio among cocoa farmers decreased from 46.35 to 24.36 per cent and the poverty gap from 19.3 to 13.18 per cent. Only households that partly engage in off-farm activities record even lower poverty rates. Cocoa farmers that derive at least one third of their income from off-farm employment show the lowest incidence and depth of poverty of all household groups, as classified in Table 3.1. However, they also only represent a small share of the sample.

Table 3.2 shows the absolute numbers of cocoa farmers and non-cocoa farmers in different poverty groups and the shares of households changing poverty status (poor vs. non-poor at a poverty line of US 1$/day PPP) by main farming activity (cocoa vs. non-cocoa farming) for the two sample periods 2001-2006 and 2006-2013. In the first period, farmers that cultivated cocoa in 2001 performed better than non-cocoa



(a) Sector of employement



(b) Main cultivated crops

Figure 3.2: Mean per capita (p.c.) income by sector of employment and main cultivated crops, 2001-2013

Notes: Monetary values are real Indonesian Rupiahs with base year 2001, using the provincial Consumer Price Index (CPI) for Palu provided by BPS Statistics Indonesia (2016a). Incomes are yearly. The data represent the mean of all per capita household income per income source. To calculate the per capita household income, households' income (per source) is divided by the respective and idiosyncratic household size. The mean values consider also income sources with zero income.

Source: Authors' calculation and graphical representation based on STORMA and EFForTS data.

Table 3.2: Transition matrix for USD 1/Day PPP poverty line for cocoa farmers (C) and non-cocoa farmers (NC), 2001-2013

2006		**Poor (USD 1/day)**		**Non-Poor**		
2001		C	NC	C	NC	Σ
Poor (USD 1/day)	C	43.6 [41]	7.5 [7]	45.7 [43]	3.2 [3]	100 [94]
	NC	20.0 [18]	48.9 [44]	15.6 [14]	15.6 [14]	100 [90]
Non-Poor	C	33.3 [26]	1.3 [1]	60.3 [47]	4.1 [4]	100 [78]
	NC	21.2 [7]	33.3 [11]	21.2 [7]	24.2 [8]	100 [33]
	Σ	31.2 [92]	21.4 [63]	37.6 [111]	9.8 [29]	100 [295]

2013		**Poor (USD 1/day)**		**Non-Poor**		
2006		C	NC	C	NC	Σ
Poor (USD 1/day)	C	28.8 [30]	8.7 [9]	58.7 [61]	3.8 [4]	100 [104]
	NC	15.9 [11]	39.1 [27]	15.9 [11]	29.0 [20]	100 [69]
Non-Poor	C	12.6 [15]	1.7 [2]	79.8 [95]	5.9 [7]	100 [119]
	NC	4.0 [1]	40.0 [10]	24.0 [6]	32.0 [8]	100 [25]
	Σ	18.0 [57]	15.1 [48]	54.6 [173]	12.3 [39]	100 [317]

Notes: Currency conversion based on the World Bank PPP conversion factor for private consumption (Local Currency Unit (LCU) per international $). Values are rounded. Numbers of households are in parentheses. Since most households in our region have adopted cocoa during the first period, we assume as cocoa farmers all households with at least two observations and with a cocoa plantation of at least 0.25 hectare.
Source: Authors' calculation based on STORMA and EFForTS data.

farmer with a lower share of poor households remaining poor (43.6 per cent of all initially poor cocoa farmers) and a higher share escaping poverty while remaining cocoa farmer (45.7 per cent). The share of initial non-cocoa farmers who stick to their activity and remain poor is slightly higher with 48.9 per cent. Interestingly, and in line with the above assessment of poverty changes among cocoa farmers, the transition to cocoa cultivation might not pay off immediately: some initially non-poor non-cocoa farmers switching to cocoa fall into poverty (21.2 per cent of all initially non-poor non-cocoa farmers) over the first period. Similarly, 20 per cent of initially poor cocoa adopters cannot escape poverty. Moreover, within the first period cocoa cultivation seems even to raise the vulnerability to poverty: a considerable amount of (initially) non-poor cocoa farmers (33.3 per cent) fall into poverty between 2001 and 2006. The first period is thus characterized by more chronic manifestations of poverty and a higher share of non-poor households falling back into poverty.

In the second period, a much more dynamic upward mobility can be observed among cocoa farmers. The share of cocoa farmers escaping poverty increases significantly to 58.7 per cent (of initially poor cocoa farmers) and is considerably higher than the share of those remaining poor or falling into poverty. This trend holds also for the (initially) non-poor cocoa farmers whose share of farmers remaining non-poor rises from 60.3 per cent in the first period to a 79.8 per cent in the second period. Non-cocoa farmers' income levels also improve, but less than for cocoa farmers. The share of non-cocoa farmers escaping poverty or remaining non-poor is substantially lower than for cocoa households. Moreover, the share of non-cocoa households falling into poverty is higher than in the first period.

Hence, the results clearly suggest that cocoa production is a long-term driver of overall poverty reduction. Yet, despite the increasing opportunity to escape poverty between 2006 and 2013, it is important to recognize that a significant share of cocoa farmers remains poor. This heterogeneity in poverty dynamics and outcomes raises questions concerning the individual determinants of cocoa income and its poverty-reducing potential.

3.6 Productivity heterogeneity of cocoa farmers

The direct determinants of cocoa income, i.e. cocoa yield, cocoa area and farm gate prices are shown in Table 3.3. Whereas cocoa area per household is only slightly rising over time, we observe that average productivity increases significantly over the whole sample period. Cocoa yields increase slightly between 2001 and 2006, but more than double between 2006 and 2013, explaining most of the long-term increase in cocoa income over time. As shown above, real cocoa price fell between 2001 and 2006 and recovered somewhat until 2013.

The increase in average cocoa yields in the second period was accompanied by a considerable increase in their variance, i.e. rising heterogeneity. One important ex-

Table 3.3: Measures of variance for cocoa income and its components for cocoa farmers, 2001-2013

	2001	**2006**	**2013**
	mean (standard deviation)		
P.c. household cocoa income	513,551 (1,255,471)	496,847 (603,385)	1,353,738 (1,875,858)
Crop area (are)	1.4 (1.3)	1.4 (1.2)	1.5 (1.7)
Yield (kg/are)	211.6 (328.9)	349.0 (273.0)	815.6 (822.3)
Price (IDR/kg)	8,527 (1,206.4)	5,266.9 (423.7)	6,446.5 (279.6)

Notes: Households with an cocoa plantation of at least 0.25 hectare are included. Monetary values are real IDR with base year 2001, using the provincial CPI for Palu provided by BPS Statistics Indonesia (2016a). Local land units are measured in are. One are is equal to 100 m^2. Prices are village medians of farm gate prices.
Source: Authors' calculation based on STORMA and EFForTS data.

planatory factor for these trends is the yield cycle of the cocoa tree. The average tree age of cocoa farmers increases from 3.8 years in 2001 (sd = 3.2 years) to 6.3 years in 2006 (sd = 4.1 years) up to 11.2 years in 2013 (sd = 6.3 years). As cocoa trees start to produce at the age of 3 to 5 until the age of 20 to 25 and reach their productivity peak at the age of 10 (Wood and Lass 2001), the cocoa plantations of the farmers in the study region have on average reached their most productive age in 2013.

The strong variation of yields means that many cocoa farmers are not exploiting full potential yields. Figure 3.3 illustrates the average yield gap, i.e. the yield potential and the mean achieved yield for four tree age groups. Following van Ittersum et al. (2013), we estimate yield potentials by upper percentiles in the yield distribution from the surveys. We rely on the 90^th percentile of yields among our survey farmers to estimate the maximum potential yield. Most farmers obtain yield levels that are well below the potential yields for the region: on average, they achieve about half of the yield potential. For example, while the farmer at the 90^th yield percentile produces 1280 kilogram cocoa per hectare for cocoa trees aged 5 to 10 years, the average cocoa farmer only achieves 642 kilogram per hectare. Yield gaps are present for all age groups, suggesting that the plantation age is not the only determinant of heterogeneity among cocoa farmers.

We therefore analyse cocoa yield determinants (or 'correlates' acknowledging the limited causal content of this type of exercise) using pooled ordinary least squares (OLS) and static panel data methods (Fixed Effects (FE) model). We estimate the following equation that relates productivity, management practices as well as farm and farmer

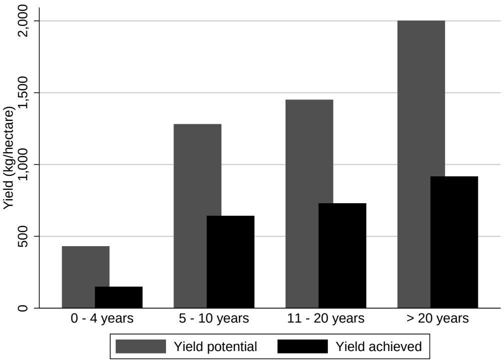


Figure 3.3: Yield gaps, 2001-2013.

Source: Authors' calculation and graphical representation based on STORMA and EFForTS data.

characteristics:

$$\ln Y_{it} = \alpha + \sum_j \beta_j P_{i,it} + \sum_k \beta_k M_{k,it} + \sum_l \beta_l H_{l,it} + \delta D_{it} + \gamma_i + \lambda_t + \varepsilon_{it} \tag{3.1}$$

where Y_{it} is productivity defined as household's yield measured in cocoa beans harvested (in kg) per hectare, P is a matrix of j variables of plot characteristics, M is a set of k variables on management practices, H is a set of l household characteristics, D_{it} is a dummy controlling for the presence of pests, λ_t are time fixed effects and ε_{it} is the idiosyncratic error. The Fixed Effects (FE) model also includes household fixed effects γ_i that control for unobserved and time-invariant characteristics, such as unobservable ability of farmers. Time fixed effects λ_t (year dummies) further capture time-specific shocks common to all households, like time trends in average productivity or weather shocks that affect all households in the same year. All estimations are performed using cluster-robust standard errors. Summary statistics on the key variables used in our econometric analyses are given in the Appendix B, Table B.1.

Management practices are proxied by both chemical inputs (fertilizer[5] and herbicides) and manual techniques, such as manual weeding, pruning, the removal of diseased fruits and the frequency of harvests. Fertilizer application is included as the household's expenditures for fertilizer per hectare. All other management proxies are included as dummies. We also have information on participation in the GERNAS Pro Kakao program and include a corresponding dummy in some regressions without implying that this dummy will be able to capture causal program impacts. We control for tree age by adding cocoa tree age and its squared term. Moreover, we include a dummy for pests, mainly the Cocoa Pod Borer and the black pod disease.

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[5] For our sample, only about one quarter of farmers applies fertilizer.

We further account for wealth (assets), education and migrant status as household characteristics.

We estimate a log-linear model[6] and some explanatory variables (agricultural area, expenditure on inputs and households' assets) are transformed to their natural logarithm to comply with the assumption of normal distribution, mitigate the problem of heteroskedasticity, and to make the model less sensitive to outliers. The estimated coefficients can thus be interpreted as (semi-)elasticities. The model potentially suffers from endogeneity, in particular without household fixed effects. The OLS estimates of the effects of management practices are likely to be affected by omitted variable bias, as it is plausible that they are related to the same – unobserved – farmer ability as cocoa yields. To mitigate reverse causality of wealth, which might be determined by cocoa yields giving the farmer financial capacity to engage in input-intensive activities, we use lagged values of assets.

Table 3.4 shows the results of our analysis of yields. Columns (1) to (4) present the results of the pooled OLS model with time effects and column (5) without time effects. Our baseline model (column 1) regresses yield on the main plot conditions as well as labour input. The coefficient of cocoa area is statistically significant and indicates that an 1 per cent increase in total cocoa area under cultivation is on average associated with a 0.18 to 0.32 per cent decrease in yields. This result indicates that larger cocoa plantations of smallholders are less intensively managed (for example, by intercropping with other plants). As expected, the estimated coefficient for tree age is significantly positive while the estimate for its squared term is negative. This reflects the yield curve for cocoa with first increasing and then decreasing yields and a turning point at about 16 to 19 years in our estimation. Labour input as measured by expenditures for hired workers is also associated with higher yields; the number of family members working on the plot does not seem to play a role though. Column 2 adds variables on management practices and we find input-intensive as well as labour-intensive activities to be an essential means to achieve high yields. The yield elasticity of fertilizer expenditure is 0.02. Similarly, the application of herbicides is positive and significant. Furthermore, manual practices seem to be an important ingredient for successful cocoa cultivation. A striking example is that farmers who prune their cocoa trees on average achieve about 1.5 times the yield than those refraining from doing

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[6] Using the log value of yield removes observations with zero yields (e.g. during the initial phase of cocoa cultivation) from the estimation. As a robustness check, we also include observations with zero yields into the regression by adding 1 to each observation before transforming into logs. Results are similar and displayed in the Appendix B, Table B.2.

it (referring to column 2). Also removing diseased cocoa pods is essential, whereas controlling the growth of weeds by hand does not make a difference (only statistically significant in column 5).

Results on household characteristics (added in column 3) are mixed. Financial conditions of farm households – as measured by the ownership of assets – are statistically significant and positively correlated with yield. In other specifications, we use lagged values of assets to avoid reverse causality and the effect is no longer significant. The dummy on migration status is significantly negative (equals 1 in case of a local farmer) and hence indicates that migrants are more successful in cocoa cultivation than the local population. We further control for education of the household head and find the completion of primary and tertiary education to be positively correlated with cocoa yield.

Column (4) adds a pest dummy which is available for observations in 2006 and 2013. As expected, we find a negative effect which is insignificant though. However, we are hesitant to take this insignificant result at face value because pests are endogenous to a number of other regressors, in particular to management practices. Instead, we below investigate the correlates of crop failure to shed more light on the effects of pests.

Column (5) controls for the frequency of harvests and participation in the national cocoa program GERNAS that, among other things, trains farmers on cocoa cultivation (data is only available for 2013). Productivity remains unaffected by harvest frequency but there is evidence of a strong impact of GERNAS: farmers that participate in the GERNAS program achieve on average 82 per cent higher yields.[7]

Column (6) shows the findings of the long-term analysis based on the FE model.[8] The FE model is preferable to OLS as it takes the panel structure into account and controls for time-invariant heterogeneity across farm households which may bias estimation results. The FE model confirms our finding that both chemical (application of fertilizer) as well as labour inputs (pruning, removal of diseased fruits) have a positive impact on yields. To sum up, cocoa yields mainly depend on proper management practices which include both the application of chemical inputs and manual strategies. The farmers' choice of management practices hence can explain a large share

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[7] This result is likely to suffer from endogeneity given the self-selection into the GERNAS program.

[8] An alternative panel data method is the Random Effects (RE) model. Performing the (robust) Hausman tests, however, allows us to reject the null hypothesis of exogeneity of explanatory variables with the time and household fixed effects at the 1% level of significance for our baseline model and hence confirms our choice for the FE model specification.

Table 3.4: Determinants of cocoa productivity (pooled OLS and FE model), 2001-2013

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)
Estimation	OLS	OLS	OLS	OLS	OLS	FE
Cocoa area (log)	-0.175***	-0.211***	-0.267***	-0.296***	-0.320***	-0.460***
	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Tree age	0.221***	0.195***	0.183***	0.118***	0.099**	0.164***
	(0.000)	(0.000)	(0.000)	(0.002)	(0.015)	(0.000)
Tree age^2	-0.006***	-0.006***	-0.005***	-0.003***	-0.003**	-0.005***
	(0.000)	(0.000)	(0.000)	(0.006)	(0.016)	(0.000)
Labour exp. (log)	0.049***	0.035***	0.032***	0.020*	0.015	0.017
	(0.000)	(0.000)	(0.000)	(0.052)	(0.414)	(0.139)
Family workers (#)	-0.017	-0.016	-0.014	0.018	0.028	0.011
	(0.582)	(0.571)	(0.635)	(0.608)	(0.646)	(0.804)
Fertilizer exp. (log)		0.018**	0.007	0.014	0.007	0.031**
		(0.046)	(0.463)	(0.148)	(0.605)	(0.034)
Use of herbicides		0.323*	0.305*	0.553**	1.146***	0.330
		(0.081)	(0.100)	(0.015)	(0.003)	(0.120)
Manual weeding		0.046	0.086	0.212	0.775**	0.084
		(0.795)	(0.626)	(0.331)	(0.035)	(0.688)
Pruning		0.445***	0.405**	0.417**	0.189	0.734***
		(0.007)	(0.022)	(0.044)	(0.432)	(0.000)
Removing pods		0.661***	0.667***	0.617***	0.486**	0.383*
		(0.000)	(0.000)	(0.000)	(0.048)	(0.078)
Migrant status			-0.273***	-0.274***	-0.525***	
			(0.004)	(0.008)	(0.003)	
Primary edu.			0.143	0.234	0.656**	
			(0.258)	(0.141)	(0.025)	
Secondary edu.			-0.187	-0.123	0.126	
			(0.271)	(0.576)	(0.715)	
Tertiary edu.			-0.002	0.275	0.585**	
			(0.988)	(0.104)	(0.046)	
Assets (log)			0.062**			
			(0.018)			
Lagged assets (log)				0.035	0.023	
				(0.221)	(0.558)	
Pest				-0.091	-0.019	
				(0.423)	(0.892)	
GERNAS					0.598***	
					(0.001)	
Harvest frequency					0.152	
					(0.255)	
Year = 2006	0.081	0.065	0.148			0.265*
	(0.508)	(0.584)	(0.216)			(0.066)
Year = 2013	0.537***	0.481***	0.590***	0.445***		0.771***
	(0.001)	(0.001)	(0.000)	(0.000)		(0.000)
Constant	4.273***	3.290***	3.050***	3.524***	3.615***	3.222***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	554	554	551	368	209	554
R-squared	0.312	0.384	0.405	0.355	0.306	0.472
Adj. R-squared	0.303	0.370	0.386	0.324	0.241	
Number of id						257
Within R-squared						0.472
Between R-squared						0.151

Note: Pval in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, year dummies included, cluster-robust standard errors. Households with a cocoa plantation of at least 0.25 hectare are included.

Source: Authors' calculation based on STORMA and EFForTS data.

of the observed heterogeneity among our sample. Following a strategy of agricultural intensification (heavy use of fertilizer as well as application of herbicides) helps to increase yields. Also plot maintenance practices (especially pruning and the removal of diseased pods) have a great potential to considerably increase yields. These management practices appear to primarily affect yields in a direct way and rather not through preventing disease infestations.

To further explore the heterogeneity of production we apply a quantile regression, i.e. an approach that allows the parameters in equation (2.1) to vary across different quantiles of cocoa yields (here the 10th, 25th, 50th, 75th and 90th quantile). The Breusch-Pagan test for heteroskedasticity rejects the null hypothesis of homoskedasticity and hence rules out that heteroskedastic errors are driving our results. Table 3.5 shows ageing the estimation results for our main covariates. It becomes apparent that yields of less productive and more productive farmers are determined by different factors. We find coefficients on plot conditions, management practices as well as household characteristics to vary across quantiles and to differ from the OLS model. The pseudo R^2 which varies between 0.25 and 0.28, however, indicates that the quantile regression model explains yield more or less equally well at different parts of the distribution.

With regard to plot conditions, the coefficients on plantation age are very instructive. They reveal that the shape of the cocoa yield curve varies markedly across quantiles. In contrast to the successful farmers, the productivity of low performers has a much steeper rise in the beginning, reaches the turning point at an earlier stage (e.g. at a tree age of 13 years for the 10th quantile compared to 17 years for the 90th quantile) and records a steeper downturn afterwards. Moreover, the quantile regression results suggest that low and high performers have varying degrees of success with regard to management strategies.

At the lower tail of the yield distribution (10th quantile), farmers' agricultural practices do not have an effect on yield at all. Only the dummy on migrant status has a significant impact showing that being local has a strong negative effect on yield for the low performers. The low- to medium-performers (25th and 50th quantile) successfully rely on labour-intensive strategies (pruning and removal of diseased fruits, hired labour) to increase their yields. The effective application of fertilizer at the 50th and 75th quantile suggests that a well-managed intensification strategy could also help the lower quantiles to increase their yields. The high performers' (75th and 90th quantile) labour input (hiring labour and plot maintenance practices such as pruning and removal of diseased fruit) has also a positive effect, though with a slightly lower magni-

Table 3.5: Quantile regression of determinants of yields (pooled OLS), 2001-2013

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)
Estimation	OLS	Q(10th)	Q(25th)	Q(50th)	Q(75th)	Q(90th)
Cocoa area (log)	-0.240***	-0.276*	-0.193*	-0.272***	-0.215***	-0.290***
	(0.000)	(0.059)	(0.064)	(0.000)	(0.000)	(0.000)
Tree age	0.189***	0.397***	0.252***	0.172***	0.129***	0.101**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.011)
Tree age^2	-0.006***	-0.015***	-0.009***	-0.005***	-0.004***	-0.003*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.075)
Labour exp. (log)	0.035***	0.040	0.041**	0.034***	0.024**	0.022*
	(0.000)	(0.147)	(0.024)	(0.000)	(0.015)	(0.092)
Family workers (#)	-0.012	-0.037	-0.010	-0.008	-0.023	-0.001
	(0.679)	(0.637)	(0.858)	(0.706)	(0.446)	(0.983)
Fertilizer exp. (log)	0.010	0.014	0.008	0.012**	0.016*	0.011
	(0.252)	(0.565)	(0.611)	(0.042)	(0.075)	(0.345)
Use of herbicides	0.348*	0.233	0.438	0.219*	0.040	0.076
	(0.055)	(0.481)	(0.202)	(0.092)	(0.824)	(0.722)
Manual weeding	0.096	0.094	0.269	-0.027	-0.123	-0.076
	(0.578)	(0.762)	(0.416)	(0.828)	(0.472)	(0.721)
Pruning	0.428**	0.351	0.554*	0.474***	0.456***	0.346
	(0.014)	(0.203)	(0.081)	(0.000)	(0.006)	(0.136)
Removing pods	0.662***	0.421	0.666***	0.786***	0.569***	0.397**
	(0.000)	(0.201)	(0.004)	(0.000)	(0.000)	(0.022)
Migrant status	-0.300***	-0.696***	-0.442**	-0.142**	-0.109	-0.189*
	(0.001)	(0.010)	(0.013)	(0.034)	(0.254)	(0.088)
Primary edu.	0.158	0.302	0.095	0.057	0.074	0.235
	(0.213)	(0.439)	(0.720)	(0.561)	(0.599)	(0.164)
Secondary edu.	-0.150	-0.130	-0.412	-0.350***	0.092	0.315
	(0.377)	(0.777)	(0.200)	(0.003)	(0.587)	(0.151)
Tertiary edu.	0.089	0.287	0.015	0.083	0.110	0.283
	(0.552)	(0.521)	(0.959)	(0.450)	(0.477)	(0.121)
Year = 2006	0.090	0.110	0.201	0.179**	0.078	-0.245
	(0.451)	(0.723)	(0.380)	(0.029)	(0.513)	(0.135)
Year = 2013	0.559***	0.333	0.624**	0.656***	0.593***	0.455**
	(0.000)	(0.372)	(0.024)	(0.000)	(0.000)	(0.011)
Constant	3.413***	1.941***	2.533***	3.517***	4.540***	5.383***
	(0.000)	(0.006)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	554	554	554	554	554	554
R-squared	0.400					
Adj. R-squared	0.382					
Pseudo R-squared		0.273	0.267	0.245	0.227	0.253

Note: Pval in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, year dummies included. Households with a cocoa plantation of at least 0.25 hectare are included.

Source: Authors' calculation based on STORMA and EFForTS data.

tude compared to the low- to medium-performers. To sum up, the quantile regression reveals that heterogeneity in yield among cocoa farmers illustrates the importance of both the choice of management practices and their effective implementation for the observed productivity heterogeneity of farmers.

In a final exercise of our empirical analyses, we examine the incidence and determinants of crop failures, which may be a threat to sustainable income gains of cocoa farmers. In line with the above mentioned reports on problems in Indonesia's cocoa sector at large we observe a sharp increase in crop failures in our sample (see Table 3.6): in 2006, 9 per cent of cocoa farmer report on crop failure for the last 5 years. This share increases to 44 per cent alone for the year 2013. These losses are mostly due to pests and diseases, which explain 96 per cent of all crop failures in 2006 and 78 per cent in 2013 (other reasons are drought, flood or other weather phenomena). Hence in 2013, about one third of farmers is affected by pests and diseases. The reported pests and diseases are mainly the black pod disease and – to a slightly lesser extent – the Cocoa Pod Borer.

Table 3.6: Cocoa tree age: yield and crop failures, 2006-2013

		2006				**2013**		
Tree age	Cases	Yield (kg/ha)	Crop failure	Lost yield (%)	Cases	Yield (kg/ha)	Crop failure	Lost yield (%)
Years	*n*	*mean (sd)*	*N*	*mean (sd)*	*N*	*mean (sd)*[9]	*n*	*mean (sd)*
0 – 4	89	154.3 (200.2)	2	0.6 (3.7)	22	236.9 (386.3)	0	0
5 – 10	115	462.0 (240.9)	13	3.6 (12.2)	110	905.0 (967.8)	52	18.5 (23.8)
11 – 20	28	497.9 (247.8)	7	8.25 (16.1)	84	823.8 (656.1)	40	18.1 (24.0)
> 20	1	513.3 (-)	0	0	18	938.0 (689.9)	10	28.0 (31.6)
0 – 36	233	349.0 (273.0)	22	3.0 (10.7)	234	815.6 (822.3)	102	17.4 (24.1)

Notes: Households with a cocoa plantation of at least 0.25 hectare are included.
Source: Authors' calculation based on STORMA and EFForTS data.

The incidence and intensity of crop failure increase both across tree age groups within the respective year as well as over time. To explore this trend further, we run an auxiliary regression that relates crop failure, management practices and agricultural shocks (see Table 3.7). We first regress crop failure on basic plot conditions and management practices (column 1), then add household characteristics (column 2), and finally the pest dummy (column 3). We measure crop failure by the percentage of regular yield lost, due to natural disasters (droughts, storms) or infestations with pest and diseases. Results are available only for 2006 and 2013, for which data on agricultural shocks do exist.

As expected, proper management practices that are related to disease and pest management such as the application of herbicides, manual weeding and the removal of diseased pods are associated with lower yield losses. The same is true for harvest frequencies: harvesting the cocoa trees more than once per month decreases the magnitude of yield loss. Additionally controlling for household characteristics (column 2)

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[9] Cases where trees have been rehabilitated or rejuvenated (e.g. method of 'Sambung Samping') were dropped as they are no longer representative for tree age descriptives (in total 13 cases).

Table 3.7: Determinants of crop failure (pooled OLS), 2001-2013

	(1)	(2)	(3)
Variables	Crop failure	Crop failure	Crop failure
Cocoa area (log)	-0.802	-0.676	-1.053
	(0.556)	(0.672)	(0.366)
Tree age	0.873	1.143*	0.410
	(0.109)	(0.061)	(0.345)
Tree age^2	-0.020	-0.025	-0.001
	(0.269)	(0.175)	(0.945)
Labour exp. (log)	0.411**	0.525***	-0.023
	(0.015)	(0.006)	(0.873)
Family workers (#)	1.034	1.198	1.382**
	(0.123)	(0.116)	(0.011)
Fertilizer exp. (log)	-0.168	0.012	-0.195
	(0.429)	(0.960)	(0.243)
Use of herbicides	-24.279***	-23.701***	-13.018**
	(0.000)	(0.000)	(0.013)
Manual weeding	-21.173***	-19.955***	-12.370**
	(0.000)	(0.001)	(0.021)
Pruning	3.363	9.670**	4.195
	(0.608)	(0.047)	(0.137)
Removing pods	-6.550**	-7.344**	-5.323**
	(0.023)	(0.021)	(0.024)
Harvest frequency	-3.721*	-4.859**	-4.076**
	(0.066)	(0.026)	(0.011)
Migrant status		4.498**	-0.461
		(0.041)	(0.782)
Primary edu.		-0.987	0.923
		(0.719)	(0.677)
Secondary edu.		5.572	6.030*
		(0.160)	(0.076)
Tertiary edu.		1.075	6.000**
		(0.741)	(0.027)
Lagged assets (log)		-0.538	-0.374
		(0.394)	(0.370)
Pest			31.316***
			(0.000)
Year = 2013	14.469***	12.066***	4.872***
	(0.000)	(0.000)	(0.001)
Constant	21.541**	13.813	10.042
	(0.017)	(0.171)	(0.187)
Observations	430	365	365
R-squared	0.224	0.233	0.595
Within R-squared	.	.	.
Between R-squared	.	.	.

Note: Pval in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, cluster-robust standard errors. Households with a cocoa plantation of at least 0.25 hectare are included.

Source: Authors' calculation based on STORMA and EFForTS data.

does not affect the estimated coefficients on the management practice proxies, which reinforces that we are actually observing an effect of those practices rather than the effect of some unobserved farmer ability that would be correlated with them. We find further evidence that especially the production of local farmers is affected by pests as the migrant status dummy is highly significant and positive. When we add a pest dummy (column 3) we can see that pests indeed explain the largest proportion of the variance in crop failures, as R-squared increases from 0.233 to 0.595. The effect is large: if a pest occurs, yield is on average diminished by 30 per cent. The coefficients on management practices, in particular the use of herbicides, weeding, and removal of diseased pods, are smaller when the pest dummy is included. In other words, the omission of the pest dummy induced an upward bias of the mitigating effect of these practices in the first two specifications of Table 3.7. This indicates that a major transmission channel of better management practices on yields runs through the prevention and mitigation of pests. In addition, there is a significantly positive time trend in crop failures indicating that crop failures become more frequent in the region. In contrast to productivity, the magnitude of yield loss is largely unrelated to cocoa tree age and plantation size (when controlled for management practices). Further, the use of hired labour is significantly raising crop losses, but turns insignificant when including the pest dummy. This might indicate that farmers count on labour in the event of a crop failure, especially for pesticide spraying. Also the migrant status dummy gets insignificant in column (3), suggesting that the yield loss of locals, and probably lower yields in general, is partly due to pest infestations.

3.7 Heterogeneity in cocoa yields and poverty outcomes

To connect our findings, we explore in a final step how productivity heterogeneity and the associated management practices are linked to long-term poverty reduction among cocoa farming households in the Lore Lindu region. To proxy good management practices of cocoa plantations, we draw on three key determinants of cocoa productivity derived from the OLS and FE model above. First, we include the practice of tree pruning, which is highly positively correlated with cocoa yield and hence crucial for farmers' successful management of cocoa trees. Second, we consider the regular removal of diseased fruits as a key method to reduce the susceptibility to pests, especially the Cocoa Pod Borer and the black pod disease. Third, we use the application of fertilizer, herbicides or both as proxy for advanced management practices with chemical inputs. Accordingly, to be classified as a cocoa farmer with good management practices, a farmer has to prune his cocoa trees, has to remove diseased fruits from his trees and has to apply any chemical input. Applying these criteria, we separate our sample into well-managing and not-well managing farmers, resulting in 33 farmers with good management practices in 2001, 82 in 2006 and 131 farmers in 2013 (see Table 3.8). Management practices on average thus improve considerably over time.

Table 3.8: Numbers of well managing and not-well managing cocoa farmers

	2001	**2006**	**2013**
No. of well managing farmers	33	82	131
No. of not-well managing farmers	143	151	103
No. of all farmers	176	233	234

Notes: Households with a cocoa plantation of at least 0.25 hectare are classified as cocoa farmers.
Source: Authors' calculation based on STORMA and EFForTS data.

We combine this information with the respective poverty status of farmers' households and illustrate in a next step all transitions in both farmers' management quality and income status over the total sample period. To this end, Table 3.9 shows all transitions of cocoa farmers between 2001, 2006 and 2013.[10]

The results indicate that initially poor households can benefit from applying better management practices (23.4 per cent of all initially poor and not-well managing farmers), but that a transition out of poverty is also possible without doing so (a third of all initially poor and not-well managing farmers). Staying poor is associated with continued worse farm management while well-managing farm households find it much easier to escape poverty (59.3 per cent from the initially poor, well-managing households).

Looking at non-poor households confirms an important role for farming practices. The majority of cases (N=54 and 72%) of initially non-poor, well-managing households are households continuing their good management practices and maintain non-poor income levels. The latter holds also for the 43 farmers that improve management practices. And while only 10 initially non-poor farmers who manage well fall into poverty, this happens to 27 households without good management practices.

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[10] In total, 275 farmers could be interviewed concerning their management practices in 2001, 2006 and/or 2013. Of those 275 households, 141 could be interviewed three times (i.e. two transitions), 86 could be interviewed twice (i.e. one transition) and 48 could be interviewed once (i.e. no transition), adding up to 643 observations and 368 transitions.

Table 3.9: Transition matrix for USD 1/day PPP poverty lines for cocoa farmers with well and not-well agricultural practices, 2001-2013, total transition cases

TRANS$_{i,t+n}$ with $n = \{1; 2\}$ / **TRANS**$_{i,t}$		**Poor (USD 1/day)**		**Non-Poor**		
		WELL	NOT WELL	WELL	NOT WELL	Σ
Poor (USD 1/day)	WELL	3.7 [1]	14.8 [4]	59.3 [16]	22.2 [6]	100 [27]
	NOT WELL	10.4 [16]	33.1 [51]	23.4 [36]	33.1 [51]	100 [154]
Non-Poor	WELL	13.3 [10]	0.0 [0]	72.0 [54]	14.7 [11]	100 [75]
	NOT WELL	4.0 [5]	24.1 [27]	38.4 [43]	33.0 [37]	100 [112]
	Σ	8.7 [32]	22.3 [82]	40.5 [149]	28.5 [105]	100 [368]

Notes: Currency conversion based on the World Bank PPP conversion factor for private consumption (LCU per international $). Households with a cocoa plantation of at least 0.25 hectare are classified as cocoa farmers. Transitions are considered for at least one change.
Source: Authors' calculation based on STORMA and EFForTS data.

3.8 Conclusion

The present study shows that cash crop farming can be associated with strong and sustainable poverty reduction. In our study region in Central Sulwesi and over the analysed time horizon of more than 10 years, cocoa farmers fare considerably better than non-cocoa farmers and the welfare gains are less volatile than might be anticipated in light of the problems, in particular the occurrence of pests, faced by the Indonesian cocoa sector at large in the period under consideration. The large increases in cocoa income can mainly be attributed to increasing cocoa yields. However, yield gaps remain large and are increasingly heterogeneous. We can trace back this productivity heterogeneity to farm management practices that include both the application of chemical inputs and manual practices. The farmers' choice of management practices hence can explain a large share of the observed productivity heterogeneity in our sample. These management practices seem to have a direct positive effect on yields as well as indirect positive effect through the prevention and mitigation of crop failures, which tend to become increasingly common because of more frequent pest infestations in the region.

Taken together, increased cocoa yields and the importance of management techniques suggest that the improvement of management practices can be linked to improved livelihoods. And indeed, we can empirically establish this link: we can show that better management practices facilitate the transition out of poverty and shields against income losses. In light of the still gasping yield gaps of cocoa farmers in the region, our findings are good news as they show the potential of improving agricultural productivity to raise living standards. However, poverty persistence and the persistence of bad management among a substantial fraction of farmers may imply that these farmers may be much harder to reach. Finally, the increasing incidence of pests, especially the Cocoa Pod Borer and the black pod disease, might require more focused interventions. While intensification strategies have in the past helped cocoa farmers to considerably increase yields, they may, together with ageing plantations, aggravate the incidence of pests and diseases. Thus, management skills may have to improve beyond the simple intensification techniques and replanting will have to accelerate. This may be required to sustain the livelihood improvements that the cocoa sector has brought to many smallholders in Sulawesi.

4 Towards an integrated ecological-economic land-use change model[1]

4.1 Introduction

Land-use changes have dramatically transformed tropical landscapes throughout the past decades. Large stretches of pristine rainforests – once belonging to the world's hotspots of biodiversity – have been replaced by land used for agricultural purposes (Powell et al., 2015). In recent years, these transformed landscapes are anew subject to human induced land-use changes. Former slash-and-burn cropping systems are turning towards intensified monoculture plantations with cash crops, for example oil palm plantations or rubber plantations (Feintrenie et al., 2010a). It is well documented that the replacement of previous forests, grass or fallow land by plantations can lead to losses in ecosystem functions (Dislich et al., 2015). At the same time, it has to be considered that agriculture intensification provides the opportunity for economic development, especially in rural areas in developing countries (Sayer et al., 2012, Klasen et al., 2013).

Interdependencies between different functions both within and between the ecological and the socio-economic spheres are likely to be complex, often non-linear, and are not well understood. For example, the spatial configuration of land uses plays an important role for both the ecological and socio-economic functions. Considering the spatial dimension is essential to assess biodiversity (e.g., via edge effects, connectivity, buffer zones, or homogenization) and ecosystem functions (e.g. hydrological functions via riparian buffer zones). Also for economic functions the spatial structure matters. For example, the proximity to and accessibility of input and output markets as well as processing facilities influence the production decisions. Understanding the complexity of functions is of utmost importance to identify ways to maintain ecosystem functioning and biodiversity in the face of economic development.

Agent-based ecological-economic simulation models are a promising tool to develop a better understanding of the complex dynamics and interactions between ecological and socio-economic functions in agricultural landscapes (Villamor et al., 2014). Agent-based models (ABMs) are particularly useful in situations where there are important differences between individuals, interactions between individuals differ (according to, e.g., proximity), and/or individuals make independent decisions and pur-

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[1] This paper has been written in co-authorship with Claudia Dislich, Johannes Heinonen, Jann Lay, Katrin M. Meyer, Kerstin Wiegand and Surya Tarigan.

sue their own objectives (Railsback and Grimm, 2012). ABMs are also '*across-level* models' (Railsback and Grimm, 2012, p. 10). They can simulate the behaviour of the system as a result of the behaviour of individual agents and *vice versa*. Thus they can incorporate decisions of agents, such as individual farming households, and evaluate the effects of these decisions on ecological and socio-economic functions at different scales (e.g. local or landscape scales). Thereby these models are able to explicitly link the socio-economic and the ecological sphere. Although ABMs are rather an unconventional approach to simulate economic behaviour - in contrast to models describing a simultaneous equilibrium – they are also a well suited tool to model adjustment processes (Berger, 2001).

Interest in socio-/economic-ecological modelling has grown in recent years, and a number of models, including ABMs, have been published. These models tackle a variety of specific real-world situations (Holdo et al., 2010, Le et al., 2008, 2010) and many of them are based on real data to the extent possible. However, there often is a lack of data available for all aspects covering such complex systems, in particular data that link the relevant socio-economic and ecological functions. Such data should build on complex household surveys that can be matched with context-specific data on ecological functions. However, when data are available and modelling techniques are carefully applied, ABMs allow for testing different scenarios, e.g. how 'external' effects like policies or price shocks; or 'internal' effects like the adoption of new production technologies affect the behaviour of agents, then landscape mosaics, and, eventually, ecological functions.

This paper presents an agent-based ecological-economic simulation model describing the land-use change in the Jambi Region of Sumatra, Indonesia. In this region, oil palm and rubber plantations represent the dominant land-use types. The landscape mosaic is shaped by different actors, most importantly smallholders with typical field sizes around two hectares and private or state-owned companies with comparatively large monoculture plantations. Using the Jambi region as a case study, our model draws on data provided by the ongoing interdisciplinary research centre EFForTS (Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems, Indonesia) which has been started in 2012. This project has provided a dataset of 701 farm households with information on households' land holdings, agricultural and non-agricultural activity, endowments and household composition. Drawing on this comprehensive database, our guiding research question is: what kind of landscape mosaic can improve the ensemble of ecosystem functioning, biodiversity and economic benefit based on the synergies and trade-offs that we have to account for?

In this paper, we describe an agent-based model that we have developed to address this question. The model – which we call EFForTS-ABM – is sufficiently complex to capture all factors and processes relevant to our questions yet simple enough to be able to understand the model's mechanisms and the forces that drive model outcomes (cf., Evans et al., 2013). The model description is structured according to the ODD protocol for describing individual-based models (Grimm et al., 2006, 2010) and the ODD+D extension of the protocol for describing agent-based models that involve human decisions (Müller et al., 2013).

4.2 Methods

Following the OEDD protocol of Grimm et al. (2006, 2010) and its extension considering human decision-making within the ODD+D by Müller et al. (2013), this section will give insights in the overview, the design concepts and the model scenarios.

4.2.1 Overview

The overview of the model presents the purpose, the entities, state variables and scales, the process overview and scheduling of the model.

4.2.1.1 Purpose

The purpose of our model is to provide an integrated, exploratory tool to analyse how land use and land-use change affect ecological and socio-economic functions. Relationships between different functions on different spatial and functional scales in the form of trade-offs or synergies will be investigated with the model.

As smallholders manage the majority of farm land in our study region, we focus on smallholder land management and decisions. Land-use and land management decisions are modelled on the household level, based on household capital and external economic drivers like prices for inputs and products. Socio-economic functions in the model are economic development and welfare effects, on the ecological side we focus on carbon storage. Further ecological functions, e.g. species diversity will be incorporated in the near future. Concerning land-use types, we consider the perennial land-use types oil palm and rubber plantations, and secondary forest as a near natural habitat.

We choose a spatially explicit approach, as the location of the household and its farmland in the landscape might affect the decision-making process as well as ecolog-

Table 4.1: Spatial units of the model

Spatial unit	Meaning
cell	smallest spatial unit of the model (50m x 50m)
field	contiguous cells of the same land-use type and age belonging to the same household (i.e. an agricultural field)
household area	cells belonging to the same household
patch	contiguous cells of the same land-use type and same/similar age (i.e. same type of habitat, independent of ownership)
landscape	largest spatial unit of the model: set of all cells

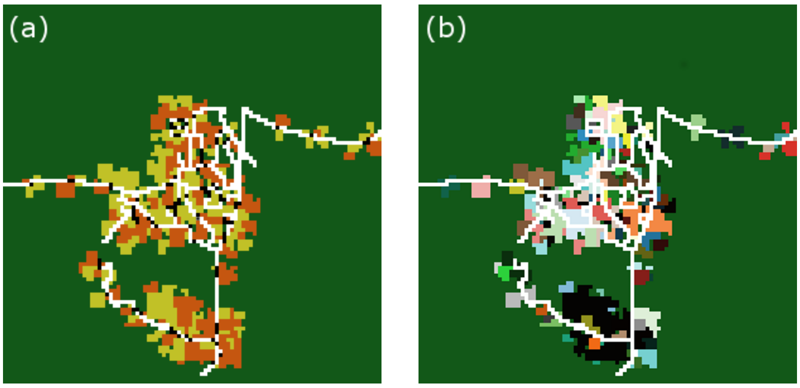

Figure 4.1: Initial land-use and household maps

Note: (a) Initial land-use map, orange: oil palm plantations, yellow: rubber plantations, green: secondary forest, white: roads. (b) Household map: different colors represent areas of different households, black patches represent household home bases.

ical functions. For instance, biodiversity can be affected by the degree of landscape fragmentation. A combined agent-based and grid-based approach provides the flexibility needed to model diverse ecological and socio-economic functions. Interactions between grid cells, e.g. animal movement and intra-household dynamics, as well as interactions between households can be included explicitly in such a framework.

4.2.1.2 Entities, scales and state variables

The model simulates ecological and socio-economic aspects of land use and land-use change and therefore comprises different entities: cells, fields, households, patches and the landscape (see Table 4.1). These spatial units capture the hierarchical structure of the system and facilitate structurally realistic representation of the links between ecology (environment) and socio-economic functions (households). The smallest spatial unit of the model is a square cell where cell size corresponds to the typical size of small fields (in our case 50m x 50m; Fig. 4.1(a)). Each cell is characterized by its position in the landscape, land-use type and age, which is the time since current land use has been planted. A field is defined as a number of contiguous cells under the same land use of the same age belonging to one household. Each household can own several fields and decide on land use and management of these fields (Fig. 4.1(b)). The size of existing fields remains constant throughout a simulation. Similar to fields, patches are contiguous cells of the same land use and the same (or similar) age, but regardless of ownership. While fields are important units in the economic submodel, patches define areas of similar habitat suitability and may thereby play an important ecological role for species diversity and distribution. Households are characterized by their location in the landscape, the sizes and locations of fields belonging to the household and specific household characteristics. The landscape comprises a regular grid of cells and is the highest level entity of the model (in our case 100 x 100 cells, i.e. 25 square kilometres). All processes in the model, i.e. vegetation growth as well as household-related processes, work with an annual time step. Prices for yield are external and do not vary within the landscape. Household variables describe the size and production of the land owned by the household as well as the financial resources of the household (details in Table 4.2). A detailed description of the household model is given in Appendix C.4.

Cell variables describe ecological and economic properties of the land use in that cell such as type (e.g. oil palm), age, technical input, production and amount of carbon stored in the vegetation of that cell (details in Table 4.3).

4.2.1.3 Process overview and scheduling

Each model run starts with the initialization procedure (see Appendix C.2). After initialization, each grid cell has a certain land use (oil palm, rubber or secondary forest). Each grid cell under agriculture (oil palm or rubber) has an owner (smallholder farmer or big company) and a certain age. Within each time step (year) the following processes are scheduled (Fig. 4.3).

At the beginning of each year, the economic household model is executed. At first, household wealth is reduced by the planned consumption which comprises a subsistence component and a wealth-based component (for details see Appendix C.4). Subsequently, households decide on land management and land-use change (Fig. 4.2). This decision is based on expected profits from different land-use options and available financial resources. The actual annual profit from agricultural land use is then calculated for all household cells according to age-specific yields and costs and actual commodity prices. At this point also the costs for land-use change in this time step are accounted for. Afterwards, household wealth is updated by adding profits from agriculture and potential external income and deducting a profit-based part of house-

Table 4.2: List of the most important household variables

Variable name	**Unit**	**Meaning**
h_id	[-]	Household identifier
h_area	[-]	Number of cells belonging to the household
h_wealth	[USD]	Amount available for the household
h_inefficiency_op	[-]	Inefficiency factor for oil palm [0,1]
h_inefficiency_rubber	[-]	Inefficiency factor for rubber [0,1]
h_debts	[USD]	Annual debts taken up for agricultural production
h_capitalstock	[USD]	Amount of capital fixed in plantations
h_exincome	[USD]	Annual external income, i.e. income external to agriculture
h_netcashflow	[USD]	Net cash flow from all household cells
h_consumption	[USD]	Annual consumption of household (fixed + variable consumption)
h_cost_investment	[USD]	Annual investment costs from all household cells
h_cost_labor	[USD]	Annual labour costs from all household cells
h_cost_tinput	[USD]	Annual technical input costs from all household cells
h_cost_capital	[USD]	Annual capital costs from all household cells
h_cost_land	[USD]	Annual land rent costs from all household cells
h_revenue	[USD]	Annual revenue from agriculture
h_op_production	[ton]	Annual production of oil palm fruit bunches from all household cells
h_rubber_production	[ton]	Annual production of rubber from all household cells
h_debt_years	[-]	Number of consecutive years in which the household had debts > 0

Table 4.3: List of the most important cell variables

Variable name	**Unit**	**Meaning**
p_landuse	[-]	Land use of the cell (oil palm, rubber, secondary forest)
p_age	[year]	Age of the plantation in the cell
p_fieldsize	[-]	Total number of cells belonging to the same field as this cell
p_carbon	[ton]	Carbon stored in the vegetation of this cell
p_owner	[-]	h_id, if this cell is owned by a household, otherwise -1
p_homebase	[-]	h_id, if this cell is the homebase of a household, otherwise -1
p_production	[ton]	Annual production from this cell
p_id	[-]	Field identity; all cells belonging to the same field have the same field identity
p_labor	[h]	Labour hours invested in this cell in one year
p_tinput	[kg]	Technical input invested in this cell in one year
p_capitalstock	[USD]	Capital stock of this cell

hold consumption. This updated household wealth serves as a basis for the land-use decision module in the next time step. After the economic household model, the ecological part of the model is updated, i.e. new carbon stocks are calculated for all

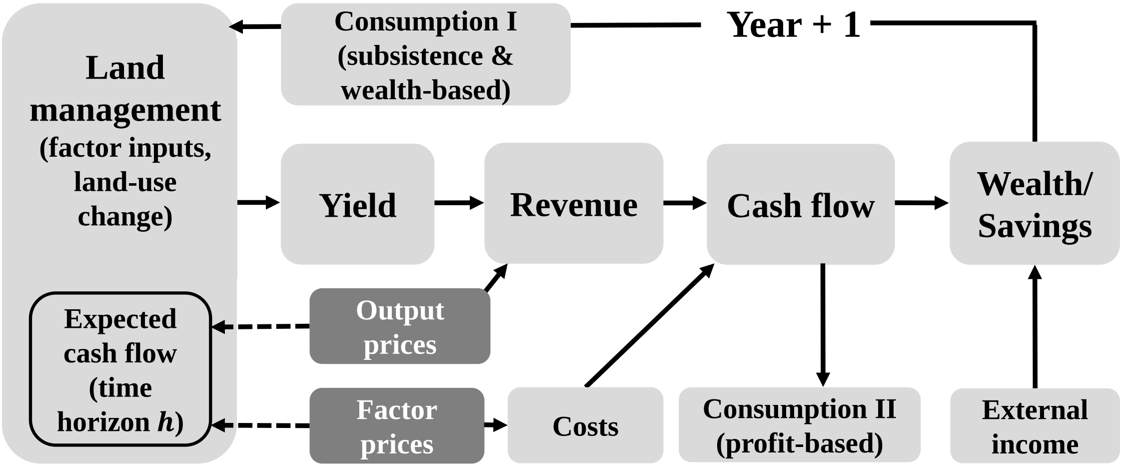

Figure 4.2: Process overview of the economic household model

cells and ecological functions are calculated.

4.2.2 Design concepts

This paragraph describes the general concepts underlying the design of the EFForTS-ABM (Grimm et al., 2006).

4.2.2.1 Theoretical and empirical background

The following two brief sections introduce the theoretical background of the ecological-economic model.

4.2.2.1.1 Economic household model

The economic household model is based on the concept of 'agricultural household models' (Singh et al., 1986). In this type of model, a rural household simultaneously decides on production and consumption under given constraints, for example initial endowments with land or access to credit. The land management decision comprises the decision on land-use change and production, including the use of factor inputs.

4.2.2.1.2 Ecological submodels

The currently applied carbon submodel describes carbon stored in the vegetation and utilizes simple age-dependent carbon stock equations for the land-use types oil palm and rubber plantation, and constant carbon stock values for forest cells. Other factors that might influence carbon stocks, e.g. edaphic conditions, fertilizer management etc. are not considered in this model version.

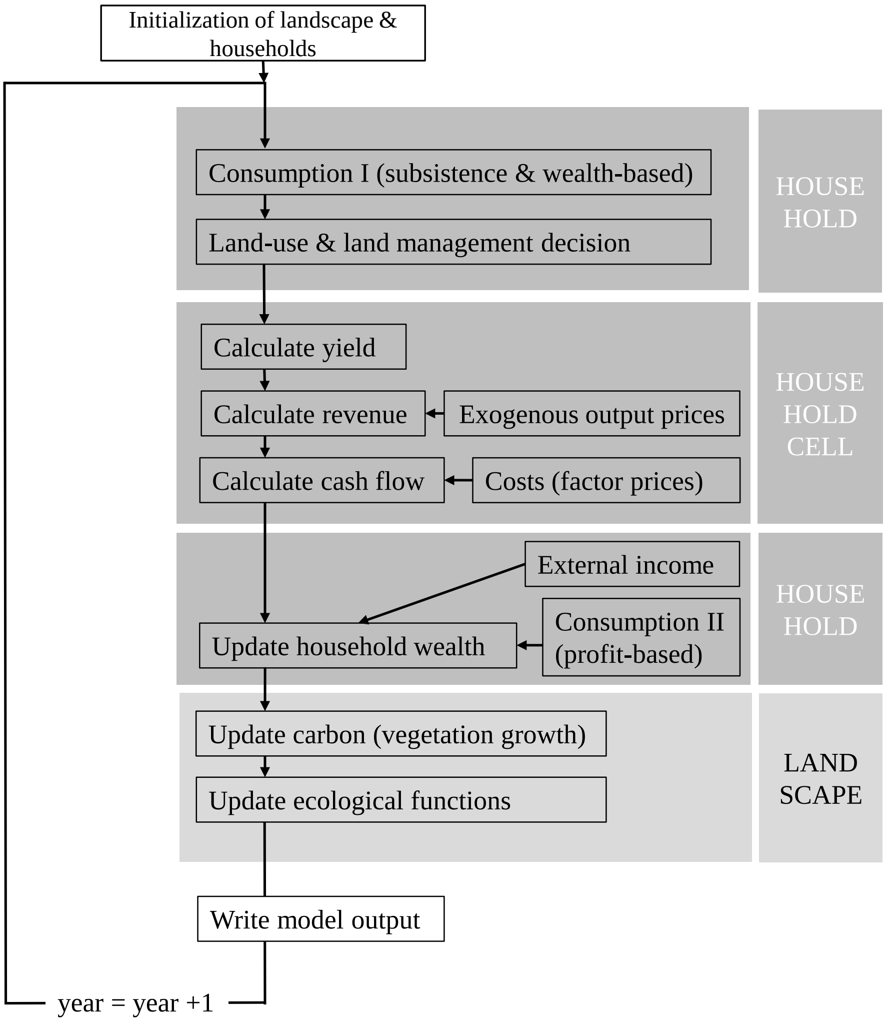

Figure 4.3: Process overview of the ecological-economic model

4.2.2.2 Individual decision-making

Every year, households decide on land management and land-use change on the cells that belong to the household. These decisions are driven by the agricultural production choices of the household, which, in turn, are determined by production technologies, initial conditions, and household endowments. Households maximize profits and decide between different land uses according to the relative profitability of different options, i.e. households compare expected profits for different land-use options over a certain time horizon. In computing these profits, household-level constraints are taken into account, for example with regard to the availability of capital needed for investment. Households hence produce and invest, thereby accumulating capital. The proceeds from agricultural production are used to finance investments, to save and to consume.

4.2.2.3 Individual learning, sensing and prediction

The model in its present basic form does not include adaptive behaviour, e.g. learning of agents. Each agent makes its decision independently, i.e. no neighbour effects are incorporated. The agents hence do not sense the other agents. Agents' knowledge is restricted to current commodity prices, therefore they forecast future prices by current prices and anticipate zero change. The current prices are used for the computation of future expected cash flows from agriculture.

4.2.2.4 Interaction, collectives and heterogeneity

The model does not incorporate interactions between agents. Also, no collective groups, e.g. groups of agents that behave differently, are considered. Agents differ in their land and capital endowments, as well as their initial land uses and ages of fields. An additional optional parameter which introduces heterogeneity between agents is household inefficiency which affects the production function of households (see Appendix C.4).

4.2.2.5 Stochasticity

During initialization, the amount and spatial distribution of land use is randomly assigned (see Appendix C.5). The initial wealth of households is drawn from a log-normal distribution and resulting values are assigned to households according to household areas (for details see Appendix C.5 and C.6). Parameters for crop- and household-specific inefficiency (see Appendix C.2) are drawn from a normal distribution and stay constant throughout the simulation. Different options of stochastic price dynamics are implemented (e.g. Gaussian random walk, see Appendix C.4). However, this option can be turned off to use constant prices.

4.2.2.6 Observation

Patterns observed at the household level are land-use changes and the dynamic development of yields, cash flows and household wealth. On the landscape level we observe the fractions of different land-use types and carbon stocks.

4.2.3 Model scenarios

We ran two different scenarios to look at the influence of output price fluctuations on the landscape pattern:

- Constant output prices for oil palm and rubber, set to values derived from household survey data, gathered in the Jambi region in 2012 (Table C.2),

- historical price trends, which can be thought of as an illustration of actual price fluctuations in world commodity markets.

4.3 Results and Discussion

The main result of this study is an integrated ecological-socioeconomic land-use model, called EFForTS-ABM. Kelly (Letcher) et al. (2013) identified five types of integration in environmental modelling. The model we present is not only an integrated model in terms of disciplines and processes but also in terms of scales (e.g. for spatial scales see Table 4.1). In line with Kelly (Letcher) et al. (2013) the purpose of the model is to develop system understanding but not prediction or forecasting. Hence, we chose an ABM modelling approach because it is good at incorporating complexity and details at the individual level (Kelly (Letcher) et al., 2013). We have both quantitative and qualitative data available on social, economic and ecological functions and aspects of the system (Barnes et al., 2014, Gatto et al., 2015). Both the qualitative purpose and the ABM approach of the model facilitate the incorporation of such different types of data. Moreover, we are in the unique situation that data collection follows an integrated scheme which has jointly been developed by modellers and empiricists (Faust et al., 2013, Jeltsch et al., 2013, Drescher et al., 2016). Thus, the relationship between the data collection and monitoring in the field and the modelling can resemble an integrated environmental modelling and decision process, with feedback between different stages of the two procedures, providing a more holistic approach (Laniak et al., 2013).

Villamor et al. (2014) have also developed an agent-based model of land-use change in Jambi, Sumatra: the LB-LUDAS. However, the two models differ in at least two important aspects: (i) the LB-LUDAS employs a bonded-rational approach to household decision-making, based on household preference coefficients for the existing circumstances, derived from field data; our model is focused on rational decision-making built on both theory and field data; (ii) the LB-LUDAS is focused on schemes such as payment for ecosystem services (PES) and willingness by households to adopt these schemes; our initial interest is in understanding land-use decisions and how these decisions change tropical landscapes.

The key mechanism of EFForTS-ABM is – so far – the land management decision of the households. Farmers will tend towards the more profitable land use and will convert land with some time lag conditional on the current land use. For instance, the household's capital endowment needs to be sufficient to cover the investment costs

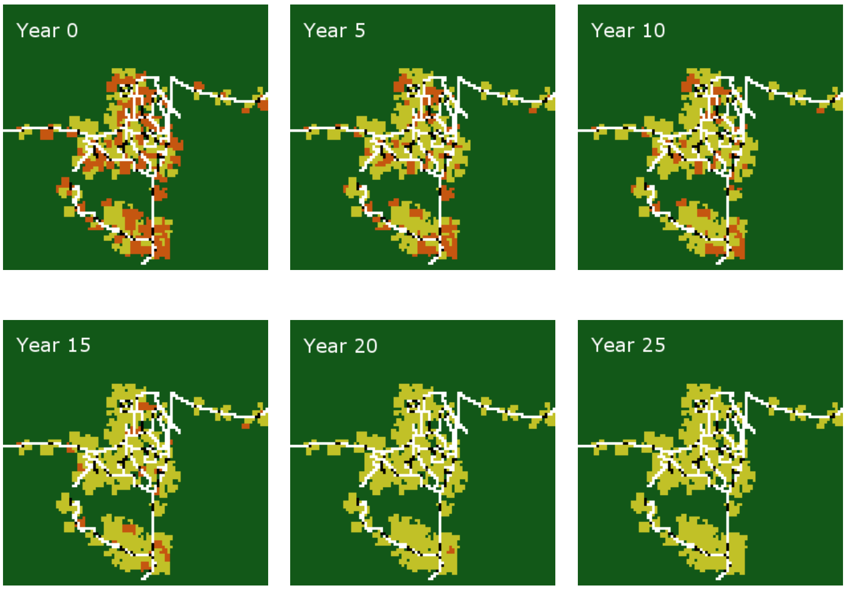

Figure 4.4: Snapshots of the simulated landscape in different years (0, 5, 10, 15, 20 and 25) of an exemplary simulation run with constant prices

Note: Roads are marked in white, household home bases in black, oil palm plantations in orange, rubber plantations in yellow. Dark green is the area which is not used for agriculture.

of conversion. This implies that the model should produce convergence towards the more profitable land use, at least if productivity is homogeneous and input and output prices are constant and common to all farmers. Indeed, we observe this behaviour in the model. For example, at the farm gate prices of the last quarter of 2012 with rubber at USD 1100 per ton and oil palm at USD 90 per ton of fresh fruit bunches (FFB), rubber turns out to be more profitable than oil palm regardless of the time horizon used for how far into the future the household calculates expected net cash flows (Fig. C.9 (a)). In such a scenario and with default settings (see Table C.2), the fraction of fields planted with rubber increases to 1.0 and the fraction of fields planted with oil palm decreases to 0.0 (Fig. 4.4 and Fig. 4.5). The transition phase from a fraction around 0.5 for both crops in the initial situation to complete dominance of rubber is about 20 years under the current specification and parametrization of the model. Note that the model can produce more diverse land-use patterns if we introduce heterogeneity in productivity, i.e. differences in household efficiency. Then, the relative profitability of rubber and oil palm will possibly differ between farmers and therefore also their choice between rubber and palm oil.

The simulated land-use change scenario is associated with a considerable increase in household consumption (Fig. 4.5 (b)). In general, two forces are at work in the model that can increase profits and thus consumption over time: one is the 'natural' yield

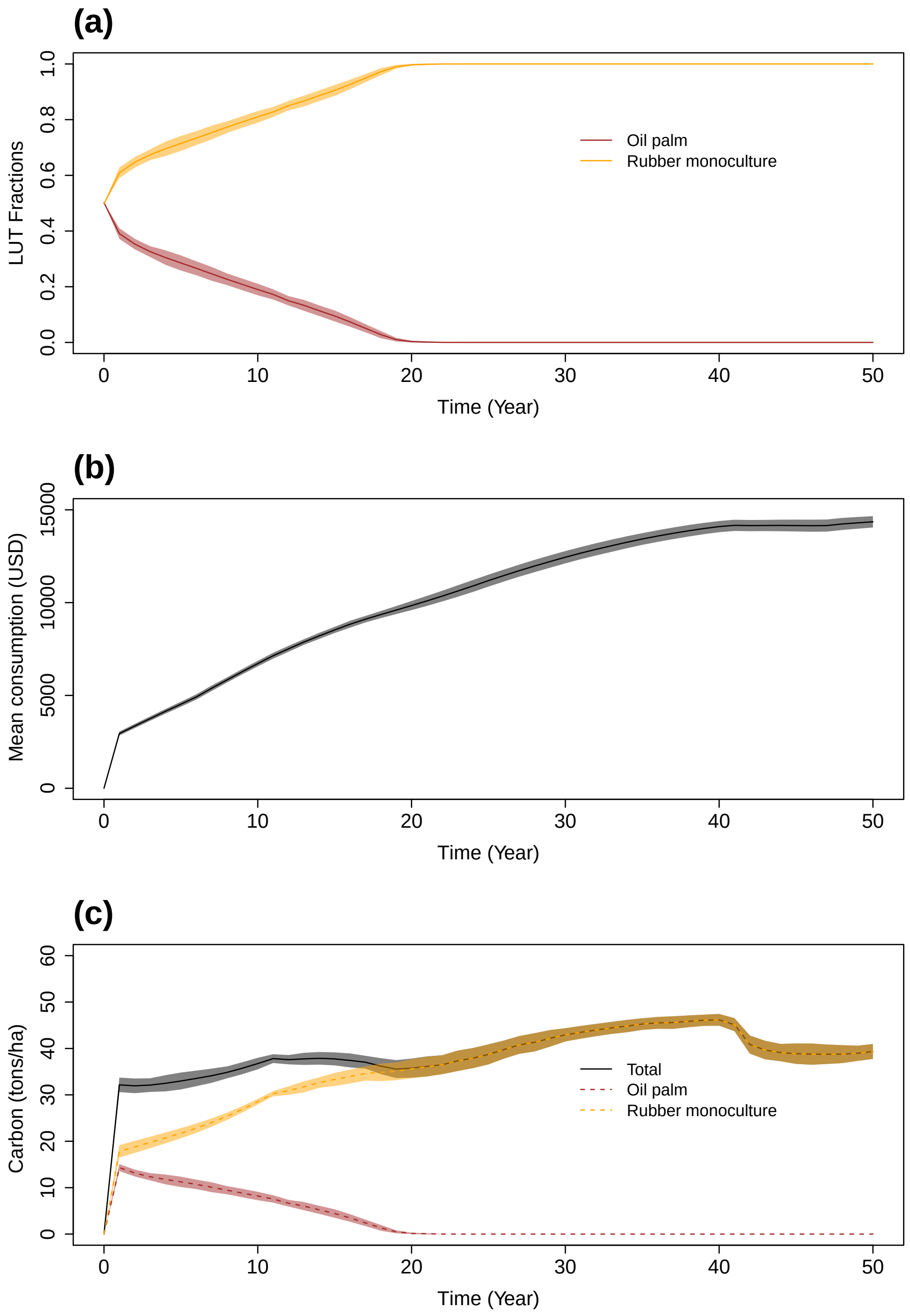

Figure 4.5: Temporal dynamics under constant price scenario

Note: Fractions of different land-use types (LUT) within the agricultural area, mean household consumption, and vegetation carbon stocks over time with constant output prices. The dark lines represent mean values and for each the surrounding shaded polygon represents the standard deviation.

growth of both crops; the second force is the option to switch to a more profitable crop. However, the investment costs of switching will cut into consumption and may temporarily decrease household welfare. The model results show the average implications of these mechanisms for the consumption levels of farmers (see Fig. 4.5 (b)), the key indicator for household's welfare in the model. Overall, consumption more than doubles within a time horizon of about twenty years. This is driven by both switching to more profitable rubber as well as increasing yields in rubber. Increase in yields clearly drives the observed consumption increase after year 15. After year 40, the growth of consumption slows down again as the necessary replanting of rubber plantations involves new investments. This fairly steady improvement of average household welfare is accompanied by relatively constant vegetation carbon dynamics (Fig. 4.5 (c)). The amount of carbon in the agriculturally used area fluctuates around 35-40 tons per hectare within the first 20 simulation years, i.e. as long as there is a mixture of oil palm and rubber plantations. During this time, the reduction of vegetation carbon stock due to land-use change is roughly balanced by vegetation growth on those plots where land use does not change. After all oil palm plantations are replaced by rubber plantations, the vegetation carbon stock increases up to almost 50 tons per hectare, and then slightly decreases again. The decrease in carbon after year 40 is caused by the replanting of old rubber plantations. This means that with the applied land-use decision criterion and at the spatial scale the number of households of the model, we observe a tendency towards synchronization not only of land-use types but also of plantation ages, which might have both socio-economic and ecological consequences, such as a possible reduction in economic inequality and amplified cycling in landscape-scale carbon stocks.

When the oil palm and rubber output prices fluctuate like past prices for palm oil and rubber, the choice of land use no longer settles to a stable state (Fig. 4.7). Instead, the dominant land-use type varies with the relative changes in the output prices (Fig. 4.6 (a)). The increased heterogeneity between households can be explained by the differences in household wealth and sizes of fields that largely originate from initial model conditions; households with greater wealth and smaller fields (i.e. higher investment capacity and lower required investment costs) can be more reactive to price changes and can more easily switch to a new, more profitable land use. Because of the continued switching between land uses, mean household consumption never reaches the levels seen in the scenario with constant output prices (Fig. 4.5 (b)); however, similar levels of carbon accumulation under agriculture are reached in the two scenarios (Fig. 4.5 (c) and Fig. 4.6 (c)).

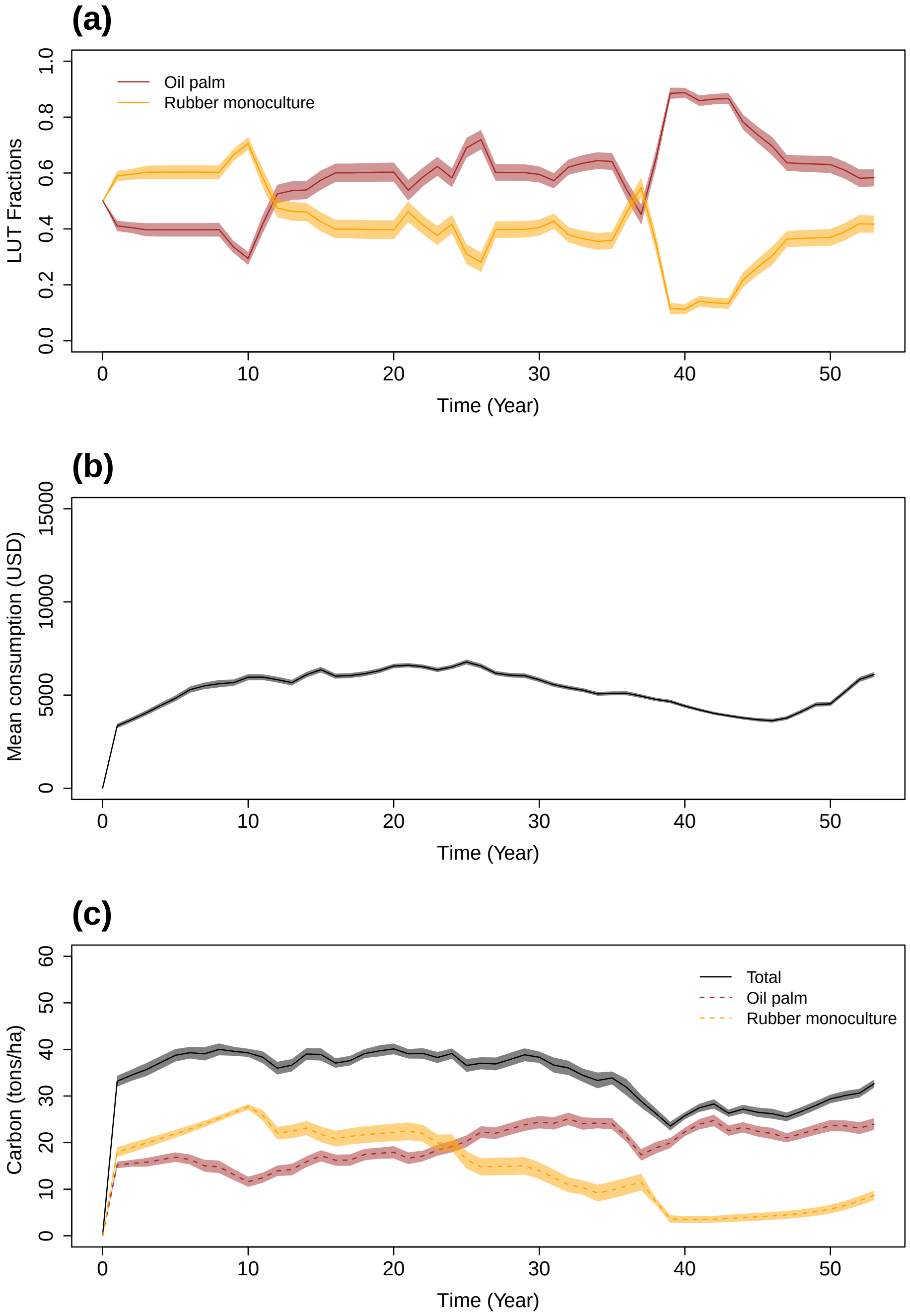

Figure 4.6: Temporal dynamics under historical price scenario

Note: Fractions of different land-use types (LUT) within the agricultural area, mean household consumption, and vegetation carbon stocks over time with historical output price trends. The dark lines represent mean values and for each the surrounding shaded polygon represents the standard deviation.

To return to the question we proposed in the introduction: 'what kind of landscape mosaic can improve the ensemble of ecosystem functioning, biodiversity and economic benefit based on the synergies and trade-offs that we have to account for?', we can say that although carbon storage in oil palm and rubber fields is lower than in primary or secondary forest, the relationships between carbon accumulation/storage and economic benefit might not be completely straightforward, especially if the practice of leaving land to fallow is taken into account. Koh et al. (2009) propose that in order to reach the goal of this guiding question a combination of wildlife-friendly and land sparing farming practices are required. This can be reached through the provision of less intensive agroforestry buffers separating areas of high conservation value, set aside for biodiversity, from intensive agriculture such as oil palm or rubber monoculture. After model extension (see outlook below), we could test such scenarios and compare them to similar settings without buffers and under different allocations of high conservation value areas and intensive agricultural use areas. This will help us to assess the effectiveness of this approach for identifying the landscape mosaic we should aim for.

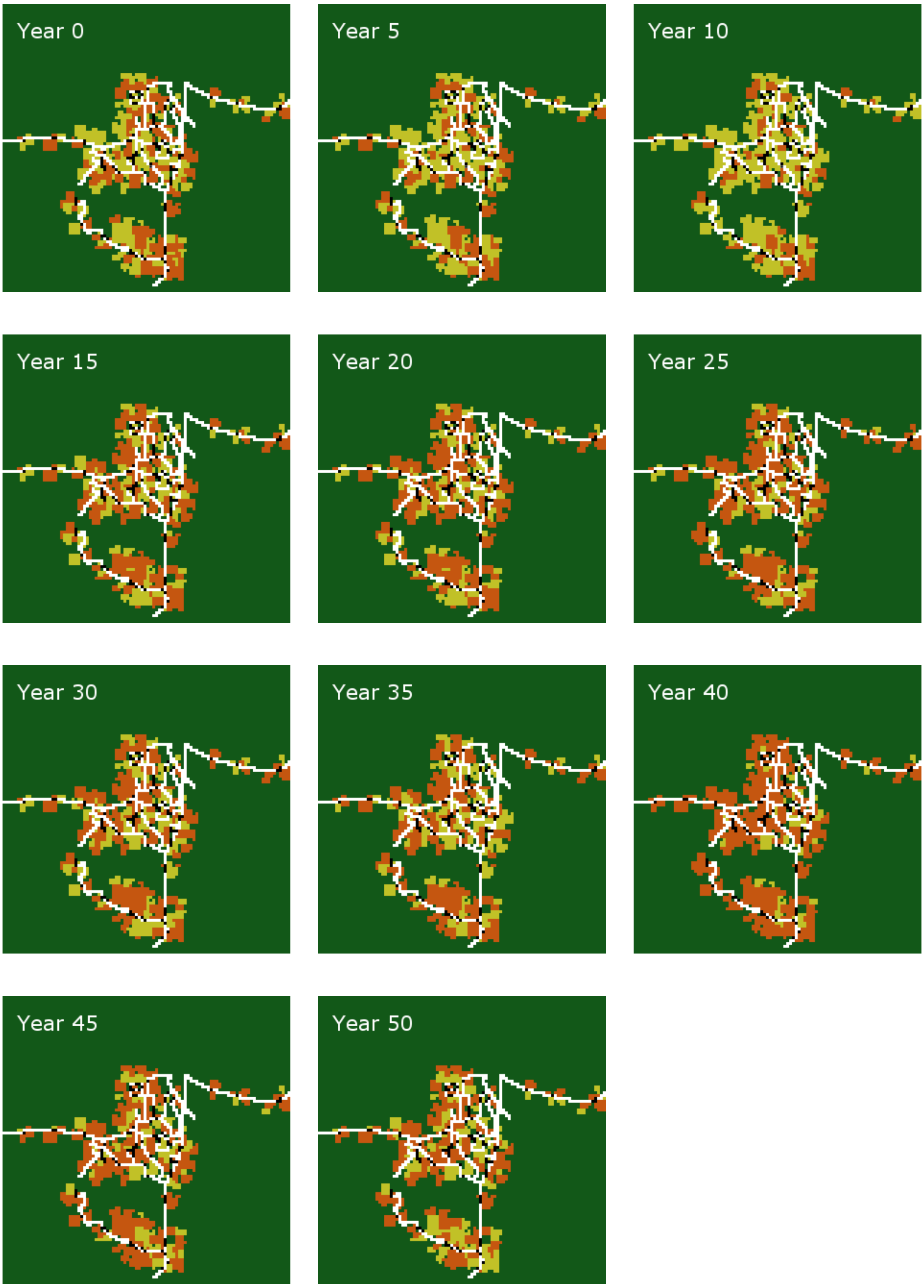

Figure 4.7: Snapshots of the simulated landscape in different years (0 to 50) of an exemplary simulation run with historical price trends

Note: Roads are marked in white, household home bases in black, oil palm plantations in orange, rubber plantations in yellow. Dark green is the area which is not used for agriculture.

5 Economic and ecological trade-offs of agricultural specialization at different spatial scales[1]

5.1 Introduction

For poor smallholder households that depend largely on the use of natural resources for their livelihood, increasing agricultural incomes is critical to escape poverty (Lipton, 2005, The World Bank, 2007, Klasen et al., 2013). In an environment of well-functioning markets and infrastructure, a possible economic option to increase incomes is to specialize on the most profitable crop for given soil, climate, and weather conditions (Lambin and Meyfroid, 2011, Ruiz-Pérez et al., 2004). At the same time, there are some costs and constraints to complete specialization which partly relate to land tenure, farm size, social capital stocks, and idiosyncratic decision making of farmers and partly relate to the availability, access, and functioning of markets for inputs, outputs, labour, and credit. For example, complete specialization often requires highly seasonal labour demand which often cannot be procured locally; similarly, concentration on one crop exposes farmers to high risk against which they can only imperfectly insure themselves (Di Falco and Chavas, 2008, Abson et al., 2013); third, jointness in production can also lead to advantages of diversified production (Allen and Lueck, 1998, Ballivian and Sickles, 1994, Klasen and Waibel, 2012, Kurosaki, 2003).

However, the better labour, capital, insurance, input, and output markets function, the lower are these constraints to specialization. If, for example, seasonal labour demand can be met with migrant labour, farmers have access to insurance, and improved infrastructure promotes intra-regional and international trade in competitive input and output markets, these constraints to specialization at increasingly broader scales are much less serious and specialization at increasingly larger scales becomes an important route to improve farm incomes, also for smallholders (Kurosaki, 2003). In the extreme, this could lead to monocultures not only at the level of the individual household, but at the level of the village, or even region. Hence, the degree of specialization may change along spatio-organizational scales depending on market

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[1] This chapter has been published by Stephan Klasen, Katrin M. Meyer, Claudia Dislich, Michael Euler, Heiko Faust, Marcel Gatto, Elisabeth Hettig, Dian N. Melati, Nengah Surati Jaya, Fenna Otten, César Pérez-Cruzado, Stefanie Steinebach, Suria Tarigan and Kerstin Wiegand (2016): 'Economic and ecological trade-offs of agricultural specialization at different spatial scales', in: *Ecological Economics* 122, pp. 111-120, http://doi.org/10.1016/j.ecolecon.2016.01.001.

functioning (Figure 5.1).

To be sure, this discussion so far focuses on the economic rationale for specialization of the individual farmer. Of course, other drivers of specialization can often also be operative and they often relate to politics and power. For example, large and politically well-connected land owners might push specialization through evicting subsistence farmers or specialization might be promoted by subsidies for particular cash crops, again benefiting particular groups of farmers (e.g. Pritchard, 2013, Binswanger and von Braun, 1991, Binswanger et al., 1995). Thus policies, politics, and power can also influence the degree of specialization either directly or indirectly via their influence on market functioning (Herath and Weersink, 2009).

While these instances can be important drivers of specialization in particular circumstances, we want to focus here on the possible dilemma posed that improvements in the functioning of markets can provide increasingly powerful economic incentives for specialization even without such political interference by the powerful. This can pose a dilemma since, at the same time, there can be substantial ecological and also socio-cultural costs in terms of reduced ecosystem functions and services if such monoculture agricultural systems emerge at the level of a village or an entire region. Ecosystem functions are the capacity of natural processes to provide goods and services that directly or indirectly satisfy human needs (De Groot et al., 2002). There might be losses in plant and animal biodiversity (Foster et al., 2011), but also reduction of pollination services (Priess et al., 2007) or biological pest control (Stamps and Linit, 1997) as well as hydrological functions (Comte et al., 2012, Nedkov and Burkhard, 2012, Ojea et al., 2012). Decomposition services and carbon sequestration may possibly be impaired, too. Furthermore, information functions or cultural services may be lost (Gasparatos et al., 2011, Millennium Ecosystem Assessment, 2005). These losses crucially depend on the level of scale at which specialization on monoculture crops occurs, with specialization at broader scales generating more problems. There can also be a mismatch on a temporal scale: in the short term, the progressive loss of ecosystem functions and associated services may only have a small impact on the profitability of specialized monocultures; in the longer-term, the sharp reduction or entire disappearance of important functions might, however, undermine the profitability of monocultures at broader spatial scales. The economic, socio-ecological, and cultural consequences depend therefore, to a large extent, on the spatial scale at which specialization occurs. For example, specialization within a village at the level of an individual farm might already generate some benefits of specialization for the respective farmer with few ecological costs compared to broader-scale specialization if

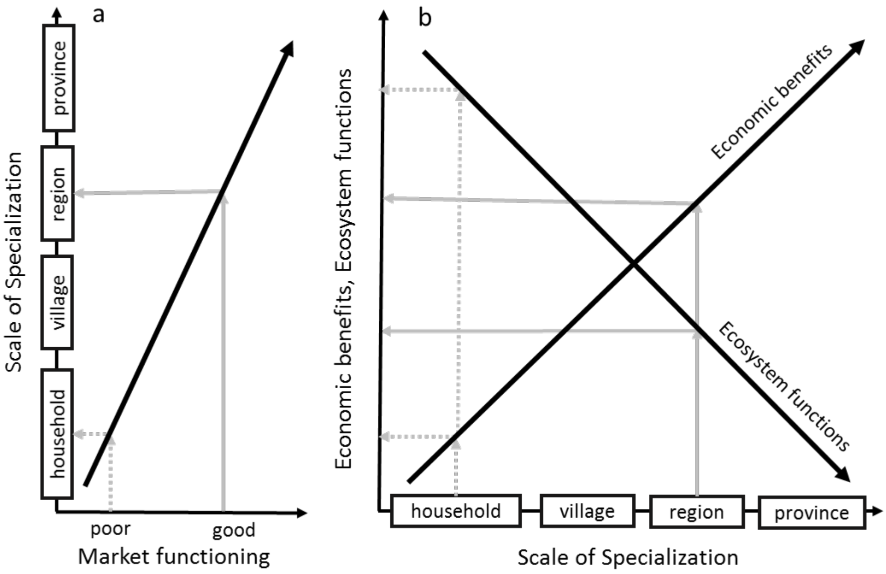

Figure 5.1: Conceptual framework of agricultural specialization at different spatial scales

Note: Market functioning can drive the level of scale at which specialization occurs (a), which in turn drives economic benefits and ecosystem functions (b; black arrows). Other drivers (not depicted here) such as policies, politics and power may influence the scale of specialization either directly or via their influence on market functioning. Two scenarios are illustrated (grey arrows): In the poor market functioning scenario (dotted grey arrows), specialization is only possible at the household level (see a) which leads to low economic benefits and high ecosystem functionality (see b). In the scenario with good market functioning (grey line arrows), specialization is possible at broader scales such as the region (see a). This leads to loss of ecosystem functions and high economic benefits compared to the poor market functioning scenario (see b). Note that in this illustration the location of the crossing of the arrows is arbitrary. The general message is that there is a scale-dependent trade-off between specialization and ecosystem functions driven by market functioning.

the diversity of crops remains high within a village. Figure 5.1 illustrates this point by showing two scenarios: one where poorly functioning markets allow only specialization at the household level; economic benefits of specialization are low but ecosystem functions are high. In scenario two, well-developed markets allow specialization at the regional level generating higher benefits but specialization at this broader scale reduces ecosystem services (see also Timmer, 1997).

This development of specialization can also be driven or exacerbated by policies, politics and power. For example, policies can actively promote monocultures through supporting and subsidizing the development of cash crops in particular regions; in the case of Indonesia discussed below, the promotion of the palm oil sector was supported by various policies of the government, including migration policies, land policies, or infrastructure (McCarthy and Cramb, 2009). In addition, however, policies aimed primarily at promoting growth and poverty reduction may also affect this trade-off between economic benefits and socio-ecological and cultural consequences of specialization. For example, policies to improve access and functioning of markets (e.g. through improved infrastructure, information systems) are likely to increase the economic benefits of specialization as they may increase the scope for specialization for poor producers, but such policies might cause harm from an ecological point of view as they push specialization to a broader spatial scale.

Some of these issues have been studied individually in both the economics (e.g. Belcher et al., 2004, Hazell and Wood, 2008, Kurosaki, 2003, Ruiz-Pérez et al., 2004, Timmer, 1997) and ecological (e.g. Lambin and Meyfroid, 2011, Smith et al., 2008) literature. Many studies have also commented on the general trade-offs between intensive agricultural production and the loss of ecosystem services (e.g. Evans, 2009, Hazell and Wood, 2008, Lambin and Meyfroid, 2011, Millennium Ecosystem Assessment, 2005). However, the interplay of specialization and ecosystem functions and services at different spatial scales, and how they are influenced by markets and policy has not been studied at any level of detail so far. The purpose of this conceptual paper is to lay out these issues and the ensuing trade-offs between economic benefits and ecosystem functions at different scales and illustrate them with examples from the literature and with on-going research on oil palm plantations in the province of Jambi in Indonesia.

5.2 Optimal specialization from an economic perspective

Economic benefits of specialization are very closely linked with the presence of economies of scale in production. Economies of scale are defined as the advantage of large-scale production that results in lower costs per unit of output (Kislev and Peterson, 1996). Hence, the total production costs are spread over more units of output. Economists tend to distinguish between internal economies of scale and external economies of scale (Hallam, 1991, Marshall, 1920). Internal economies of scale are cost advantages due to conditions inside the production unit (e.g. the farm or the firm), while external economies of scale are cost advantages from greater production of a sector or region (or even an entire economy, Caballero and Lyons, 1990). In the case of agriculture, both internal as well as external economies of scale can be present. For the case of cash crop agriculture, we identify four most relevant *internal* economies of scale. Firstly, the increasing scale of production can reduce outlays per unit of output, for example in purchasing chemical inputs or in reducing transportation and processing costs – especially, if distance to input and output markets is high. Second, internal economies of scale can result through the indivisibility of machines since the use of a more powerful machine, e.g. a tractor, is only profitable for larger plantations. Third, larger production units can sometimes employ workers with more specialized knowledge, for example in the application of chemical inputs (even though this seems not to be the case in our example in Jambi, see section 4.4). Lastly, a finer division of labour is possible which might increase the efficiencies of performing tasks and facilitate the monitoring of labour in completing these tasks.

Given these potentially large internal economies of scale, the question of optimal farm size arises. If these economies of scale are so substantial, why does cash crop production not take place exclusively on large plantations? And why do smallholders survive in the face of the cost advantages of large plantations? This is because large production units in agriculture also have to contend with substantial diseconomies of scale (e.g. Allen and Lueck, 1998, Binswanger et al., 1995, Lipton, 2005). They are due to the need for large farms to rely on hired labour where principal-agent problems (Levinthal, 1988), information and incentive problems might lead to high costs of monitoring labour and/or low labour effort and productivity. As a result, the family farm has remained a competitive production unit where these information and incentive problems are much less prevalent. As argued by Binswanger et al. (1995), large plantations will prevail if the economies of scale in processing are substantial (as is the case, for example, with bananas and tea) and/or when smallholders cannot easily be linked to larger processing facilities, as is possible in some cases in our case study (see section 4.4). A key message emerging from this discussion is that internal economies of scale generate substantial benefits for farms to specialize on one output, even if it is not optimal for production to take place exclusively on large plantations (see also Herath and Weersink, 2009).

A key driver for *external* economies of scale in cash crop agriculture is the total growth of the respective crop industry in a particular region. This facilitates the development of local processing industries and the development of transportation facilities; both reduce transport costs and promote trade. Growth of the industry in a local area can also help develop and improve the functioning of input, output, and factor markets by ensuring more volume of transactions in these markets which will increase the number of participating actors, thus promoting competition as well as lowering transaction costs. Lowered transaction costs further promote trade and allow an increasing separation between production and consumption of agricultural households (Timmer, 1997): production is specialized on the most profitable crop given soil and climatic conditions, while consumption of food and other needs is procured through trade. Despite these substantial scale advantages in production, there are barriers and limits to specialization on one output. One limit can be product-specific. For example, joint production of several outputs can be technically optimal (e.g. in the case of inter-cropping or crop rotation to optimally use existing soil resources or preserve/improve soil fertility, e.g. Ballivian and Sickles, 1994). It may also be the case that local heterogeneity of soil, water, and weather conditions recommend a more diversified portfolio of optimally adapted outputs. Second, resilience in production over time is usually a key concern of smallholders (Chuku and Okoye, 2009). A resilience-oriented strategy would promote a diversified output portfolio. Third, there may be an intrinsic value attached to maintaining a diversified portfolio of output, particularly also if these portfolios ensure adequate provisioning of households with the most important necessities and/or the diversified portfolio has itself ethnic or cultural significance (Laird et al., 2011). Socio-cultural ecosystem services have been recognized in many studies (De Groot et al., 2002, Millennium Ecosystem Assessment, 2005). Nevertheless, cultural aspects too often have been neglected in the ecosystem services assessment (Chan et al., 2012, Schaich et al., 2010) and therefore the analysis of land-use and landscape development may produce misleading results. Altogether, however, non-material benefits and intrinsic values related to culture and ethnicity as well as the social embedding or sentimental attachment to places usually constitute limits to specialization.

Apart from these technical and socio-cultural limits to specialization, the main other basic constraint to complete specialization relates to the functioning of markets and the associated transaction costs of engaging heavily with input, output, and factor markets. If transport costs are high and labour markets absent, farmers will maintain a diversified portfolio of outputs at a local scale that includes all major food necessities (Timmer, 1997). Production decisions will then also be made depending on the availability of family labour; and a diversified portfolio will be beneficial if labour demands can then be spread over the year. Moreover, concentration on one crop can be risky as there are high output and price risks; in the absence of functioning markets for credit and insurance, such risks can devastate farmers if production fails or prices fall (Klasen and Waibel, 2012, Morduch, 1995, Ray, 1999, Di Falco et al., 2007, Abson et al., 2013). Since poor farmers live close to subsistence, the absence of well-functioning credit and capital markets will be one reason for them to rely on a diversified production portfolio to reduce these risks (Morduch, 1995). Also choosing crops that are particularly resilient to shocks and risks will then be an important concern for farmers (Chuku and Okoye, 2009).

Conversely, this implies that improvements in the functioning of these markets could reduce those constraints to specialization, which could enable also smallholder farmers, including poor ones, to specialize much more. They can then increasingly rely on credit and insurance markets to deal with production and price risks, they can rely on labour markets to deal with seasonal labour demand problems, and they can ensure reliable access to food and other needs through trade. With well-functioning markets, potential competitive advantages due to local environmental conditions favouring one particular crop can be capitalized at the level of scale that shares these conditions. If the local or regional variability in environmental and soil conditions is low, or a particularly lucrative crop can profitably be grown in landscapes with some environmental and soil variety, this could lead to complete specialization at quite a broad spatial scale. Of course, these markets will never function perfectly and not all farmers may benefit from improved physical access to markets due to unfavourable power relations, prevailing societal structures or high transaction costs for access (Poulton et al., 2010), but the point to emphasize here is that as the functioning of these markets improves, specialization may become economically more attractive. Moreover, specialization can then move to a broader spatial scale. In particular, if input, output, and labour markets improve substantially, complete specialization on one cash crop may move from the household and the village level to the regional or even national level.

A related point of note is that policies that improve the functioning of input, output, labour, capital, and insurance markets are likely to promote this specialization at an increasingly broader scale. Thus, while these policies may be beneficial to smallholder producers as they promote higher and more stable incomes (while also providing benefits to traders and international investors), they will come at a cost of increasing specialization and monocultures at broader spatial scales with important consequences for ecosystem functions and services.

5.3 Ecological consequences of specialization

Specialization leads to monocultures, and monocultures are usually less beneficial for ecosystem services and associated biodiversity than more diverse polycultures. In addition, specialization often leads to intensification which is typically accompanied by higher inputs and the removal of remnant vegetation, and may lead to ecosystem simplification and loss of quantity and quality of products and services (Günter et al., 2012). A range of provisioning, regulating and supporting ecosystem services can potentially be affected by the reduction of crop diversity towards monocultures. Provisioning services such as crop production may suffer significant losses due to reduced crop diversity (Di Falco et al., 2007, Smith et al., 2008). In the long run, high fertilizer inputs may lead to eutrophication (Tilman et al., 2001) and altered soil physical characteristics and microbial communities. This may also reduce production services. Mediated by reduced crop production following low crop diversity, specialization could thus even threaten food security (see also Palmer and Di Falco, 2012), at least for subsistence farmers and at local scales unless product markets are, as discussed above, able to provide sufficient food diversity at affordable costs.

Regulating ecosystem services such as biological pest control may also be more efficient in polycultures or when remnant vegetation is present. For instance, most insect herbivore species have lower densities in polycultures than in monocultures (review on 287 species in 209 studies by Andow, 1991). Complex agronomic multicropping systems have lower pest insect populations than simpler systems (Stamps and Linit, 1997). Temperate forests that consist of multiple tree species have fewer pest outbreaks than single-species stands (Stamps and Linit, 1997). However, supporting services such as soil fertility and regulating services such as nitrogen-use efficiency have been shown to depend more on management than on crop diversity (Snapp et al., 2010). A reduction of coffee yields due to declining pollination services under diversity loss due to deforestation may be counteracted by preserving patches of forest (Priess et al., 2007). Hence, specialization can have positive or neutral effects on some ecosystem services, but in most cases, specialization reduces ecosystem services. Associated biodiversity is often, but not always enhanced in polycultures as compared to monocultures. For instance, polycultures of different annual crops harbored greater weed species richness than monocultures of these crops (Palmer and Maurer, 1997). However, in Malaysia, bird species richness was found to be higher in monoculture oil palm plantations than in polycultures (Azhar et al., 2014), probably due to higher human disturbance during weeding and harvesting in polycultures.

With increasingly broader spatial scales at which specialization occurs, the spatial extent of the resulting monocultures and their ecological effects will likely also be scaled up. This means that not only crop diversity may be lost over larger areas, but also that landscape configuration might be affected. For instance, technological and environmental factors (e.g. road access, topography) may cause the few crop types to be clustered in space. This causes large-scale heterogeneity in the landscape and may augment the loss of associated diversity because species that depend on a certain uncommon crop type are less likely to find the remnants of this crop type. Moreover, landscape fragmentation has non-linear effects on species survival, with extinction setting in long before the last remnants of this crop type have vanished (Bascompte and Sole, 1996). Thus, specialization at broad scales may exacerbate the ecological consequences of specialization at local scales.

5.4 Illustrating specialization trade-offs in Jambi, Indonesia

5.4.1 The case study of Jambi

Indonesia is the country with the largest increase in forest cover loss from 2000 to 2012 (Hansen et al., 2013). At the same time, monoculture cash crops expand rapidly. Since 2007, Indonesia has been the largest palm oil producer in the world (Coordinating Ministry of Economic Affairs, 2011), and it is also the second largest producer of natural rubber. Seventy per cent of the palm oil area in Indonesia is located in Sumatra and approximately 42% of palm oil land is managed by smallholders (Coordinating Ministry of Economic Affairs, 2011, p. 53) of which more than 50% have some kind of contract with a company. Similarly, the majority of the rubber production is produced by smallholders (Coordinating Ministry of Economic Affairs, 2011, p. 57).

The province of Jambi has a total land area of 5,300,000 ha (BPS Provinsi Jambi, 2013, p. 3, Figure 2) and is a showcase of high dependency on the agricultural sector. The total area under oil palm and rubber cultivation are approximately 936,500 ha and 1,284,000 ha, respectively (BPS Provinsi Jambi, 2011, updated after personal communication with an Indonesian government representative). The average per capita income in Jambi province is roughly 17.5 million IDR/year (equivalent to about 1200 USD/year; BPS Provinsi Jambi, 2011), which is substantially below the national average of 26.8 million IDR/year (equivalent to about 1850 USD/year; Kopp et al., 2014, p. 2). Fifty-two per cent of the workforce in Jambi is employed in the agricultural sector. An increase in the number of large plantations has contributed to reducing the area of farmland accessible to smallholders. Government promotion of the forestry and later the oil palm sector has contributed to agricultural intensification (Potter, 2001) and induced an agricultural transition towards oil palm (Rigg, 2005). More specifically, subsistence strategies of smallholders in the province shifted from extensive swidden farming to cash crop production. But this specialization has also been supported by rising global demand for cash crops, especially for oil palm, improved access and infrastructure, and the suitability of this crop to the area. Rubber remains the second most-important cash crop and currently, 99.6% of the rubber in

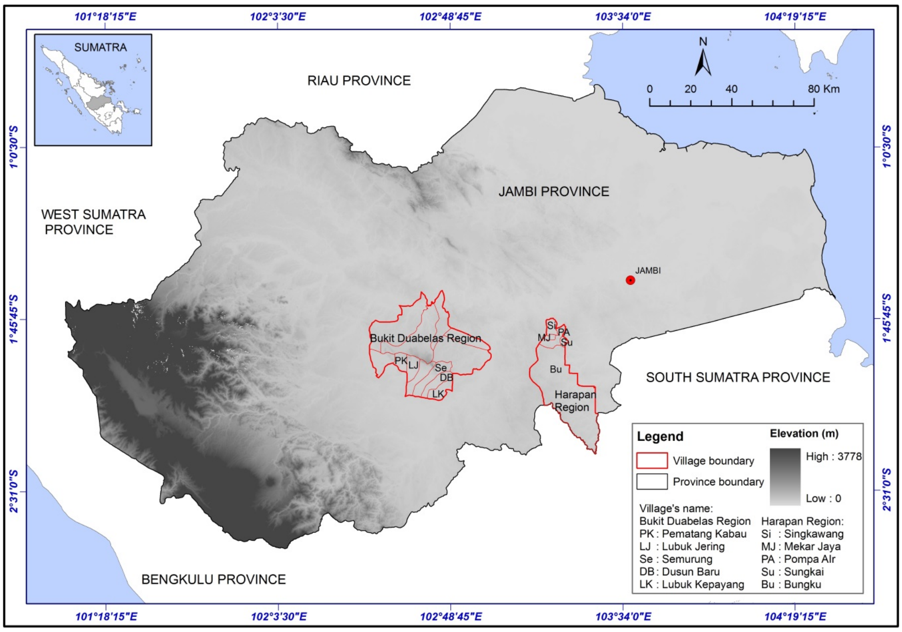

Figure 5.2: Map of Jambi, Indonesia

Note: The figure shows the map of Jambi province on Sumatra, Indonesia, where our case study was conducted, indicating the locations of the two example regions Bukit Duabelas and Harapan and the official boundaries of the five example villages per region selected for the specialization-scale study whose results are reported in Figure 5.4.

Jambi province is cultivated by smallholders (Estate Crop Services of Jambi Province, 2012).

Transformation of the Jambi lowland forests started in the 19th century when the Dutch colonial power exploited the natural resources in the region. In the early 1970s, the Indonesian state sold almost the entire lowland rainforests of Jambi Province as logging concessions. While the earlier concessions exploited already existing timber resources, the current concessions accommodate cash crop plantations, primarily oil palm and industrial timber. This change from a predominantly extracting economy to a production economy resulted in the establishment of an agricultural frontier zone where government-led transmigration programs were implemented from 1983 to 2002 to meet the demand for labour force on oil palm plantations (Hauser-Schäublin and Steinebach, 2014). Migration resulted either from state-organized transmigration projects or from 'informal rural migrants' (Bock, 2012) and led to strong increases in population size. The population in Jambi grew from 1.1 million people in 1971 (16 people/km) to 2.4 million people in 2000 and reached 3.4 million in 2014 (63 people/km^2)(Drake, 1981, p. 473; BPS Provinsi Jambi, 2013, pp. 136-137). Between

1967 and 2007 reportedly 96,401 families or 394,802 people were resettled to Jambi by transmigration projects as a measure of poverty alleviation and regional economic development (Pemerintah Provinsi Jambi, 2008). These households received parcels of land (about 2.5 ha each) and contracts with agribusiness companies to cultivate oil palm within a smallholder-contract-system. In summary, land-use transformation in Jambi province is closely linked to immigration because immigration is essentially triggered by the rising agro-business and oil palm economy to which migrants either act as a workforce for plantations or hope to be set up with land and begin production by themselves. In 2012 the share of residents with migratory background reached about 80% (Suara Pembaruan, 2012).

In the case of Jambi, specialization on oil palm or rubber plantations has been considered the (economically) best land-use option because returns to land and labor are higher compared to rubber agroforests (Feintrenie and Levang, 2009) and other non-commercial land-use systems (Zen et al., 2005). While Belcher et al. (2004) found higher returns to land in oil palm plantations compared to rubber agroforests and rubber plantations in East Kalimantan, Feintrenie et al. (2010a,b) observed the opposite in Jambi where returns to land are higher in rubber plantations than in palm oil plantations and rubber agroforests. All authors found higher returns to labour in oil palm than in rubber plantations. However, these plantations rarely provide any non-material benefits or other cultural services, nor do they provide intrinsic values. Interestingly, this coincides with the fact that in the native habitat of oil palms in Western Africa, socio-cultural importance is not related to monocultures but to the palm individual, or parts of it (Atinmo and Bakre, 2003).

On the contrary, non-financial considerations such as ethnic (and thus also migratory) background can play an important role (Belcher et al., 2004): ethnic-specific perceptions of the environment apparently have a serious impact on land and resource management (Manik et al., 2013, Pfund et al., 2011, Reenberg and Paarup-Laursen, 1997, Steinebach, 2013). Indigenous households often also depended to a much greater extent on a diverse range of habitats and species than non-indigenous households (Laird et al., 2011). Differences in livelihood dependency on forest can cause varying conservation attitudes (Mainusch, 2010). In Jambi province, the local indigenous communities of Orang Rimba and Batin Sembilan feel that they have suffered from large-scale land transformation due to their historically strong livelihood dependency on forest resources (Manik et al., 2013). Such livelihood dependency on prevailing land-use systems constitutes an important factor determining land use and specialization.

5.4.2 Specialization across scales in Jambi

As predicted by our conceptual framework, the level of specialization differs by the level of scale considered (Figure 5.4). To assess scale dependence, we analyse land-use types based on the Land Use/Land Cover (LULC) maps derived by visual interpretation (GOFC-GOLD, 2013, Liu et al., 2005) of the most cloud-free mosaics of Landsat and RapidEye images with the guideline of land cover mapping produced by the Indonesian Ministry of Forestry (Ministry of Forestry, 2008, Figure 3). This analysis does not cover the household level, but the village, region, and province levels. We find that specialization on one or a few crops is strongest at the village level, whereas differentiation increases at the region level and is highest at the province level (Figure 5.4). More detailed data are available for the household and village levels from a household survey (N = 701 smallholder households in 45 villages) and a village survey (N = 98, containing the 45 villages of the household survey) conducted in 2012 in the province of Jambi with structured interviews (Faust et al., 2013).

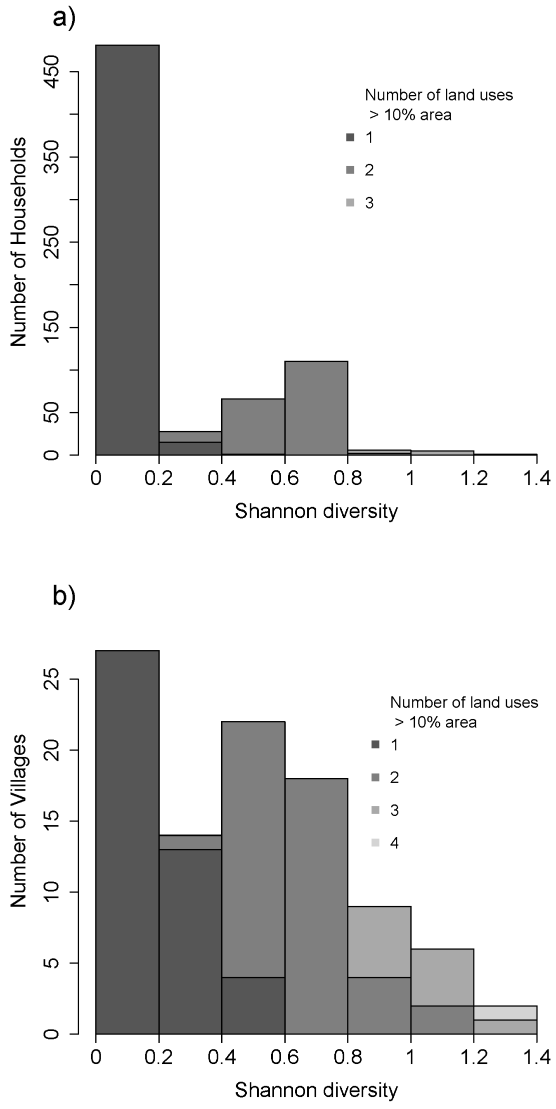

Figure 5.3: Categorization of households (a) and villages (b)using Shannon diversity

Note: Number of smallholder households (a) and villages (b) that fall into different categories of Shannon diversity (Magurran, 1988), an inverse measure of specialization. The number of land-use types with a minimum share of 10% of the total cultivated area per household or village, respectively, is indicated in grey shades. Overall, there are more households and more villages that specialize on one or two crops than households or villages that grow a more diverse portfolio of crops. Specialization is much stronger at the household level (a) than at the village level (b).
Source: Own calculation.

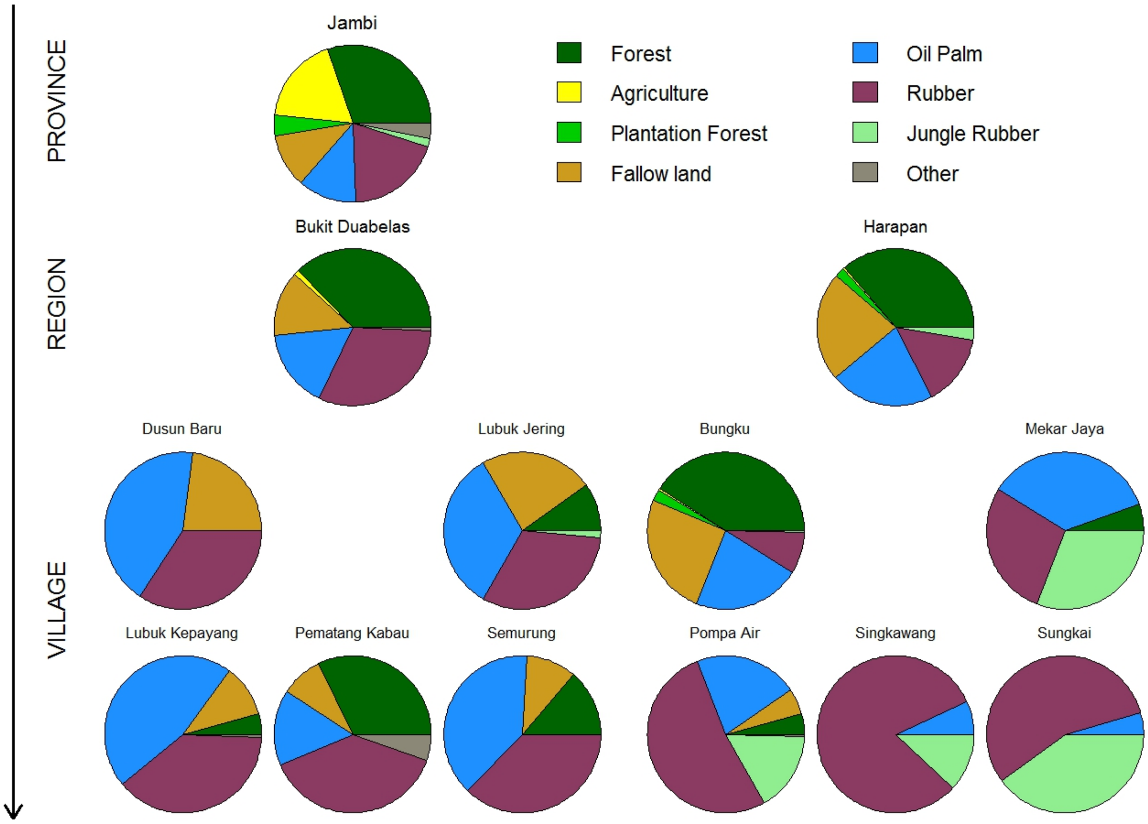

Figure 5.4: Land-use types in the province of Jambi in Indonesia

Note: Land-use types in the province of Jambi in Indonesia in 2011 show that specialization decreases from the fine to the broad scale, i.e. from the village level (five example villages per region, bottom rows) to the region level (two example regions Bukit Duabelas and Harapan, second row) to Jambi province (top row; see also map in Figure 5.2).

Source: Landsat and RapidEye images analysed according to Indonesian ministry guidelines (Ministry of Forestry, 2008).

Plantation age group	**Small plantations**, i.e. $\leq$ 50% percentile				**Large plantations**, i.e. $>$ 50% percentile			
	Mean yield[MT/ha]	**Mean factor costs/ha**		**Profit** [US$/ha]	**Mean yield** [MT/ha]	**Mean factor costs/ha**		**Profit** [US$/ha]
		Mean labour costs [US$/ha]	*Mean input costs* [US$/ha]			*Mean labour costs* [US$/ha]	*Mean input costs* [US$/ha]	
	N_S=244	N_S=241	N_S=244	N_S=241	N_L=135	N_L=124	N_L=135	N_L=124
1	0.23	184	114.85	-98.24	0.34	70.28	103.7	138.75
N_S=46, N_L=42	(1.07)	(271.56)	(121.17)	(930.2)	(1.87)	(91.07)	(98.09)	(1,631.33)
2	12.33	409.56	157.13	9,680.01	9.88	208.49	132.7	7,997.01
N_S=60, N_L=59	(9.66)	(302.89)	(-131.65)	(8,095.78)	(7.65)	(239.56)	(111.86)	(6,519.13)
3	16.96	425.9	181.18	13,809.95	17.3	292.64	203.81	14,597.71
N_S=87, N_L=30	(10.42)	(403.14)	(142.43)	(8,705.82)	(8.54)	(401.01)	(164.47)	(7,166.6)
4	20.43	377.65	269.59	16,720.72	14.56	181.01	94.88	12,100.11
N_S=51, N_L=4	(7.5)	(363.66)	(271.02)	(6,311.65)	(6.08)	(80.25)	(69.56)	(5,216.16)

Table 5.1: Oil palm cultivation and specialization in Jambi

Note: Yearly values on mean yield, mean factor costs (costs for labour and inputs), and mean profits of oil palm plots per plot size category for plantations in different age groups. The first age group contains plantation ages 0 to 3 years, because most trees start to produce harvestable fruits in the third year. Further age groups are group 2 (4-9 years), 3 (10-17 years), and 4 (18-23 years). Standard deviations are shown in parentheses. The number of observations is given per column and per age group for small (N_S) and large (N_L) plantations.
Source: Own calculation.

For the present study, we analyse the main land-use types in the area, i.e. oil palm, rubber, paddy, fruits, and vegetables. At the household level, we find very strong specialization (Figure 5.3 (a)). Most households specialize on a single crop and only very few grow two or three crops. Most cultivated land is owned by pure rubber farmers and by households that focus on rubber and oil palm plantations. Similarly, at the village level, there are more villages that specialize on one or two crops than villages with more land uses (Figure 5.3 (b)). However, specialization is much weaker at the village level than at the household level.

Hence, overall, specialization decreases from household via village to province level. In itself, this is not surprising, because villages are nested in regions which are nested in provinces, so that the level of specialization can only stay constant or decrease towards broader levels of scale. However, our conceptual framework predicts that well-functioning markets lead to the possibility of high (not necessarily maximal) levels of specialization at the broadest scales. When we interpret this finding in line with our conceptual framework, this would suggest that markets are not functioning well enough (yet) to allow for a greater specialization at broader spatial scales. At the same time, there is, as expected, already considerable specialization at the household and village levels which appears to be the optimal economic strategy for households (at least in the short term). Of course, leaving our conceptual framework aside, other causes than the absence of well-functioning markets could also explain these patterns, such as heterogeneous environmental conditions (as discussed in Hanspach et al., 2014) that prevent specialization at scales broader than the household, or that there are only sizeable internal but no large external economies of scale. Resilience and risk spreading strategies of individual farmers are less likely causes here, because we found very high specialization at the household level.

To investigate further to what extent economies of scale drive specialization in the Jambi case study, we take the example of oil palm cultivation and analyse both the production output and the production costs of oil palm farmers. Since output and factor costs differ across plantation age, we categorize the age in accordance to the yield cycle of oil palms into four age groups. For each age group we determine the median plot size and divide the plots into one group with smaller-than-median plot sizes and one group with larger-than-median plot sizes. As has been found in many studies (see, e.g. review by Binswanger et al., 1995, Ray, 1999), output per unit land is larger for small farms (Table 5.1). This is partly due to more intensive input use (especially labour, but also other inputs) on small plots (Table 5.1). It can also be due to more intensive and improved use of these inputs as the incentive problems afflicting large farms with hired labour are less prevalent here (see discussion in section 4.2). Production costs are investigated in the form of labour and input costs per hectare and year. Labour comprise operations such as land clearing, pits taking, seedling transportation, planting and replanting, manure and fertilizer application, chemical and manual weeding, harvesting, and pruning and marketing. Inputs costs refer to costs for seedlings, plant and animal waste, soil amendments, fertilizer, herbicides, machinery, and input and output transportation. Results for input and labour costs suggest lower costs for larger-sized plots (Table 5.1). This is especially apparent for labour costs in immature and young plantations (age groups 1 and 2). However, profits per hectare do not support cost advantages of larger farms in our study region. Only for the third age group the profit per hectare of larger plantations exceeds the profit of smaller plantations. Hence, our results for the Jambi case study suggest only weak evidence for economies of scale for larger production units.

Thus, as discussed in our conceptual framework, we can confirm the finding from many other countries that there are gains from specialization at the farm level but that this specialization does not inevitably lead to a consolidation of smallholder farms to ever-larger units; instead specialization is taking place among smallholders at the household and, as we have shown above, increasingly at broader scales such as the village level as well. However, such lower-level specialization could maintain regional diversity, and this could be valuable for sustainable development in multiple dimensions.

5.4.3 Policy influence on agricultural specialization in the Jambi case study

Two main policies affected the agricultural specialization process in Jambi fundamentally, the transmigration programs and the current master plan of the Indonesian government. The Indonesian government's transmigration program played a key role for the start and spread of oil palm cultivation in Jambi and the significant involvement of smallholder farmers (Gatto et al., 2014). The oil palm cultivation was organized in so-called nucleus-estate and smallholder (PIR-NES) schemes. The government support in terms of technical and financial assistance and land titles provided to the oil palm NES schemes was instrumental for increasing the specialization of transmigrant smallholders on oil palm.

The master plan for Indonesian Economic Development designated Jambi as part of the Sumatra Economic Corridor as a 'Center for Production and Processing of Natural Resources and as Nation's Energy Reserves' (Coordinating Ministry of Economic

Affairs, 2011, p. 46). The economic development strategy for the corridor focuses on three main economic activities: palm oil plantations, rubber plantations, and coal. To support the development of the main economic activities within the corridors the government will contribute around 10% the development cost. The remaining costs will be provided by state-owned enterprises, private sector, and through public private partnership (PPP) (Coordinating Ministry of Economic Affairs, 2011, p. 55). Furthermore, regulatory requirements, infrastructure improvements, technology development and research activities will be supported which will altogether lead to further specialization on palm oil and rubber plantations from the household to the province levels of scale.

Thus, policy has strongly supported and driven specialization directly through the economic development strategy in Jambi and indirectly through the provision of infrastructure and improvements in the functioning of markets. This has surely contributed to raising incomes in the region, but the associated specialization at increasingly broader scale is exacerbating precisely the trade-off that we have discussed above.

5.5 Conclusions: How can the trade-offs caused by specialization be addressed?

Specialization causes trade-offs between economic benefit and ecosystem functions that increase with the spatial scale of specialization which, in turn, can be influenced by market functioning. When testing this concept in a smallholder landscape in Indonesia, we indeed found differences in the level of specialization across scales, but with high specialization only at household and village levels and high diversification at broader levels of scale. Beyond market functioning, other drivers such as heterogeneous environmental conditions or only weak external economies of scale in our study area could have caused this cross-scale specialization pattern. However, smallholder farmers are not the only stakeholders influencing the specialization of agricultural productions, there are also large companies, international investors, conservation managers, and politicians; those actors have tended to promote specialization through the various policy actions and initiatives we have discussed above.

Since economic benefit and ecosystem functions and services are both legitimate concerns, a solution that satisfies all stakeholders is not straightforward. Such a solution must address the spatial distribution of agricultural production in the landscape, be consistent with policy goals, and should also consider long-term consequences that are not necessarily considered in specialization debates. The concept of mosaic landscapes with intensive plantations intermingled with both agroforestry zones and high conservation value areas (Koh et al., 2009, based on earlier ideas by Noss, 1983) might illustrate how agricultural production can be distributed in the landscape across scales with both economic and ecological benefits. Intensive plantations cover areas of high specialization and high ecological costs while agroforestry would reflect areas with a greater crop- and biodiversity. Mosaic landscapes would be especially promising in areas where both large companies and smallholders are present, as is the case in Jambi. Companies with their efficient work schemes would benefit from economies of scale, could engage in intensive plantations and set some land aside for conservation (Koh et al., 2009, Tscharntke et al., 2012). Smallholders may often prefer the less specialized and more diverse agroforestry systems, also due to cultural or historical backgrounds, livelihood dependencies or sentimental attachment, and especially if supported by policy incentives.

Policies should not directly promote specialization, but rather aim at improving incomes, lowering poverty, and safeguarding ecosystem services. This might or might not lead to increased specialization at different spatial scales. Certification programs such as the Roundtable on Sustainable Palm Oil may help to reconcile economic benefits with ecological functions by supporting sustainable production modes. These might include diversification to a certain degree and at some levels of scale. Furthermore, it has been shown that the promotion of landscape heterogeneity should be included in the certification schemes to the benefits of both agricultural production and biodiversity (Azhar et al., 2015). Payment for Ecosystem Service Schemes can also more directly support the maintenance of ecosystem services. Taking the example of oil palm, lowland plantation owners could be asked to compensate upland farmers beyond 600 m elevation where oil palm cannot grow for water-related ecosystem services. These services, such as the provisioning of drinking water and electrical power generation, might be compromised in the lowland oil-palm plantations otherwise. Such policies might be able to turn the specialization-driven ecological-economic trade-off into win-win situations at least for some spatial scales and over longer temporal scales.

Temporal scales and especially long-term consequences of specialization were not the focus of this paper, but could provide a worthwhile perspective for future research on the topic. Specialization may have long-term costs as it may destroy vital ecosystem services required for the long-term viability of crop production. Furthermore, diversification incentives may lead to a greater sustainability also in economic terms, e.g. via improved biological pest control or pollination services, when considering sufficiently long time horizons. This would then also be in the long-term interest of smallholder producers, so that the mostly small-scale specialization-driven trade-offs between economic benefit and ecosystem functions can be converted into win-win situations.

Appendices

Appendix A to Chapter 2

A questionnaire was constructed to systematically record information from the 70 studies selected to be included in the Appendix, Table A.1. The entries were recorded and cross verified by two of the three authors and a research assistant working with the authors. The data is available upon request from the authors. For more information on the data entry, please contact the corresponding author at the following email address: elisabeth.hettig@giga-hamburg.de.

Table A.1: Review questionnaire

Question number	**Question/Issue**	**Comments**
1	Who authored the paper?	List authors according to publication order
2	What are the academic backgrounds of the authors?	Here look at the authors academic qualifications and profiles
3	When was the paper published?	
4	In which (peer-reviewed) journal was the paper published?	
5	On which region (tropical or subtropical) the study focus?	
6	Which country is the focus of the study?	
7	What type of analysis is conducted in the study?	
8	What type of specific methodology is used by the authors in the study?	
9	What type of spatial analysis is used in the study?	
10	What type of data is collected in the study?	
11	When was the household data used in the study collected?	
12	What variable(s) do the authors use to identify land-use change?	
13	Which explanatory variables are found to have a significant impact on the land change variable identified in question 12?	Here only record the variable that are reported to significantly affect LUC
14	What are the main socio-economic drivers of land-use change identified by the authors?	Here only include the main drivers that are cited by the authors within the result and conclusion section
15	How can the drivers identified in questions 14 be classified to match our coding scheme?	Here classify the drivers in question 14 into the 7 main categories

Table A.2: Coding of reported land-use change drivers

Reported drivers in reviewed studies	**Categorization of the drivers for the meta-analysis**
Population density	Demography
Population pressure/growth	Demography
Migration	Demography
Agriculture output prices/Cash cropping	Markets
Agriculture input prices	Markets
Off-farm income/ Off-farm labour/ Off-farm wages	Markets
Hired labour	Markets
Credit (access)	Markets
Farm size	Endowments
Household size	Endowments
Household composition children	Endowments
Household composition gender	Endowments
Household composition labour	Endowments
Household education	Endowments
Social networks	Endowments
Technological progress	Technology
Land property rights	Institutions
Land tenure security	Institutions
(Key) policies	Key policies
Market access	Infrastructure
Infrastructure	Infrastructure

Table A.3: Coding of reported endowments

Reported endowments and characteristics in reviewed studies	**Categorization of endowments for the meta-analysis**
Farm size	Physical capital
Wealth and capital endowment	Physical capital
Income	Physical capital
Household size	Labour
Household children	Labour
Household labour	Labour
Household education	Human capital
Social networks	Social capital

Appendix B to Chapter 3

Table B.1: Summary statistics for variables used in the regression model, 2001-2013

Variables	Unit	Year	Average	Min	Max	Median	Std. Dev.	N
Dependent variables								
Cocoa yield	kg/hectare	2001	211.6	0.0	2933.3	93.0	328.9	176
		2006	349.0	0.0	1140.0	300.0	273.0	233
		2013	815.6	0.0	4800.0	592.9	822.3	234
Crop failure	% of yield	-	-	-	-	-	-	-
	lost	2006	3.0	0.0	75.0	0.0	10.7	233
		2013	17.4	0.0	90.0	0.0	24.1	234
Basic agricultural parameters								
Cocoa area	hectare	2001	1.4	0.25	8.3	1.0	1.3	176
		2006	1.4	0.25	8.0	1.0	1.2	233
		2013	1.5	0.25	15.0	1.0	1.6	234
Tree age	years	2001	3.8	1.0	20.0	3.0	3.2	166
		2006	6.3	0.3	22.0	5.0	4.1	233
		2013	11.2	0.3	36.0	10.0	6.3	234
Labour exp.	000 IDR/ha	2001	25.3	0	500.0	0	76.9	176
		2006	39.0	0	966.7	0	111.9	233
		2013	52.2	0	1982.3	0	250.1	234
No. of family workers	number	2001	3.0	0	8	3	1.6	176
		2006	2.5	0	7	2	1.3	233
		2013	1.9	0	6	2	1.2	233
Management practices								
Fertilizer exp.	000 IDR/ha	2001	29.5	0	710	0	110.5	176
		2006	17.5	0	433.7	0	60	233
		2013	69.3	0	1397.2	0	170.7	234
Use of herbicides	dummy	2001	0.1	0	1	0	0.3	176
	0=no	2006	0.4	0	1	0	0.5	233
	1=yes	2013	0.5	0	1	0	0.5	234
Manual weeding	dummy	2001	0.6	0	1	1	0.5	176
	0=no	2006	0.5	0	1	1	0.5	233
	1=yes	2013	0.5	0	1	1	0.5	234
Pruning	dummy	2001	0.7	0	1	1	0.5	176
	0=no	2006	0.9	0	1	1	0.3	233
	1=yes	2013	0.9	0	1	1	0.3	234
Removing pods	dummy	2001	0.9	0	1	1	0.3	176
	0=no	2006	0.8	0	1	1	0.3	233
	1=yes	2013	0.9	0	1	1	0.4	234
Harvest freq.	dummy	-	-	-	-	-	-	-
	0=less than 2 times/month	2006	0.7	0	1	1	0.5	210
	1=more than 2 times/month	2013	0.4	0	1	0	0.5	221
GERNAS	dummy	-	-	-	-	-	-	-
	0=no	-	-	-	-	-	-	-
	1=yes	2013	0.1	0	1	0	0.3	234
Pest incidence								
Pest	dummy	-	-	-	-	-	-	-
	0=no	2006	0.1	0	1	0	0.3	233
	1=yes	2013	0.3	0	1	0	0.5	234
Household characteristics								
Migrant status	dummy	2001	0.7	0	1	1	0.5	176
	0=migrant	2006	0.7	0	1	1	0.5	233
	1=local	2013	0.8	0	1	1	0.4	233
Primary Edu.	dummy	2001	0.6	0	1	1	0.5	176
	0=no	2006	0.5	0	1	1	0.5	233
	1=yes	2013	0.6	0	1	1	0.5	233
Secondary Edu.	dummy	2001	0.2	0	1	0	0.4	176
	0=no	2006	0.1	0	1	0	0.3	233
	1=yes	2013	0.1	0	1	0	0.3	233
Tertiary Edu.	dummy	2001	0.2	0	1	0	0.4	176
	0=no	2006	0.2	0	1	0	0.4	233
	1=yes	2013	0.2	0	1	0	0.4	233
Assets	000 IDR	2001	4321.1	15.0	58050.0	1025.0	7775.1	175
	000 IDR	2006	3555.0	3.7	97473.6	68.1	9264.0	232
	000 IDR	2013	6820.0	3.1	331381.9	2698.4	24533.8	231

Source: Authors' calculation based on STORMA and EFForTS data.

Table B.2: Robustness check: Inclusion of zero yields, determinants of cocoa productivity (pooled OLS and FE model, 2001-2013)

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)	Cocoa yield (log)
Estimation	OLS	OLS	OLS	OLS	OLS	FE
Cocoa area (log)	0.020	-0.010	-0.053	-0.194**	-0.319***	-0.078
	(0.816)	(0.903)	(0.525)	(0.017)	(0.000)	(0.638)
Tree age	0.568***	0.458***	0.448***	0.238***	0.099**	0.370***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.014)	(0.000)
Tree age^2	-0.017***	-0.014***	-0.013***	-0.007***	-0.003**	-0.012***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.016)	(0.000)
Cocoa labour exp. (log)	0.040***	0.016	0.015	0.025**	0.015	-0.010
	(0.006)	(0.228)	(0.255)	(0.029)	(0.413)	(0.557)
Family workers (#)	0.047	0.018	0.012	0.050	0.028	0.000
	(0.329)	(0.689)	(0.798)	(0.235)	(0.647)	(0.996)
Fertilizer exp. (log)		0.018	0.009	0.008	0.007	0.038**
		(0.107)	(0.457)	(0.476)	(0.605)	(0.043)
Use of herbicides		0.501*	0.477*	1.090***	1.143***	0.422
		(0.061)	(0.078)	(0.002)	(0.003)	(0.171)
Manual weeding		0.218	0.223	0.797**	0.773**	0.090
		(0.413)	(0.408)	(0.025)	(0.034)	(0.773)
Pruning		1.496***	1.489***	1.590***	0.190	1.490***
		(0.000)	(0.000)	(0.000)	(0.429)	(0.000)
Removing pods		0.958***	0.963***	0.810***	0.482**	0.767***
		(0.000)	(0.000)	(0.002)	(0.048)	(0.010)
Migrant status			-0.240*	-0.256*	-0.522***	
			(0.074)	(0.080)	(0.003)	
Primary edu.			-0.065	0.251	0.652**	
			(0.700)	(0.156)	(0.025)	
Secondary edu.			-0.403*	-0.140	0.125	
			(0.093)	(0.579)	(0.715)	
Tertiary edu.			-0.244	0.314*	0.582**	
			(0.235)	(0.098)	(0.046)	
Assets (log)			0.030			
			(0.400)			
Lagged assets (log)				0.000	0.023	
				(0.992)	(0.556)	
Pest				-0.004	-0.019	
				(0.974)	(0.888)	
GERNAS					0.596***	
					(0.001)	
Harvest frequency					0.151	
					(0.256)	
Year = 2006	0.527**	0.436**	0.452**			0.805***
	(0.011)	(0.024)	(0.023)			(0.000)
Year = 2013	0.530**	0.416*	0.497**	0.273*		0.918***
	(0.035)	(0.071)	(0.032)	(0.091)		(0.005)
Constant	1.700***	0.014	0.197	1.056*	3.627***	0.505
	(0.000)	(0.965)	(0.634)	(0.073)	(0.000)	(0.205)
Observations	632	632	628	381	209	632
R-squared	0.447	0.551	0.553	0.464	0.307	0.524
Adj. R-squared	0.440	0.542	0.540	0.439	0.241	
Number of id						273
Within R-squared						0.524
Between R-squared						0.538

Note: Pval in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, year dummies included, cluster-robust standard errors. Households with a cocoa plantation of at least 0.25 hectare are included. Zero yields are included by adding 1 to yield before transforming into log.

Source: Authors' calculation based on STORMA and EFForTS data.

Appendix C to Chapter 4

C.1 Implementation details

The land-use change model is implemented in the open source modelling platform NetLogo 5.2.0. The model is still under further development. For questions please contact Jan Salecker: jsaleck@uni-goettingen.de.

C.2 Initialization

The most important parts of the initialization are the initial spatial distribution of the different land uses, the location of farming households and the ownership of fields. All these state variables are determined using a landscape generator (see section C.5) which was developed specifically for this purpose. The outputs of the landscape generator are different raster maps which are read into the land-use change model at the beginning of each simulation run. All raster maps used in the model have a 50m x 50m resolution. The following grid-based maps are used as inputs:

- Forest/nonforest patches
- Land-use types
- Roads
- Household home-base locations
- Field identity number
- Ownership of cells (connects households to fields)

Exemplary maps which were used for the initialization of the presented model runs are shown in Figure 4.1 in the main text.
Apart from these initial maps, the following state variables are initialized as follows:

- Initial household wealth is drawn from a log-normal distribution with parameters given in Table C.3 (see also section C.6). The resulting values for initial wealth are sorted and assigned to households in a way that households owning larger areas have a higher initial wealth.

Table C.1: List of initial values

Initialization	**Unit**	**Value**	**Justification**
Number of households	[-]	50	
Household area μ (log-normal distribution)	[ha]	1.02	Derived from household data
Household area σ	[ha]	0.91	Derived from household data
Field size μ (log-normal distribution)	[ha]	0.49	Derived from household data
Field size σ	[ha]	0.77	Derived from household data
Household wealth μ (log-normal distribution)	[USD]	7	Derived from household data
Household wealth σ	[USD]	1	Derived from household data
Household wealth scaling factor	[-]	10	Estimated
Household inefficiency factor μ (normal distribution)	[-]	1.0	
Household inefficiency factor σ	[-]	0.0	
Age range of oil palm plantations (uniform distribution)	[year]	[0,30]	Estimated from household data
Age range of rubber plantations (uniform distribution)	[year]	[0,40]	Estimated from household data
Fraction of agricultural area under oil palm and rubber	[-]	0.5:0.5	

- A factor for inefficiency is drawn for each household from a normal distribution. The inefficiency factor reduces potential yields due to lack of expertise or site-specific conditions (see Equation C.2).[2]
- The initial age of agricultural fields is drawn from a uniform distribution with typical age ranges of oil palm and rubber plantations (see Table C.1).
- The initial carbon contents of fields are set according to their initial ages (see Figure C.11).
- Initial prices for oil palm fresh fruit bunches (FFB) and rubber as given in Table C.2, (for details see section C.4.2.3).

Details on the initialization used for the simulation runs of this paper are given in section C.7, and initial values to variables are summarized in Table C.1; model parameters are presented in Table C.2 and Table C.3. Note that distributions are based on household survey data (Euler et al., 2015b).

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[2] In the current model version all households have maximal efficiency (inefficiency parameter δ of household i for land use l: $\delta_i, l = 1$).

C.3 Input data

The model uses maps which are produced by a landscape generator as external input for model initialization. Apart from that, the only external variables are the yield prices. Different price functions are implemented (see section C.4.2.3), two of which are used in simulations shown in this paper (see Section 4.3 in the main text).

C.4 Submodels

The dynamic land-use change model comprises two main submodels: the economic household submodel that models land-use decisions by rural households and the ecological submodel that simulates ecosystem functions on different spatial scales. In this section we describe the details of these submodels and their parametrization.

C.4.1 Household model

The economic household model consists of further submodels dealing with household production and capital accumulation (C.4.1.1) as well as the corresponding land-use change decisions (C.4.1.2 and C.4.1.3). In short, the economic household model includes the following processes (Figure 4.2 in the main text). At the beginning of each time step, household wealth is reduced by its planned consumption (box *Consumption I* in Figure 4.2). Each household then decides on land management (box *Land management* in Figure 4.2) including the decision on factor inputs and land-use change. This decision is based on the expected cash flows from different land-use options over a certain time horizon (e.g. 10 years).

We assume that households are credit constrained. This means that households might not be able to realize the most profitable land-use option, as they might, for example, not be able to mobilize the capital necessary for initial investment. Following the land-management decision, annual yields (box *Yield* in Figure 4.2) of all household cells are calculated. Yields are affected by the age of plantations, factor inputs and household inefficiency, reflecting inefficient knowledge and site-specific conditions. Given current output prices (*Output prices*) the realized annual revenue (*Revenue*) is derived. Given current factor prices (*Factor prices*), costs (*Costs*) for agricultural production are calculated and subtracted from the revenue, resulting in the annual cash flow (*Cash flow*) of the household. In the case of positive annual cash flow, a part of the cash flow is consumed (*Consumption II*). The households wealth (*Wealth/Savings*) is updated by adding the remaining cash flow and external income. The updated household wealth influences which land-use options are feasible for the household in the next time step.

C.4.1.1 Production function, cash flows and capital accumulation

For each household cell j we apply a Leontief production function (Diewert, 1971). This implies that factors cannot be substituted and production is determined by the input factor which is applied in the smallest relative amount. Thus, production is calculated as

$$\hat{y}_{j,l,n}(L, K, TI, \overline{LA}) = min \left\{ y_n^* \frac{L}{L_n^*}, y_n^* \frac{K}{K_n^*}, y_n^* \frac{TI}{TI_n^*}, y_n^* \frac{\overline{LA}}{\overline{\overline{LA}}} \right\} \tag{C.1}$$

with

$\hat{y}_{j,l,n}$: production [ton] from crop l of age n on cell j under the factor inputs labour L, capital K, technical inputs TI and land $\overline{LA}$

y_n^*: production [ton] of a plantation of age n on one cell with optimal factor inputs (see section C.4.2.1 for the derivation of the optimal production)

L_n^*: the optimal factor input of labour [hour] for a plantation of age n

K_n^*: the optimal capital stock [USD] for a plantation of age n

TI_n^*: the optimal factor input of technical input [USD] for a plantation of age n

$\overline{LA}$: Land [ha], which is fixed to the size of one cell.

The Leontief production function defines the potential production given a certain age of a plantation and certain levels of inputs (for oil palm plantations, yield is calculated in tons of fresh fruit bunches per hectare and year; rubber yield is calculated in tons of rubber per hectare and year). However, due to varying experience of farmers in the cultivation of different land uses, incomplete knowledge, e.g. about ideal timing of fertilization or harvesting, as well as variation in site-specific conditions, this potential production might not be realized by a household. We incorporate the gap between potential and realized yield by introducing an inefficiency factor $\delta_{i,l}$ for each household i and land-use type l. The realized production from cell j which is owned by household i is therefore

$$y_{j,l,n}(L, K, TI, \overline{LA}) := \delta_{i,l} \cdot \hat{y}_{j,l,n}(L, K, TI, \overline{LA}) \ . \tag{C.2}$$

Based on the assumption that input factors are the same for all cells belonging to one field, the production for a field consisting of m cells of crop l of age n is given by

$$yfield_{l,n} = y_{j,l,n}(mL, mK, mTI, m\overline{LA}) = m \cdot y_{j,l,n}(L, K, TI, \overline{LA}) \ . \tag{C.3}$$

The revenue [USD] from cell j in year t is

$$Rcell_{j,t} = y_{j,l,n_t}(L, K, TI, \overline{LA}) \cdot p_{l,t} \tag{C.4}$$

with
n_t: the age [year] of the plantation in cell j at time t
$p_{l,t}$: price [USD/ton] of the product of land use l at year t.

The total revenue [USD] from agricultural land use of household i in year t is thus given by

$$R_{i,t} = \sum_{household\ cells\ j} Rcell_{j,t}\ . \tag{C.5}$$

The net cash flow [USD] from cell j in year t is

$$\Pi cell_{j,t} = Rcell_{j,t} - rcost_{j,l,n_t}(L, K, TI, \overline{LA}) - icost_{j,l,n_t} \tag{C.6}$$

with
$rcost_{j,l,n_t}$: recurrent costs [USD] on cell j under crop l in year t, depending on factor inputs of labour L, capital K, technical inputs TI and land $\overline{LA}$
$icost_{j,l,n_t}$: investment costs on cell j for agricultural production of crop l in period t.

The net cash flow [USD] from agricultural land use for household i in year t is thus given by

$$\Pi_{i,t} = \sum_{household\ cells\ j} \Pi cell_{j,t}\ . \tag{C.7}$$

The recurrent costs for cell j are calculated as

$$rcost_{j,l,n_t}(L, K, TI, \overline{LA}) = \begin{cases} r_{K,t}K + r_{L,t}\overline{LA}\ , & \text{if } n_t < n_m \\ w_{l,t}L + r_{K,t}K + p_{TI,l,t}TI + r_{L,t}\overline{LA} & \text{if } n_t \geq n_m \end{cases} \tag{C.8}$$

with
n_t: the age of the plantation on cell j at time t
n_m: the maturation age of the plantation, i.e. the first year with non-zero yields
$r_{K,t}$: rental rate of capital in year t
K: the current capital stock [USD] on cell j
$r_{L,t}$: rental rate of land [USD/ha] in year t (independent of what crop is on the cell)

$w_{l,t}$: wage for one hour of work [USD/h] in crop l in year t
L: input of labour [hour] on cell j in year t
$p_{TI,l,t}$: price for one unit of technical input [USD/kg] in crop l at time t[3]
TI: technical input [kg] on cell j in year t.

We assume that investment costs occur only within the immature phase of a plantation life cycle, i.e. as long as yields are zero. The total investment costs $icost\_total_{j,l}$ for a plantation of crop l in one cell j are therefore

$$icost\_total_{j,l} = \sum_{k=0}^{n_m-1} icost_{j,l,k} \ . \tag{C.9}$$

These investment costs include non-recurrent costs, e.g. for buying seedlings, as well as all costs for labour and technical input in the immature phase. For establishing oil palms, for example, labour is needed for lining, the transportation of seedlings, and digging holes. Land is already owned by the household, i.e. part of its initial endowments, and we only consider the opportunity costs of holding this asset. During the immature period, the capital stock is built up and we assume that no further investment costs occur once positive yields are produced. From this point onwards all labour and input costs are classified as recurrent costs. We acknowledge that some of these recurrent costs could similarly be conceptualized as maintenance, i.e. reinvestment costs, but our simplification facilitates the modelling of the crop choice decision later on.

Each household cell j has a capital stock $K_{j,t}$, representing the resale value of the capital stock embodied in rubber trees or oil palms on the cell at time t (see Eq. (C.1) and (C.8)). The capital stock is calculated as the cumulative investment costs in this cell minus depreciation

$$K_{j,t} = (1 - d_l(n_t)) \cdot K_{j,t-1} + icost_{j,l,n_t} \tag{C.10}$$

with depreciation rate $d_l(n_t)$. The depreciation rate, which captures the natural productivity of the plantation, depends on the plantation age n_t: for young plantations, d is negative, for older ones positive. This is because productivity generally increases in young plantations and decreases in old plantations; the productivity inflection point

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[3] Both wages and prices for technical input as well as rental rates for capital and land can vary with time. However, in our current model version, we keep them fixed and therefore omit the index t in the remainder of the model description.

is crop-specific. The total capital stock of household i in year t is accordingly

$$Ktot_{i,t} = \sum_{household\ cells\ j} K_{j,t}\ . \tag{C.11}$$

C.4.1.2 Decision on land-use change and production

The decision on land management and production, i.e. land-use change and the corresponding factor inputs, is determined by the profitability of land-use options, as well as wealth (and consumption) of the household. Let $W_{i,t-1}$ be the wealth of household i at the end of year $t-1$, i.e. the wealth available at the beginning of year t. For simplicity we assume, that, apart from the profit-based component of household consumption, all expenditures occurring in year t need to be disbursed by the household, i.e. paid before the income from agricultural production and external sources in the year t is available. Household consumption is calculated in a two-step process, partly before and partly after net cash flow realization of that time step. The planned household consumption of household i, $C\_plan_{i,t}$ consists of a fixed base consumption $\bar{C}_i$ representing the subsistence level, and a variable additional consumption depending on the actual wealth $W_{i,t-1}$.

Thus the planned consumption of household i in year t is

$$C\_plan_{i,t} = \bar{C}_i + C_W \cdot W_{i,t-1} \tag{C.12}$$

with C_W the fraction of wealth that is additionally consumed.

The actually realized consumption $C_{i,t}$ can increase by a profit-based component, if a positive net cash flow in this year permits additional consumption (see Table C.3 for parameter values of consumption). Thus, after the calculation of the net cash flow $\Pi_{i,t}$, household consumption is updated according to

$$C_{i,t} = \begin{cases} C\_plan_{i,t} + C_\pi \cdot \Pi_{i,t} & \text{, if } \Pi_{i,t} > 0 \\ C\_plan_{i,t} & \text{, if } \Pi_{i,t} \leq 0\ . \end{cases} \tag{C.13}$$

The wealth after planned consumption is available to cover investment and recurrent costs of agricultural production. We define a minimum wealth level W_{min} that is always available to a household, assuming that the household can, if necessary, cover costs for consumption from a safety net (family, friends, etc. as a short-term credit).

Therefore, the available resources for factor inputs and land-use change in year t are

$$W_{i,temp} := \begin{cases} W_{i,t-1} - C\_plan_{i,t} & \text{, if } W_{i,t-1} - C\_plan_{i,t} \geq W_{min} \\ W_{min} & \text{, else .} \end{cases} \tag{C.14}$$

If the actual household wealth does not cover the planned consumption, the household temporarily takes up debts $D_{i,t,temp}$ of the amount

$$D_{i,t,temp} := C\_plan_{i,t} + W_{min} - W_{i,t-1} \ . \tag{C.15}$$

In each period t every household decides on management of its household fields after reducing the wealth by the annual household's planned consumption (see Eq. C.14). This choice includes the decisions on factor inputs and land-use changes, which are taken simultaneously. It depends on the available capital for agricultural production $W_{i,temp}$.

Since we consider two possible land-use types (oil palm and rubber plantation), there are three possible options for each household field: to continue the actual land use, to replant the actual land-use type or to change to the alternative land use. If a household has u fields, the number of possible options is thus 3^u. As the calculation of expected cash flows from different land-use options is the most time-consuming part of the model, we implemented two versions of this process: the 'all-fields'-option, which allows the full number of options, i.e. in principal a change of land use in all fields of a household within one year, and a 'one-field-per-year'-option in which each household can change only one field per year. The latter reduces the number from 3^u to $3u$.[4] From the set of all options, only those are potentially possible, for which total investment costs (i.e. investment costs from all household fields within the next three years) as well as unavoidable recurrent costs in the current year can be covered by the actual wealth $W_{i,temp}$ (see Eq. C.17) while not falling under the minimum wealth level.

Let o be an arbitrary option, p_k the fields of the household ($k = 1, ...g$) and let l_k be the intended land uses on these fields under option o. Let furthermore m_k be the field sizes (i.e. number of cells in the field). The discounted total investment costs under the option o within the next three years are

$$^{o}Itot_i := \sum_{household\ fields\ p_k} \left(m_{p_k} \cdot \sum_{n=0}^{2} icost_{j_{p_k}, l_{p_k}, n_t+n} \cdot (1+r)^n \right) , \tag{C.16}$$

---

[4] The option can be chosen on the GUI. For this paper, we apply the one-field-per-year option.

with j_{p_k} a representative cell of field p_k, l_{p_k} the intended land use on field p_k, n_t the age of field p_k at time t and discount rate r.

Therefore, if

$$W_{i,temp} \geq^o Itot_i + \underbrace{\sum_{household\ cells\ j} (r_K K^*_{n_t,j} + r_L \overline{LA})}_{\text{unavoidable recurrent costs}} + W_{min} \ , \tag{C.17}$$

option o can potentially be afforded by the household. This is a simplifying assumption as it neglects that a household could potentially cover the investment costs of the second and third year by the income in these years from other fields. If no option is affordable, the household chooses the 'no change' option, i.e. all land uses remain the same and no replanting takes place.

The following steps are executed for each affordable option with the goal to choose the most profitable one: in the current year t, investment costs due to the implementation of option o are

$$\sum_{household\ fields\ p_k} m_{p_k} \cdot icost_{j_{p_k},l_{p_k},n_t} \ . \tag{C.18}$$

Therefore, if option o is implemented, the remaining capital available for factor inputs in year t is

$$^oW_{i,rest} := W_{i,temp} - \sum_{household\ fields\ p_k} m_{p_k} \cdot icost_{j_{p_k},l_{p_k},n_t} \geq 0 \ . \tag{C.19}$$

If the remaining capital $^oW_{i,rest}$ is sufficient for optimal factor input on all fields, i.e. if

$$^oW_{i,rest} \geq \sum_{household\ fields\ p_k} m_{p_k} \cdot rcost_{j_{p_k},l_{p_k},n_t}(L^*_{n_t}, K^*_{n_t}, TI^*_{n_t}, \overline{LA}) \ , \tag{C.20}$$

and no additional external constraints are existent, the household will apply optimal factor inputs to maximize production and profit from agricultural land use.

If the remaining capital is not sufficient for optimal factor inputs, i.e.

$$^oW_{i,rest} < \sum_{household\ fields\ p_k} m_{p_k} \cdot rcost_{j_{p_k},l_{p_k},n_t}(L^*_{n_t}, K^*_{n_t}, TI^*_{n_t}, \overline{LA}) \ , \tag{C.21}$$

factor inputs are reduced (see section C.4.1.3). Net cash flow $^o\Pi_{i,t}$ under option o and actual factor inputs is calculated. The fictive household wealth under application of option o is updated to

$$^oW_{i,t} = W_{i,temp} +^o \Pi_{i,t} + \tilde{Y} \tag{C.22}$$

with external household income $\tilde{Y}$.

To decide which of the affordable options should be chosen by the household, we calculate the expected cash flow from agricultural use within a certain time horizon h for each potential option o. For this we also need to calculate the expected factor inputs during that time. As optimal factor inputs vary with plantation age and actual factor inputs depend on wealth, we need to simulate the wealth development of the household over the given time horizon. For this we assume, that within this period of h years no more land-use changes occur.

Prices for input, output and labour are assumed to stay constant within the considered time horizon and at the level of prices in period t. Also the external income is assumed to stay the same as in year t. Household consumption for each year is calculated based on the expected wealth in the respective year. Let ${}^{o}\Pi_{i,t}$,...,${}^{o}\Pi_{i,t+h}$ be the expected net cash flows from agricultural use under option o within the time horizon h. For each option o the discounted accumulated expected cash flow is calculated as

$$ {}^{o}\Pi\_expected_i := \sum_{j=0}^{h} \frac{{}^{o}\Pi_{i,t+j}}{(1+r)^j} \ , \tag{C.23} $$

with discount rate r. The option with the maximal expected cash flow is implemented then.

C.4.1.3 Reduction of factor inputs

In the case of Equation C.21 the household cannot afford optimal factor inputs if option o is implemented. Therefore, factor inputs need to be reduced. However, Equation C.17 assures that the unavoidable rental costs for capital and land can be covered as

$$ {}^{o}W_{i,rest} \geq \sum_{household\ cells\ j} (r_K K^*_{nt,j} + r_L \overline{LA}) + W_{min} \ . \tag{C.24} $$

We assume that costs for capital and land are fixed and only the input factors labour L and technical input TI can be reduced. The amount of available resources for factor input is

$$ {}^{o}W_{i,FI} :={}^{o} W_{i,rest} - \sum_{household\ cells\ j} (r_K K^*_{nt,j} + r_L \overline{LA}) \ . \tag{C.25} $$

To determine on which fields factor inputs are reduced, the marginal loss for a representative cell j_m of each household field m is calculated. Factor inputs are reduced on the fields with lowest marginal losses, until all remaining capital is used.

The production of one unit of output less involves less labour and technical input and thus reduces the costs by an amount of *cost_red*. Since we apply a Leontief production function, each unit of production in a plantation of age n involves factor inputs of L^*_n/y^*_n of labour and TI^*_n/y^*_n of technical input, where L^*_n and TI^*_n are the optimal factor inputs to produce the maximum output y^*_n in a plantation of age n. Therefore, the optimal factor input for the production of $y^*_n - 1$ output units on one cell is

$$\left(L^*_n - \frac{L^*_n}{y^*_n}, K^*_n, TI^*_n - \frac{TI^*_n}{y^*_n}, \overline{LA})\right) \ . \tag{C.26}$$

The cost reduction involved in producing one unit of output less on one cell is thus

$$\begin{aligned} cost\_red &= rcost(L^*_n, K^*_n, TI^*_n, \overline{LA}) - rcost\left(L^*_n - \frac{L^*_n}{y^*_n}, K^*_n, TI^*_n - \frac{TI^*_n}{y^*_n}, \overline{LA})\right) \\ &= w \cdot \frac{L^*_n}{y^*_n} + p_{TI} \cdot \frac{TI^*_n}{y^*_n} \end{aligned} \tag{C.27}$$

with

w: wage for one hour of work [USD/h]

p_{TI}: price for one unit of technical input [USD/kg].

The marginal loss (*mloss*) in net cash flow from cell j under land use l is thus

$$\begin{aligned} mloss &= \Pi cell_{j,t}(L^*_n, K^*_n, TI^*_n, \overline{LA}) - \Pi cell_{j,t}\left(L^*_n - \frac{L^*_n}{y^*_n}, K^*, TI^*_n - \frac{TI^*_n}{y^*_n}, \overline{LA}\right) \\ &= p_{l,t} - cost\_red \end{aligned} \tag{C.28}$$

with

$p_{l,t}$ the revenue for one unit of production (= price [USD/ton] of product of land use l in year t.). Those fields with high marginal losses should receive optimal factor input, if possible. Therefore factor inputs are determined starting with the field with the highest marginal loss.

Let p be the field with the highest marginal loss, m be the number of cells in p and n_p the age of the plantation in field p. If the remaining resources for factor inputs ${}^oW_{i,FI}$ cover the costs for optimal input of labour and technical input on field p, i.e.

$${}^oW_{i,FI} \geq m \cdot (wL^*_{n_p} + p_{TI}TI^*_{n_p}) \ , \tag{C.29}$$

this field will receive optimal factor input and ${}^oW_{i,FI}$ is reduced by these costs:

$${}^oW_{i,FI} :={}^o W_{i,FI} - m \cdot (wL^*_{n_p} + p_{TI}TI^*_{n_p}) \ . \tag{C.30}$$

This process is continued for the other household fields with decreasing marginal loss until the field is reached at which the remaining resources ${}^{o}W_{i,FI}$ are not sufficient any more to cover optimal factor inputs.

Let q be this field of size m_q and age n_q, where

$$
{}^{o}W_{i,FI} < m_q \cdot (wL^*_{n_q} + p_{TI}TI^*_{n_q}) \ . \tag{C.31}
$$

As each unit of production involves labour and technical input costs of

$$
w \cdot \frac{L^*_{n_q}}{y^*_{n_q}} + p_{TI} \cdot \frac{TI^*_{n_q}}{y^*_{n_q}} \ , \tag{C.32}
$$

the household can afford a production of

$$
f :=^{o} W_{i,FI} \Bigg/ \left(w \cdot \frac{L^*_{n_q}}{y^*_{n_q}} + p_{TI} \cdot \frac{TI^*_{n_q}}{y^*_{n_q}} \right) \tag{C.33}
$$

units. The factor inputs for labour and technical input on this field are thus

$$
f \cdot \frac{L^*_{n_q}}{y^*_{n_q}} \quad \text{and} \quad f \cdot \frac{TI^*_{n_q}}{y^*_{n_q}} \ . \tag{C.34}
$$

The remaining fields do not receive inputs of labour or technical inputs in this year. At the end of this step, factor inputs for each household cell are known. Thus the profit from land use under option o with these factor inputs can be calculated for each household cell and household wealth can be updated according to Equation C.22.

C.4.1.4 Implementation of the land management decision

Now it is clear which of the affordable options is implemented and also the factor inputs are known. Let o be the chosen option, then the unavoidable costs in this year are potential investment costs as well as the recurrent costs for capital and land

$$
{}^{o}costs_u := \sum_{household\ cell j} ({}^{o}icost_j + r_t K_j + r_{L,t}\overline{LA}). \tag{C.35}
$$

Similar to Equation C.14, these unavoidable costs are subtracted from the current wealth, respecting the minimum wealth level

$$
W_{i,temp2} := \begin{cases} W_{i,temp} -^{o} costs_u & \text{, if } W_{i,temp} -^{o} costs_u \geq W_{min} \\ W_{min} & \text{, else.} \end{cases} \tag{C.36}
$$

If the household needs to take up debts to assure the minimum wealth level, these debts amount to

$$D_{i,t,temp2} :=^{o} costs_{u} + W_{min} - W_{i,temp2} \ . \tag{C.37}$$

Finally, the factor inputs of labour and technical inputs under option o reduce the wealth

$$W_{i,temp3} := W_{i,temp2} - ({}^{o}cost_{L,t} +^{o} cost_{TI,t}) \ , \tag{C.38}$$

with

${}^{o}cost_{L,t}$ costs for labour in year t under option o,
${}^{o}cost_{TI,t}$ costs for technical inputs in year t under option o.

Any debts a household gets into in the current year, e.g. due to consumption or due to unavoidable costs (see Eq. C.15 and C.37), are added to the potentially remaining debts from the previous year, and if possible, paid-off at the end of the period, when cash flows are realized. Household debts in period t before paid-off are therefore

$$D_{i,t,temp3} := D_{i,t-1} + D_{i,t,temp} + D_{i,t,temp2} \tag{C.39}$$

with

$D_{i,t-1}$ debts after pay off in period $t-1$.

Now the cash flow from the realized option o as well as the external income are added to the household wealth and the cash flow dependent part of consumption is accounted for

$$W_{i,temp4} := \begin{cases} W_{i,temp3} + (1-\beta)^{o}\Pi_{i,t} + \tilde{Y}_i & \text{, if } {}^{o}\Pi_{i,t} > 0 \\ W_{i,temp3} +^{o} \Pi_{i,t} + \tilde{Y}_i & \text{, if } {}^{o}\Pi_{i,t} \leq 0 \end{cases} \tag{C.40}$$

with

${}^{o}\Pi_{i,t}$ the cash flow in this year,
$\tilde{Y}_i$: external income in year t,
β the cash flow dependent fraction of consumption (see Eq. C.13).

Finally, the household pays off debts but respects the minimum wealth level. Therefore the household wealth which is available for the next year is

$$W_{i,t} := \begin{cases} W_{i,temp4} - D_{i,temp3} & \text{, if } W_{i,temp4} - D_{i,temp3} > W_{min} \\ W_{min} & \text{, if } W_{i,temp4} - D_{i,temp3} \leq W_{min} \ . \end{cases} \tag{C.41}$$

The household debts are updated accordingly to

$$D_{i,t} := \begin{cases} 0 \ \text{ if, } W_{i,temp4} - D_{i,temp3} > W_{min} \\ D_{i,temp3} - (W_{i,temp4} - W_{min}) \ \ \text{, if } W_{i,temp4} - D_{i,temp3} \leq W_{min} \ . \end{cases} \tag{C.42}$$

Households which do not manage to pay back debts within a certain period, i.e. $D_{i,t} > 0$ for D_{max} consecutive years (see Table C.2), are assumed to be incapable of acting and are frozen in the model.

C.4.2 Parametrization of the household submodel

For the implementation of the Leontief production function, we consider the following economic functions: optimal production, optimal labour use, optimal amount of technical inputs, optimal capital stock, and the use of land. Apart from land, all economic functions depend on the age of the respective plantation. To derive these functions and their parameters we used data from a household survey in the province of Jambi, Sumatra (Euler et al., 2012, Faust et al., 2013). Jambi is the focus of the Collaborative Research Center EFForTS (Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)) which has started in 2012. Interdisciplinary research on social and economic dynamics has provided a household survey of 701 households, which include information such as households' land holdings, agricultural and non-agricultural activity, endowments and household composition (for more details see Krishna et al., 2014, Euler et al., 2015a,b, Krishna et al., 2015). The survey represents a random sample out of 40 villages which in return are randomly chosen out of 5 regencies within the province of Jambi. The respective sample sizes per village are chosen proportionally to village size.

Out of the household sample, we use information on the production of 246 oil palm farmers cultivating 385 oil palm fields and 579 rubber farmers cultivating 962 rubber fields. Drawing on the reported ages of plantations, the oil palm fields of oil palm farmers are between 0 and 23 years old and the rubber fields have an age between 0 and 45 years. This enables a data-based parametrization of the economic functions for these time spans. Since we do not assume a maximum plantation age in our model, we also need to extrapolate economic functions for plantation ages beyond the data. To derive the production function, we estimate optimal yield, labour and technical inputs. For the estimation of optimal yields we selected the 30% highest yielding fields per plantation age ($N = 105$ for oil palm and $N = 244$ for rubber) (see Figure C.1 (a) and (b)). Assuming that these fields are optimally managed, they were also used to derive model functions and parameters for optimal labour and technical input.

C.4.2.1 Production functions for oil palm and rubber

Optimal production

Yields of the 30% highest yielding oil palm and rubber fields is presented in Figure C.1 (a,b). As an estimation of the optimal, i.e. maximal potential fresh fruit bunch production over palm age, we derived a function which reproduces the bunch production of the process-based PALMSIM model, which was validated against 13 sites in Indonesia and Malaysia (Hoffmann et al., 2014, see Figure C.1 (c)). After the immature phase of three years, in which yield is zero, this function has a roughly exponential increasing phase, which is followed by a plateau and a decreasing yield phase. The applied function is

$$production_{oil\ palm}(x) = \begin{cases} 0 \text{ , if } x \leq 2 \\ p_{o1} \cdot exp(p_{o2} \cdot x) \text{ , if } 2 < x \leq 7 \\ p_{o3} \text{ , if } 7 < x \leq 11 \\ max\{0, p_{o4} \cdot x + p_{o5}\} \text{ , if } x > 11 \end{cases} \tag{C.43}$$

with parameters shown in Table C.2. As we do not assume a maximum plantation age in our model, this function is also used to extrapolate production for plantation ages beyond the data (see Figure C.1 (e)).

For rubber, we estimated the potential yield from our data and used a parabola which reflects the limited life span of tapped rubber trees. As we are interested in the maximal possible yields, we require rather an envelope function above the data than a fit. Therefore, we shift the fitted function upwards so that 95% of the data from high yielding fields are under the curve (Figure C.1 (d)). We fix the production of rubber in the first five years to zero. The resulting optimal production function for rubber is shown in Figure C.1 (f). The applied optimal production function for rubber is therefore

$$production_{rubber}(x) = \begin{cases} 0 \text{ , if } x \leq 4 \\ max\{0, p_{r1} \cdot x^2 + p_{r2} \cdot x + p_{r3}\} \text{ , if } x > 4 \end{cases} \tag{C.44}$$

with parameters shown in Table C.2.

Optimal labour input

To estimate optimal labour use we draw on the labour data from the same 30% highest

Table C.2: Parameters of the economic household model related to the Leontief production function and costs

Category	Land-use type	Parameter	Unit	Meaning	Value	Reference/Justification
Production	Oil palm	p_{o1}	[-]	Scaling (exponential growth phase)	0.3	
		p_{o2}	[-]	Exponent (exponential growth phase)	0.7	
		p_{o3}	[ton]	Plateau value (plateau phase)	40	Hoffmann et al. (2014)
		p_{o4}	[-]	Slope (decreasing phase)	−0.6	
		p_{o5}	[ton]	Intercept (decreasing phase)	46	
		p_o	[USD/ton]	Price fresh fruit bunches	90	Household data
	Rubber	p_{r1}	[-]	Quadratic parameter of parabola	−0.007	Household data
		p_{r2}	[-]	Linear parameter of parabola	0.3	Household data
		p_{r3}	[-]	Constant parameter of parabola	2.5	
		p_r	[USD/ton]	Price rubber	1100	Household data
Labour	Oil palm	l_{o1}	[y]	Breakpoint 1	5	
		l_{o2}	[year]	Breakpoint 2	7	
		l_{o3}	[year]	Breakpoint 3	25	
		l_{o4}	[h/year]	Slope segment 1	100	
		l_{o5}	[h/year]	Slope segment 2	−80	Household data
		l_{o6}	[h/year]	Slope segment 3	−0.8	
		l_{o7}	[h]	Intercept segment 1	−230	
		l_{o8}	[h]	Intercept segment 2	690	
		l_{o9}	[h]	Intercept segment 3	120	
		l_{o10}	[h]	Plateau value (old plantations)	1400	Calibrated
	Rubber	l_{r1}	[h/(ha year)]	Labour input (plantation age > 4)	700	Household data
	All land-use types l	w_l	[USD/h]	Wage	1.6	Household data
Technical input	Oil palm	t_{o1}	[kg/(ha year)]	Constant input mature phase	740	Household data
	Rubber	t_{r1}	[kg/(ha year)]	Constant input mature phase	150	Household data
	All land-use types l	p_{TI}	[USD/kg]	Price technical input	0.5	Household data
Capital	Oil palm	$icost\_total_o$	[USD/ha]	Investment costs immature phase m	[600 200 150]	Household data
		d_{o2}	[-]	Depreciation rate young plantations	−0.1	
		d_{o3}	[-]	Depreciation rate old plantations	0.1	Estimated
		c_{o4}	[year]	Age in which depreciation rate switches	10	
	Rubber	$icost\_total_r$	[USD/ha]	Investment costs immature phase m	[200 70 70 70 70]	Household data
		d_{r2}	[-]	Depreciation rate young plantations	−0.05	
		d_{r3}	[-]	Depreciation rate old plantations	0.05	Estimated
		c_{r4}	[year]	Age in which depreciation rate switches	15	
	All land-use types	r_K	[-]	Rental rate of capital	0.1	Estimated
Land	All land-use types l	r_L	[-]	Rental rate of land	0.1	Estimated
		p_L	[USD/ha]	Land price (in the model	750	Household data
Debts	All land-use types l	D_{max}	[-]	Number of consecutive years households in debt are frozen	5	Estimated

Table C.3: Parameters of the economic household model related to household wealth and consumption

Parameter	Unit	Meaning	Value
W_{min}	[USD]	Minimum wealth level	30
D_{max}	[year]	Maximum number of consecutive debt years	5
$\tilde{Y}$	[USD]	External annual household income (constant)	500
$\bar{C}$	[USD]	Base consumption (subsistence level)	1000
C_W	[-]	Consumption fraction of wealth	0.05
C_π	[-]	Consumption fraction of net cash flow	0.1

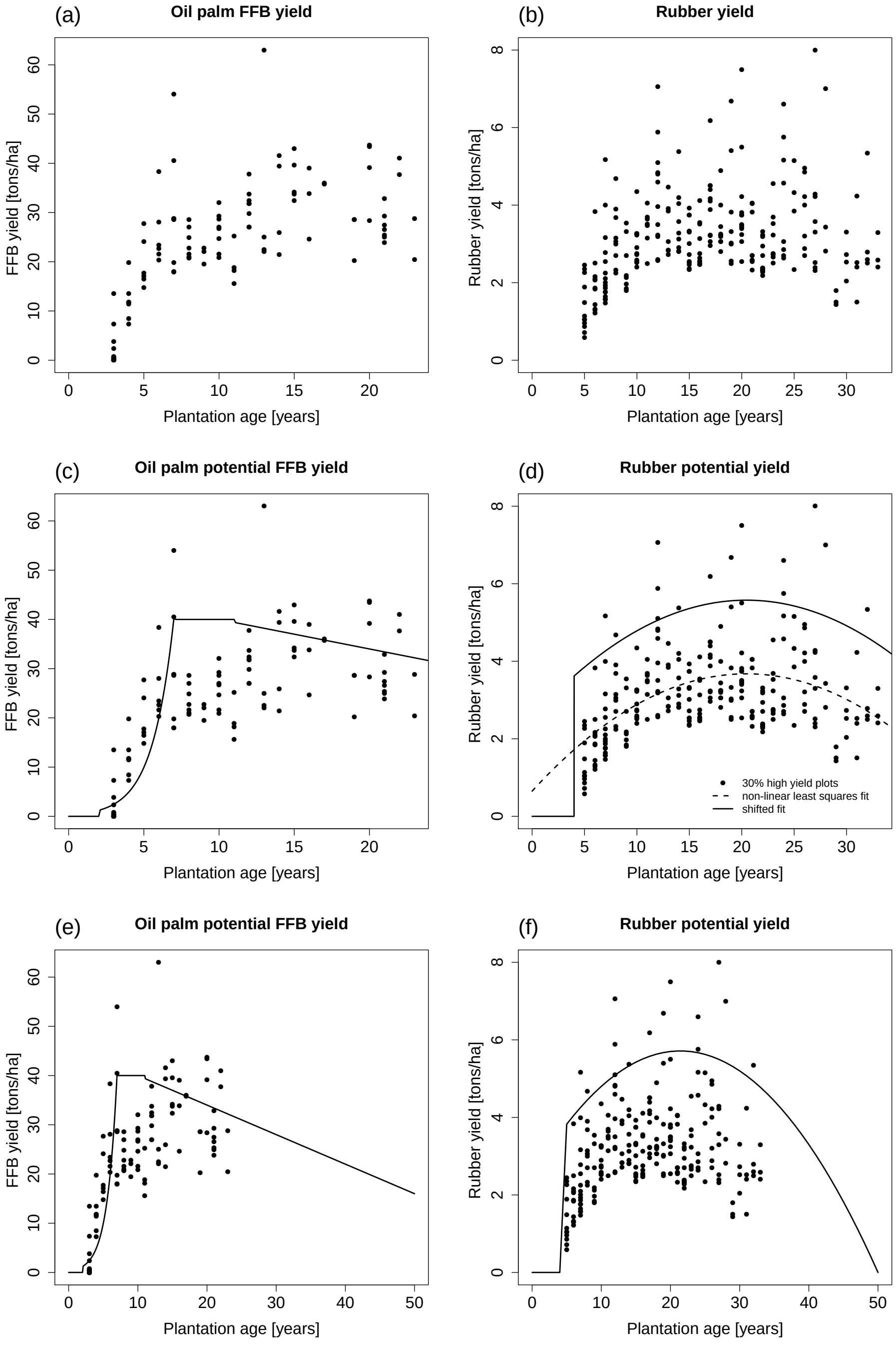

Figure C.1: Oil palm and rubber yield functions

Notes: (a) Production of oil palm fresh fruit bunches [ton/ha] of the 30% highest yielding fields per plantation age. (b) Rubber production [ton/ha] of the 30% highest yielding fields per plantation age. (c) Fit to oil palm data drawing on the bunch production used within the PALMSIM model. (d) Non-linear least square fit to rubber data (dotted line) and upwards shifted fit (95% of data under the curve). (e), (f) Optimal yield functions applied in the model (parameter values were rounded).

yielding fields per plantation age, but exclude data from the first three years for oil palm, and respectively the first five years for rubber, as we consider input of labour during this period as part of the investment. The data on labour comprise operations such as land clearing, pits taking, seedling transportation, planting and replanting, manure and fertilizer application, chemical and manual weeding, harvesting, pruning and marketing. Working hours per hectare are accumulated for each best performing field. The data are very scattered for both land uses (see Figure C.2 (a) and (b)). For oil palm an increase in labour after the plantation establishment phase followed by a slight decrease in labour input is apparent. We tested different relationships: a hump-shaped function

$$lab(x) = l_1 + \frac{x}{l_2} exp^{-\frac{x}{l_2}} \ , \tag{C.45}$$

and a segmented linear regression with one and two breakpoints (Figure C.2 (c)). An AIC comparison of the three fits resulted in the lowest AIC for the segmented linear regression with two breakpoints. We therefore apply this function in the model and set the optimal labour input for the first three years to zero. One critical aspect is the extrapolation of labour inputs beyond the age where data were available. Apparently one reason why oil palm plantations generally have a lifespan of $25 - 30$ years is that after that period, yields decrease and harvesting becomes very difficult as the trees reach a height in which the fruit bunches are difficult to harvest with the conventional pole method. Therefore, we assume a steep increase in labour costs when palms reach a height after which the conventional harvesting method with long sticks is not possible any more (see also Corley and Tinker (2008) p. 303 ff. and p. 318). As plantation cycles in our data end after about 25 years, we assume, that at this time, labour costs increase and result in plantations being unprofitable. We calibrate the amount of labour needed by assuming that at this point, the net cash flow is approximately zero, given optimal inputs and observed input and output prices.

The optimal labour input function is therefore

$$labour_{oilpalm}(x) = \begin{cases} 0 \ , \text{if } x \leq 2 \\ l_{o4} \cdot x + l_{o7} \ , \text{if } x > 2 \text{ and } x \leq l_{o1} \\ l_{o5} \cdot x + l_{o8} \ , \text{if } x > l_{o1} \text{ and } x \leq l_{o2} \\ l_{o6} \cdot x + l_{o9} \ , \text{if } x > l_{o2} \text{ and } x \leq l_{o3} \\ l_{o10} \ , \text{if } x > l_{o3} \end{cases} \tag{C.46}$$

with parameters shown in Table C.2 (see Figure C.2 (e)).

For rubber, we tested a constant, linear and hump-shaped function (see Eq.C.45), with the AIC suggesting the hump-shaped curve (Figure C.2 (d)). However, since there was no large difference between the fits and labour input in rubber plantations seems to be rather steady over the years (regular tapping, harvesting and weeding), we decided to choose the constant function for optimal labour input. Therefore the optimal labour input for rubber is

$$labour_{rubber}(x) = \begin{cases} 0 \text{ , if } x \leq 4 \\ l_{r1} \text{ , if } x > 4 \end{cases} \tag{C.47}$$

with parameter in Table C.2 (see also Figure C.2 (f)).

Optimal technical input

To estimate optimal technical input for both land uses, we use the data on technical inputs from the 30% highest yielding fields per plantation age (see Figure C.3 (a) and (b)). As for labour, technical input in the immature phase of the plantation are considered as part of the investment. The data on technical inputs refer to seedlings, plant and animal waste, soil amendments, fertilizer, herbicides, machinery and input and output transportation (measured in fuel). Except seedlings, quantities of inputs are generally measured in litres per hectare and are also accumulated for each best performing field. Seedlings are plausibly assumed to have a weight of 1 kilogram. The data on technical inputs are very scattered for both land uses. For oil palm, the data suggest an increase in technical inputs over time, while the inputs for rubber seem quite uniform.

For both land-use types we tested a linear and a constant relationship. The resulting fits are shown in Figure C.3 (c,d). For oil palm, although the AIC comparison suggests the linear increase, we decide for the constant relationship as the linear fit results in unrealistically high technical input when extrapolated for old plantations. Moreover, fertilizer recommendations for oil palm plantations typically suggest a two-level fertilization scheme and differentiate only between immature and mature plantation phase (Comte et al., 2012).

Figure C.3 (e) shows the applied relationship for optimal technical inputs, where inputs for the first three years are set to zero. The optimal technical input function is therefore

$$tinput_{oilpalm}(x) = \begin{cases} 0 \text{ , if } x \leq 2 \\ t_{o1} \text{ , if } x > 2 \end{cases} \tag{C.48}$$

with parameters shown in Table C.2.

For rubber we compared a linear regression with constant technical inputs and decide

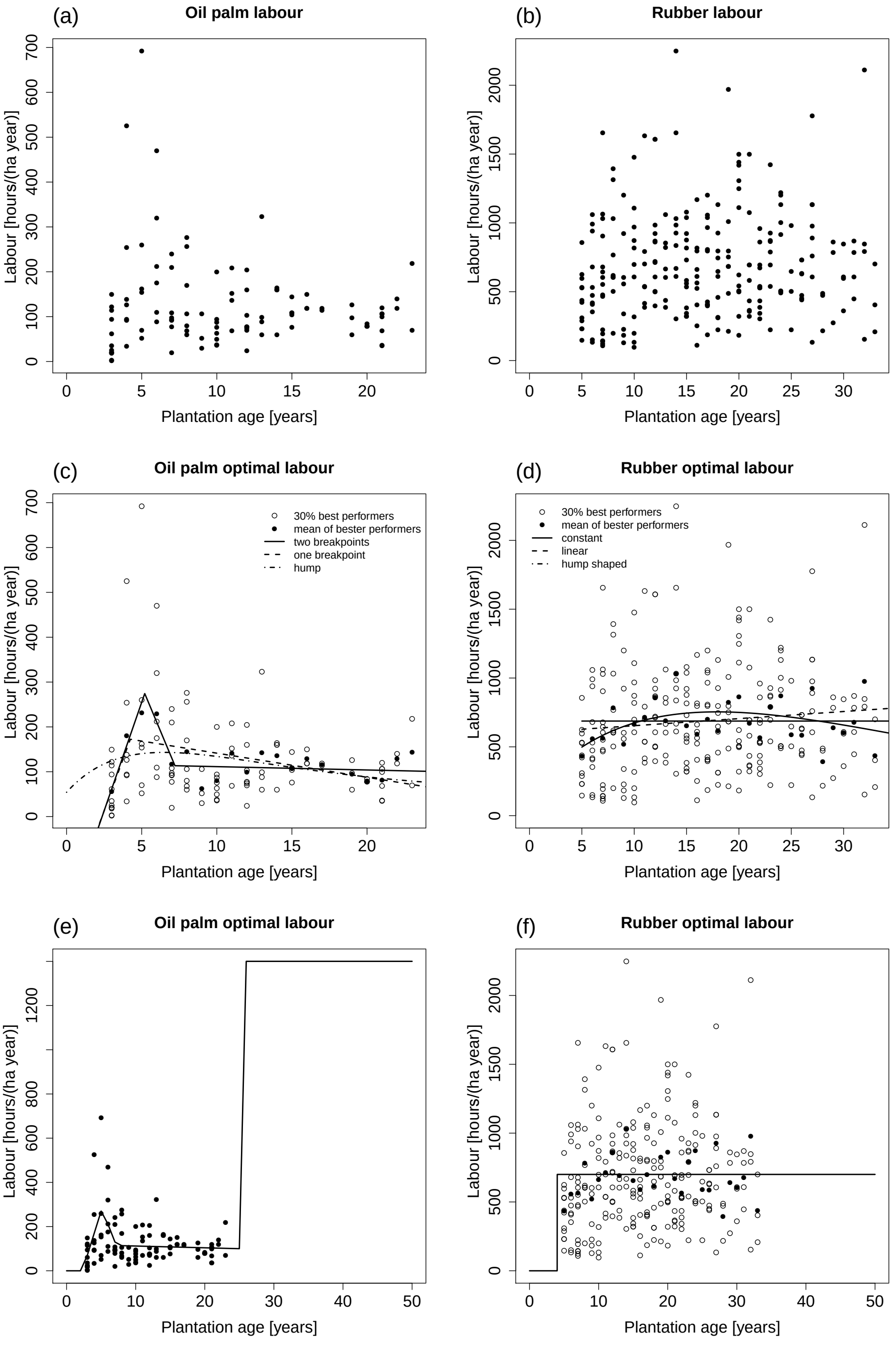

Figure C.2: Oil palm and rubber labour functions

Notes: (a) Labour input for oil palm [h/(ha year)] of the 30% highest production fields per plantation age. (b) Labour input for rubber [h/(ha year)] of the 30% highest production fields per plantation age. (c) Different fits to the data: Segmented linear regressions with one and two breakpoints and a hump-shaped function of the form Equation C.45. AIC results: 1257.5 (two breakpoints) < 1264.2 (one breakpoint) < 1271.5 (humped shape). (d) Different fits to the data: constant labour input, linear regression and a hump-shaped function of the form of equation C.45. AIC results: 3596.9 (hump shaped) < 3600.9 (linear) < 3601.4 (constant). (e), (f) Optimal labour function applied in the model (parameter values were rounded).

for the constant function which is also suggested by AIC. The applied relationship for optimal technical inputs in rubber is therefore

$$tinput_{rubber}(x) = \begin{cases} 0 \text{ , if } x \leq 4 \\ t_{r1} \text{ , if } x > 4 \end{cases} \tag{C.49}$$

with parameter in Table C.2 (see also Figure C.3 (f)).

Optimal capital input

The optimal capital input over time represents the capital stock of an oil palm or rubber plantation, i.e. the accumulated, discounted investment costs (see section C.4.1.1). During the immature period m of plantations we regard all labour costs and costs for technical inputs as investment costs. The accumulated value of costs for labour and technical inputs in this period are considered as total establishing costs of the plantation. All costs have been also derived from the household survey. As investment costs for labour we include costs for the operations land clearing, pits taking, seedling transportation, planting and replanting, manure and fertilizer application, chemical and manual weeding, harvesting, pruning and marketing. Due to the high variance within the data on labour use, all labour costs per operation are calculated in multiplying the median hours of work per operation with the mean value of wages per operation. We also include costs for out-contracted labour. The costs for technical inputs are calculated in multiplying the idiosyncratic prices of inputs with the respective quantities of inputs. The respective inputs are seedlings, plant and animal waste, soil amendments, fertilizer, herbicides, machinery and input and output transportation. The resulting investment costs during the immature phase are shown in Figure C.4 (a) and (b).

$$capstock_{oilpalm}(x) = \begin{cases} capstock_{oilpalm,x-1} * (1 + d_{o2}) + icost\_total_{o_{x,m}} \text{ , if } x \leq c_{o4} \\ capstock_{oilpalm,x-1} * (1 + d_{o3}) + icost\_total_{o_{x,m}} \text{ , if } x > c_{o4} \end{cases} \tag{C.50}$$

$$capstock_{rubber}(x) = \begin{cases} capstock_{rubber,x-1} * (1 + d_{r2}) + icost\_total_{r_{x,m}} \text{ , if } x \leq c_{r4} \\ capstock_{rubber,x-1} * (1 + d_{r3}) + icost\_total_{r_{x,m}} \text{ , if } x > c_{r4} \end{cases} \tag{C.51}$$

As described in section C.4.1.1, we assume for the calculation of the captial stock *capstock* a positive depreciation rate d_2, i.e. increasing capital stocks in young plantations, and afterwards a negative depreciation rate d_3, i.e. decreasing capital stocks (respective for oil palm o and rubber r). The age, in which the depreciation rate

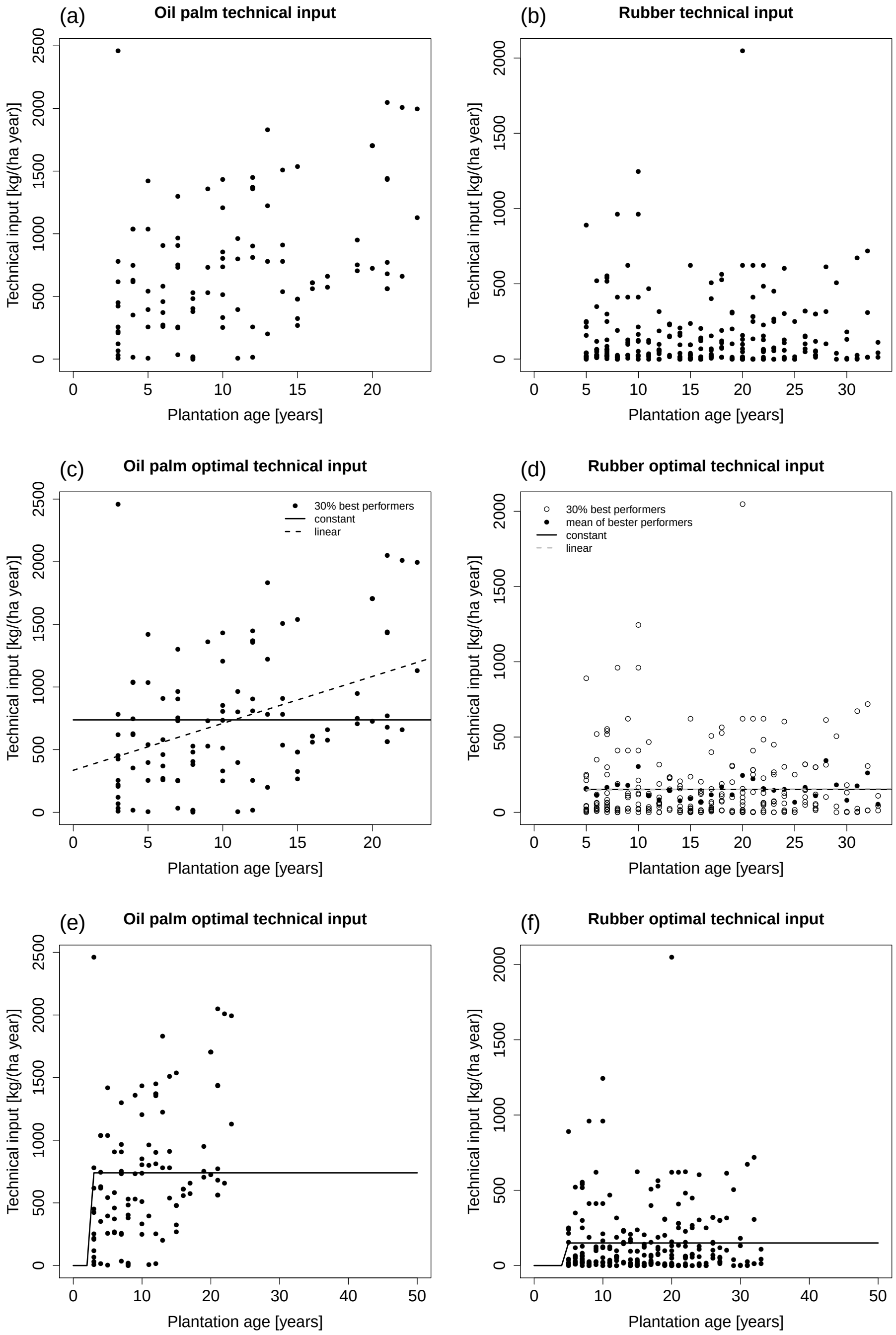

Figure C.3: Oil palm and rubber technical input functions

Notes: (a) Technical input in oil palm plantations [kg/(Ha year)] of the 30% highest production fields per plantation age. (b) Technical input in rubber plantations [kg/(ha year)] of the 30% highest production fields per plantation age.(c) Different fits: exponential increase (continuous line), linear (dashed) and power law (dotted). AIC comparison: 1600.2 (exponential) < 1601.3 (linear) < 1602.9 (power law). (d) Different fits: constant function (continuous line) and linear regression (dashed). AIC comparison: 3358.7 (constant) < 3360.7 (linear). (e), (f) Optimal technical input function applied in the model (parameter values were rounded).

switches is given by c_4. All parameters concerning capital costs in oil palm and rubber plantations are given in Table C.2. The resulting optimal capital inputs for the Leontief production function are shown in Figure C.4 (c) and (d).

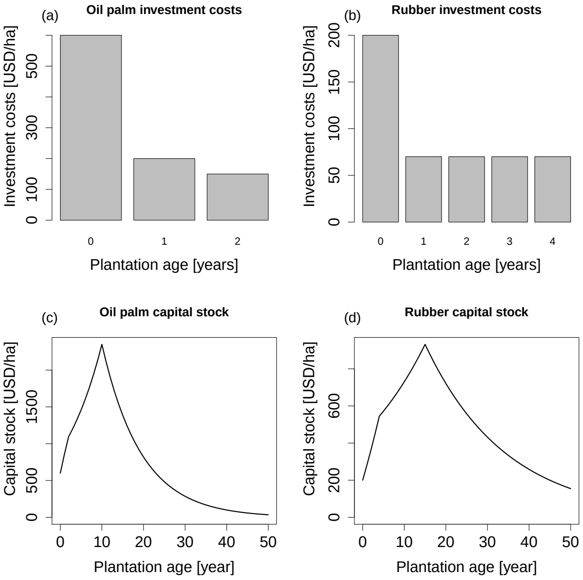

Figure C.4: Oil palm and rubber investment costs and capital stocks

Notes: (a) Investment costs [USD/ha] for the first three years of an oil palm plantation. (b) Investment costs [USD/ha] for the first five years of a rubber plantation. As there was no large difference between the years 1 and 4, we apply the average of these years. (c), (d) Capital stocks over time.

Optimal land input

Since we always calculate the Leontief production function based on a cell, the input for land is fixed to the cell size, in this case to 0.25 ha.

C.4.2.2 Costs, revenue & Cash flow

For the calculation of the different costs occurring in plantation agriculture over time, we use the household data to derive mean values for wages, prices of technical inputs and prices of land. We also include a price for capital, which captures the opportunity costs of capital referring to a rental rate of capital. Prices of fresh oil palm fruit bunches and rubber are also derived from the household survey (see Table C.2).

All data are calculated as mean values over all fields considering only the mature period after the first three or five years for oil palm and rubber, respectively. To receive the final mean value for wage measured in hours, we first calculate the average wage per day (per operation), which is divided by the average numbers of working

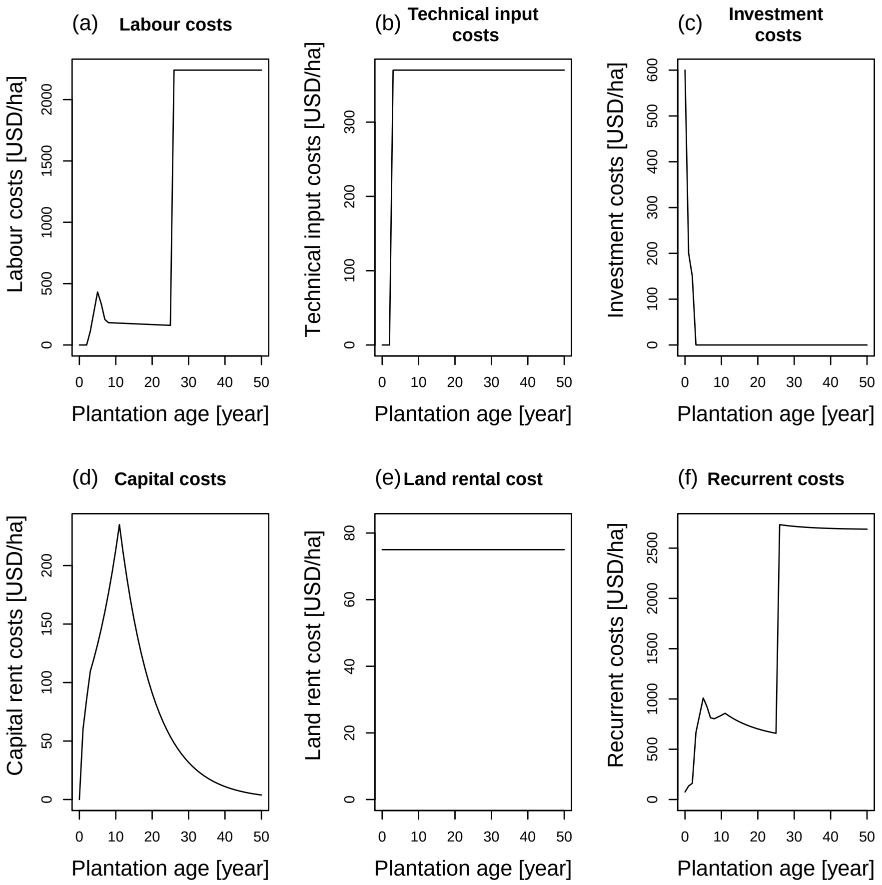

Figure C.5: Oil palm cost functions

Notes: Overview of the different cost functions for oil palm over plantation age under optimal production inputs. Recurrent costs are the sum of labour, technical input, capital and land rental costs.

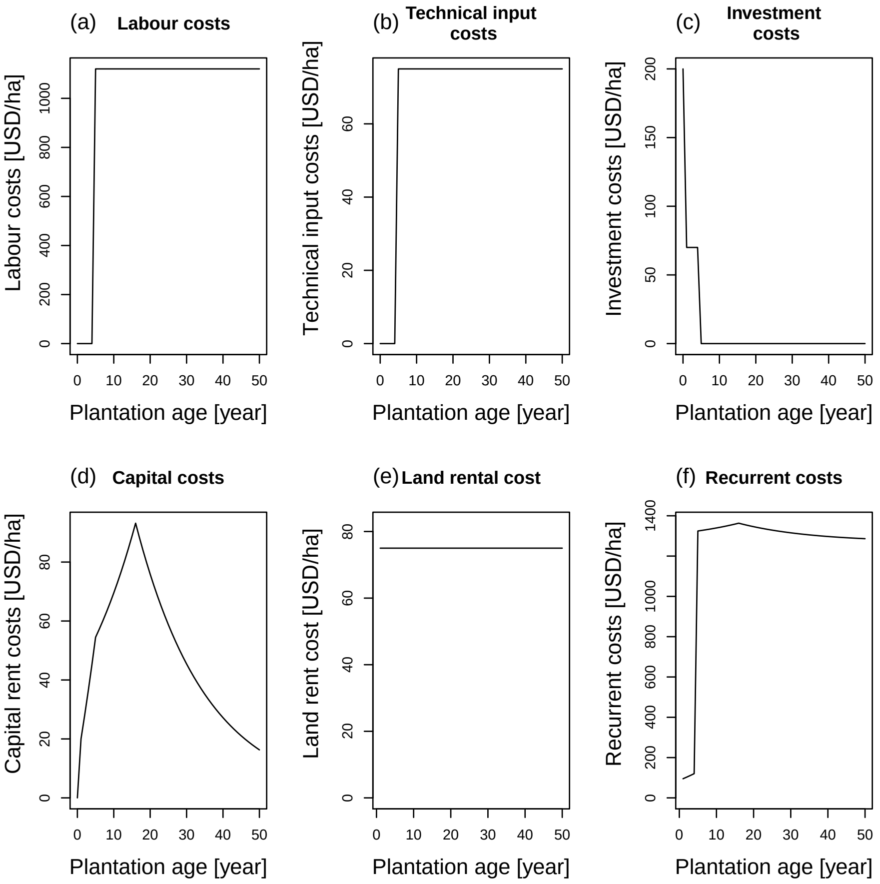

Figure C.6: Rubber cost functions

Notes: Overview of the different cost functions for rubber over plantation age under optimal production inputs. Recurrent costs are the sum of labour, technical input, capital and land rental costs.

hours (per operation). The kinds of operation we considered are land clearing, pits taking, seedling transport, replanting, manure and fertilizer application, chemical and manual weeding, harvesting, cutting leaves, marketing, intercultural operations and irrigation. From all mean wages per operations we took a final mean.

For calculating the overall mean price of technical inputs, we consider only the most applied and widely representative technical inputs used in the survey, which are fertilizer and herbicides. For each input the mean price and quantity is calculated. To generate a final price and quantity, we weight the final quantities of fertilizer and herbicides with the respective mean price and divide them by the sum of both quantities. The rental rates for capital (r_K) and land (r_l) (see Table C.2) are calculated as the average interest rate for informal and formal credits reported in the household survey. The price for land (p_l) captures the average price for land per hectare, which has been sold between 2009 to 2012 (see Table C.2). Applying theses factors to the optimal factor inputs derived in section C.4.2.1, we arrive at costs over the plantation lifetime presented in Figure C.5 (oil palm) and Figure C.6 (rubber). Applying the average farm gate prices as an example, we arrive at revenues and net cash flows shown in Figure C.7 (a,b) and Figure C.8 (a,b). Finally, Figure C.7 (c,d,e) and Figure C.8 (c,d,e) depict expected cash flows over the plantation lifetime (curves), as well as the expected cash flow for newly established plantations (straight lines). These expected cash flows are used in the model to compare different land-use change

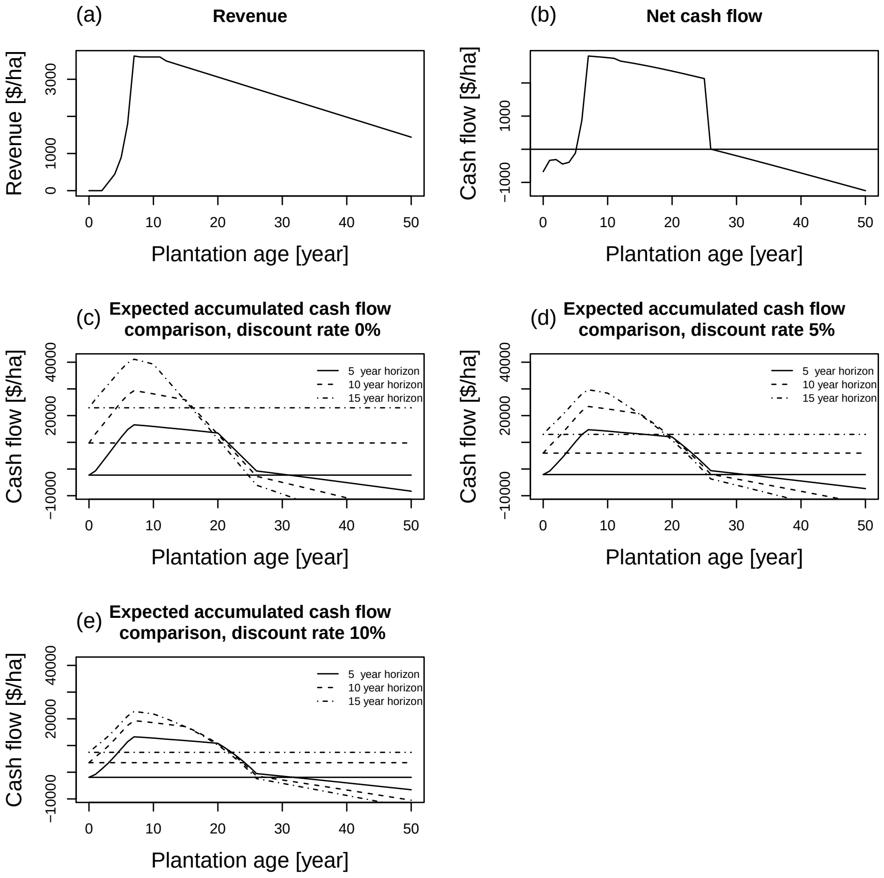

Figure C.7: Oil palm revenue, net cash flow and expected net cash flows

Notes: (a, b) Annual revenue and net cash flow of an oil palm plantation under optimal production inputs. (c), (d) and (e) Comparison of expected net cash flow of existing plantations (curves) with expected net cash flows from a newly established plantation (straight lines) under different planning horizons (5,10,15 years). Different fields represent different levels of discount rates (0, 0.05 and 0.1, respectively). The second intersection of each pair of lines marks the plantation age, in which replanting becomes the more profitable option.

options (see section C.4.1.2).

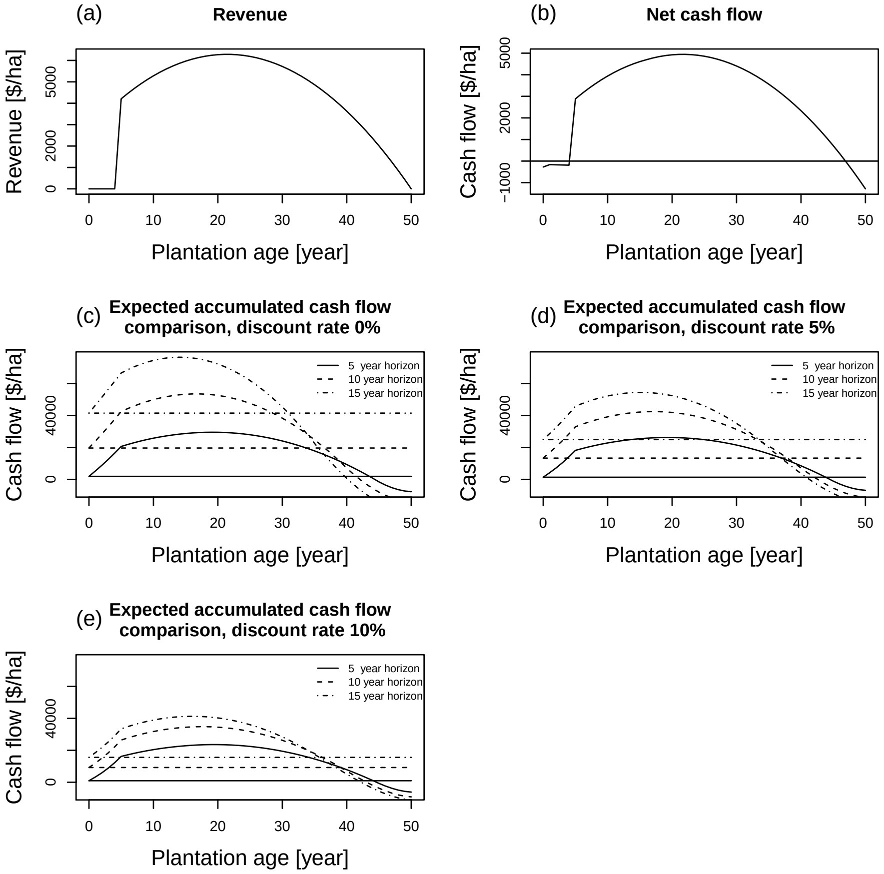

Figure C.8: Rubber revenue, net cash flow and expected net cash flows

Notes: (a, b) Annual revenue and net cash flow of a rubber plantation under optimal production inputs. (c), (d) and (e) Comparison of expected net cash flow of existing plantations (curves) with expected net cash flows from a newly established plantation (straight lines) under different planning horizons (5,10,15 years). Different fields represent different levels of discount rates (0, 0.05 and 0.1, respectively). The second intersection of each pair of lines marks the plantation age, in which replanting becomes the more profitable option.

The accumulated expected net cash flow for newly established plantations over different time horizons and different price scenarios is shown in Figure C.9. With the applied prices for oil palm fresh fruit bunches and rubber, rubber is the more profitable option, independent of the time horizon considered (Figure C.9 (a)). However, if the price relation between oil palm and rubber changes, e.g. with considerably lower prices for rubber, the profitability can depend on the considered time horizon (Figure C.9 (b)).

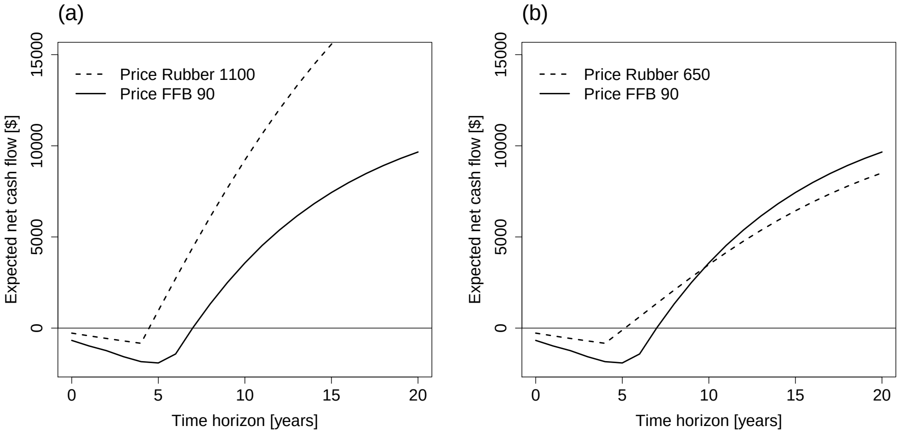

Figure C.9: Comparison of expected net cash flows for oil palm and rubber

Notes: Accumulated expected net cash flows with discount rate of 0.1 for newly established oil palm and rubber plantations under different time horizons. (a) Prices for fresh fruit bunches FFB and rubber as derived from household data. (b) Hypothetical lower price for rubber.

C.4.2.3 Price dynamics

All farmers are assumed to receive the same price for the same crop. These prices are related to world market prices of the respective crops, but additionally we used information on price transmission from survey data. Farm gate prices are considerably lower than world market prices mainly because of trade and transport margins. Average farm gate prices received by smallholders were 885 IDR/kg (about USD 0.09) of fresh fruit bunches for oil palm and 10412 IDR/kg (about USD 1.10) for rubber in the final quarter of 2012 (with an exchange rate of 9500 IDR/USD) (see Euler et al. (2012)). The world market price for rubber at that time was about 2.95 USD/kg; in April 2015 it had declined to 1.41 USD/kg. For palm oil, the prices of which cannot be readily compared to the prices for fresh fruit bunches also declined, but the decline was less pronounced; from 839 USD/metric ton in 10/2012 to 662 USD/metric ton in 04/2015 (The World Bank, 2016c). Different options for price dynamics are implemented in the model and can be chosen from the GUI. Prices can be kept constant, or variable around the initial prices with a specifiable range of variation ('price-fluctuation-%'). In the latter case, the annual price variation is drawn from a uniform distribution. Prices can also be chosen as correlated, again with a specifiable variation. In this case the price for the next year is calculated based on the current price with the variation again drawn from a uniform distribution. Fourth, prices can be chosen to follow a Gaussian random walk with crop-specific mean and standard

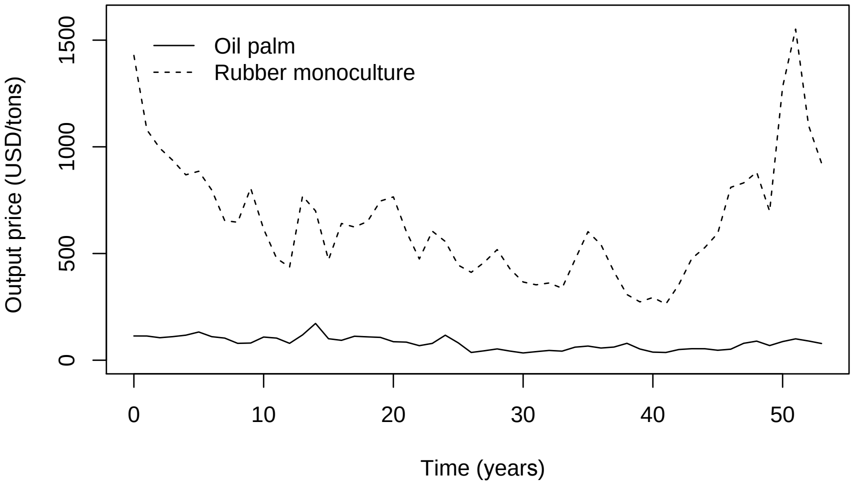

Figure C.10: Output price functions

Notes: Prices for rubber and oil palm for each simulation year when running the model with historical price trends. The values for years 0-50 are adjusted from The World Bank data for the corresponding years in the range 1960-2013.

deviation. For example, if p_n is the price per harvested ton fresh fruit bunches in year n, the price for the following year is determined as

$$p_{n+1} = p_n + r(\mu, \sigma) \tag{C.52}$$

where r is a normally distributed random variable with mean μ and standard deviation σ. While μ determines the expected slope of the price function, σ determines price volatility. Finally, prices can be set to follow trends based on nominal annual prices in the The World Bank Commodity Price Data, using 'Palm oil' for oil palm produce and 'Rubber, TSR20' for rubber produce. The prices are adjusted using a land-use-specific multiplication factor so that the prices for 2012 match the farm gate prices actually observed (and also used in the constant price scenario; see Table C.2 and Figure C.10).

The first analyses in this paper focus on basic model dynamics, so we apply the constant price option. In the second set of analyses we are interested in simulating real trends, and hence we choose the historical trends option.

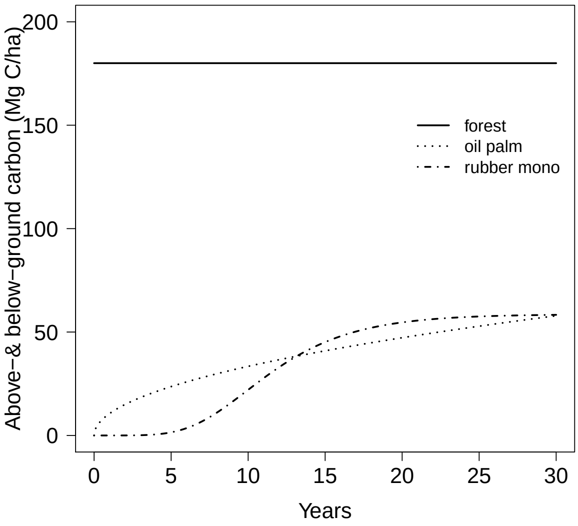

Figure C.11: Carbon stocks of different land-use types

C.4.3 Ecological model

This section presents the ecological model of the EFForTS-ABM.

C.4.3.1 Carbon storage

For the calculation of carbon stored in the vegetation of oil palm plantations, we use a function of Germer and Sauerborn (2008), that estimates aboveground biomass (AGB) of oil palm plantations as a function of plantation age

$$AGB_{oilpalm}(age)[Mg\ ha^{-1}] = 18.95 * age^{0.5} \ . \tag{C.53}$$

Assuming a carbon content of 41.3% and a constant root-shoot ratio of 0.35, i.e. 74% of total carbon is above ground and 26% is below ground (Syahrinudin, 2005), we arrive at a vegetative carbon stock of

$$carbon_{oilpalm}(age)[Mg\ ha^{-1}] = (18.95 * age^{0.5} \cdot 0.413) \cdot 1.35 \ . \tag{C.54}$$

For rubber monoculture we apply the function for rubber trees in the Mato Grosso, Brazil from Wauters et al. (2008)

$$carbon_{rubbermono}(age)[Mg\ ha^{-1}] = 58.609 * exp(-13.696 * exp(-0.264 * age)) \ . \tag{C.55}$$

For forest we assign a constant carbon content (we do not consider the option of converting plantations into forest yet). A mean carbon stock value is derived from estimations of total biomass from plot data (Kotowska et al., 2015), applying a carbon content of 0.47% (default value for insular Asian tropical rainforests (IPCC, 2006)):

$$carbon_{forest}[Mg\ ha^{-1}] = 389 \cdot 0.47 \approx 180\ . \qquad \text{(C.56)}$$

The resulting carbon stocks are shown in Figure C.11.

C.5 Landscape generator

The landscape generator is an extended version of the simple process-based landscape generator G-RaFFe (Pe'er et al., 2013), which originally simulates the extension of fields from roads and creates binary maps with forest- and non-forest cells. For our purpose we added different land uses and households as an intermediate level between fields and landscape. Households can own several fields of different sizes with different land uses. Household locations are always close to roads. For the creation of maps for model initialization, we used a section of a real road map from the Jambi region. Main input parameters for the landscape generator are the density of farming households, the distribution of household sizes, the distribution of field sizes, and the fraction of the different land uses. For a full description of the landscape generator please contact mail@kerstin-wiegand.de.

C.5.1 Parametrization of the landscape generator

Household sizes

We use data from a household survey (701 households, Euler et al. (2012), Faust et al. (2013)) to determine the distribution of household sizes (= total area available for agricultural use). We scaled the histogram of household sizes to $[0, 1]$ and fitted the density functions of a log-normal distribution to the data (see Fig. C.12) using maximum likelihood fitting (function *fitdistr* of the package MASS in the statistics software R). The resulting parameters for mean and standard deviation of household area are presented in Table C.1. Within the landscape generator, household sizes are determined by drawing a random number from the log-normal density function and rounding for the cell resolution (0.25 ha).

Field sizes

In the same manner as for household sizes, we use data from a household survey to determine the distribution of field sizes. We again fitted a log-normal distribution to

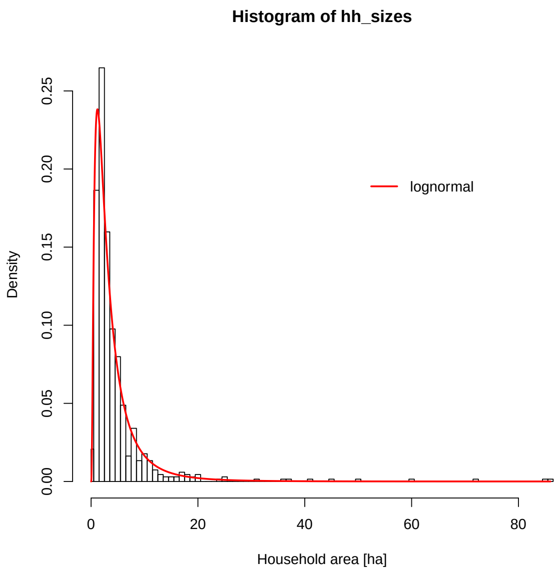

Figure C.12: Histogram of household sizes with maximum likelihood fit of the log-normal distribution

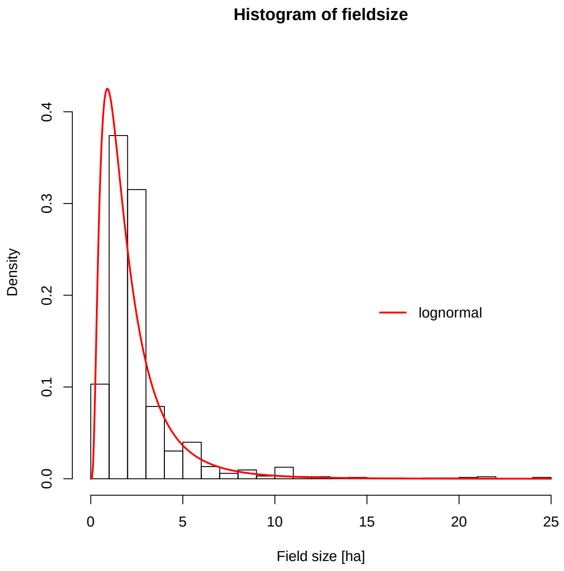

Figure C.13: Histogram of field sizes with maximum likelihood fit of the log-normal distribution

the data (see Fig. C.13). The resulting parameters for mean and standard deviation of field sizes are presented in Table C.1.

C.6 Initial household wealth

For the estimation of initial household wealth we use data on assets purchased by households between 2000 and 2012 from the household survey. Asset categories included for example cellphones, television, satellite dishes, motorbikes and cars, fridges and washing machines. Figure C.14 shows the histogram of the cumulative value of purchased assets to which we fitted a log-normal distribution. We use this distribution as a proxy for household wealth. Since these purchased assets represent only a fraction of household wealth, we multiply the drawn values with a scaling factor (in this case 10), to obtain the initial values for household wealth.

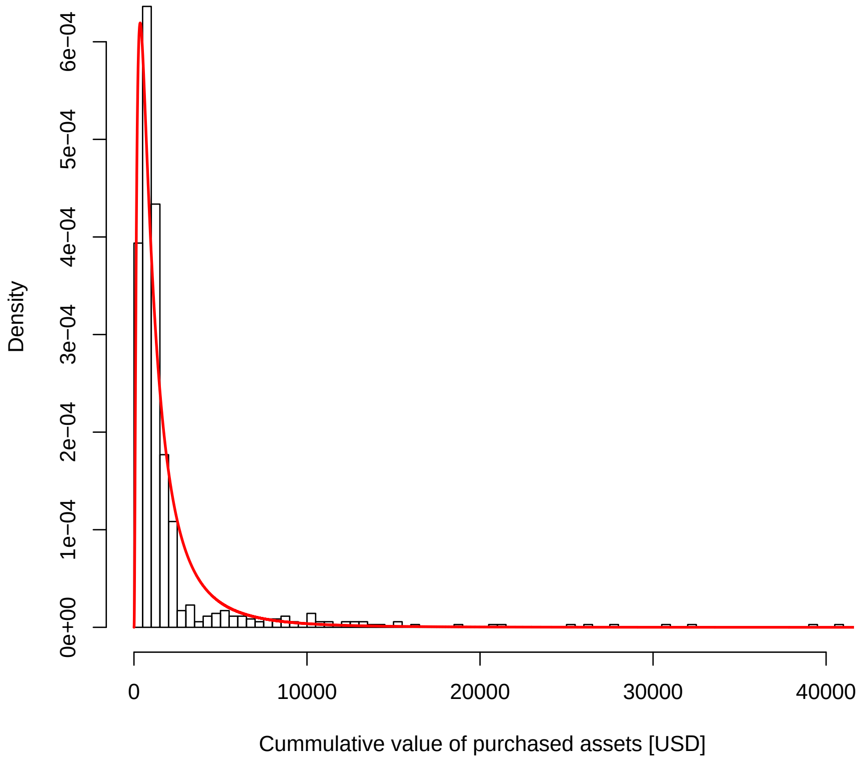

Figure C.14: Histogram of cumulative value of purchased assets by households between 2000 and 2012

C.7 Conversion of plantation plots under different land uses

Field studies show that a moderate proportion of oil palm was converted to other crops in the study area, while for rubber the respective conversion was much lower (overall, 14.47% vs. 0.99%; see Table C.4). The low proportion of rubber suggests that conversion of fields of rubber plantations to oil palm does not generally occur. Evidence from the field also indicates that during times of low rubber output prices, fields are left to fallow until prices are profitable again (V. Krisha, personal communication).

Table C.4: Plantation conversions

	Overall[a]		**1993-2002**		**2003-2012**	
	Oil palm	Rubber	Oil palm	Rubber	Oil palm	Rubber
No conversion	19.12	35.22***	25.60	40.52	18.25	46.56***
Other crops	**14.47**	0.99***	10.71	1.04	14.29	1.62***
Primary forest	13.95	3.54***	10.12	26.75	13.49	19.84*
Secondary forest (bush and grass lands)	33.07	27.38**	28.57	29.61	47.62	31.58***
No idea	19.38	3.87***	25.00	2.08	6.35	0.40***
Overall	100.00	100.00	100.00	100.00	100.00	100.00
Number of plots	*387*	*1008*	*168*	*385*	*126*	*247*

Notes: Share of plantation plots under different land uses at the time of acquisition.
[a] Includes land transformations and transactions before 1993 also.
***, **, *: The difference in the proportions of oil palm and village plots developed from a given type of land use is statistically significant at 0.10, 0.05 and 0.10 levels, respectively.
Source: Household survey data (Euler et al., 2012).

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Own contribution

The chapters of this cumulative dissertation are written in co-authorship.

The paper presented in chapter two *'Drivers of households' land use decisions: A critical review of micro-level studies in tropical regions'* has been written in co-authorship with Kacana Sipangule and Jann Lay. Elisabeth Hettig, Kacana Sipangule and Jann Lay designed and performed the research and wrote the paper.

The paper presented in chapter three *'Cash crops as a sustainable pathway out of poverty? Panel data evidence on heterogeneity from cocoa farmers in Sulawesi, Indonesia'* has been written in co-authorship with Katharina van Treeck, Martin Bruness, Jann Lay, Dewi Nur Asih and Nunung Nuryartono. The paper was conceptualized by Elisabeth Hettig, Jann Lay and Katharina van Treeck. Katharina van Treeck, Martin Bruness, Dewi Nur Asih collected the data in the field (with support by Nunung Nuryartono). Elisabeth Hettig and Katharina van Treeck did the data cleaning, panel structure and variable set up. Elisabeth Hettig and Katharina van Treeck did the literature review and developed the theoretical background. Elisabeth Hettig, Katharina van Treeck and Martin Bruness carried out the descriptive analyses. Elisabeth Hettig and Katharina van Treeck performed the empirical analyses. Elisabeth Hettig, Katharina van Treeck and Jann Lay contributed to writing the draft.

The paper presented in chapter four *'Towards an integrated ecological-economic land-use change model'* has been written in co-authorship with Claudia Dislich, Johannes Heinonen, Jann Lay, Katrin M. Meyer, Kerstin Wiegand and Surya Tarigan. Kerstin Wiegand, Katrin M. Meyer and Jann Lay designed the research; Claudia Dislich, Elisabeth Hettig, Johannes Heinonen, Jann Lay, Katrin M. Meyer, Kerstin Wiegand and Surya Tarigan performed the research; Claudia Dislich and Johannes Heinonen programmed the model code, Elisabeth Hettig and Claudia Dislich analysed the data; Claudia Dislich, Elisabeth Hettig and Johannes Heinonen wrote the paper.

The paper presented in chapter five *'Economic and ecological trade-offs of agricultural specialization at different spatial scales'* has been written in co-authorship together with Stephan Klasen, Katrin M. Meyer, Claudia Dislich, Michael Euler, Heiko Faust, Marcel Gatto, Dian N. Melati, Nengah Surati Jaya, Fenna Otten, César Pérez-Cruzado, Stefanie Steinebach, Suria Tarigan and Kerstin Wiegand. Stephan Klasen und Katrin M. Meyer designed the research, Marcel Gatto, Michael Euler and Negah Surati Jaya provided the data, Claudia Dislich, Elisabeth Hettig, Dian Melati and César Pérez-Cruzado analysed the data, Katrin M. Meyer, Stephan Klasen, Claudia Dislich, Elisabeth Hettig, Heiko Faust, Fenna Otten and Stefanie Steinebach wrote the paper.