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NATURAL RESOURCE MANAGEMENT
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My parents did not tell me how to live; they lived and let me watch them do it.

Clarence Budington Kelland

Siblings are friends given by nature.

Jean Baptiste Legouve

Fortunately, my wife realizes that husbands are not perfect.

Unknown

Whenever I make time for my children ... they teach me something.

Unknown

Dedication

To

- my parents—Don and Dolores Roshetko—for a lifelong example and inspiration of how people should live and treat others;
- my siblings—Tim, Lois, Debby, Tom, Mary and Ellen—we are blessed to have grown up together, always knowing that unconditional love and support was never in question; and
- my wife and children—Anna, Niko and Calli—for making life fun, forgiving my shortcomings, and teaching me things on a daily basis.

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SUMMARY

Smallholder agroforestry (tree farming) systems are prominent components of 'trees outside the forest'. They are primarily 'planted' systems that rehabilitate or reforest marginal lands, both private and public, where crop production is no longer biophysically or economically viable. While smallholder agroforestry systems vary greatly, most are tree-rich, species-rich systems that produce agricultural and tree products for both home use and market sale. The market orientation of smallholder systems has strengthened greatly over the last 10 to 20 years. Local, national and international markets are all supplied by smallholder agroforestry systems. Smallholder systems produce 90% of the global production of cacao, three-quarters of rubber, two-thirds of coffee, approximately 40% of oil palm and 25% of tea. Smallholder systems also provide valuable environmental services, including soil fertility replenishment, watershed protection, carbon sequestration, biodiversity conservation and land rehabilitation.

The hypothesis of this thesis is that smallholder tree-farming systems are viable agricultural and natural resources management systems that contribute significantly to global environmental goals and local economic objectives. The thesis supports the hypothesis by reviewing global and Asian trends of deforestation, human population growth, and demand for forest and tree products. The potential of smallholder tree-based systems to expand regional forest resources, produce forest products and services, and contribute to local livelihoods for rural communities is reviewed. Strategies to transform traditional smallholder systems into market-oriented systems to better serve environmental and economic goals are also assessed.

The five papers included in the thesis specifically address the capacity of smallholder systems to store carbon; the appropriateness of smallholder systems for carbon projects; the types of technical assistance and enabling conditions that facilitate the successful development of smallholder systems; how genetic diversity of smallholder systems supports adaptation to climate change; and the capacity of smallholder systems to simultaneously produce marketable timber and agricultural crops.

Most of the research presented in this thesis was conducted in Indonesia and the Philippines. However, the results and conclusions are applicable to the wide range of biophysical and socioeconomic conditions under which smallholder agroforestry systems are found in Southeast Asia and throughout the tropics. The discussion and assertions of the thesis are supported with relevant literature, including the candidate's past and ongoing research. The thesis concludes with recommendations for future work required to strengthen the recognition of smallholder tree-based systems as important contributors to global environmental goals and local economic objectives.

DANISH SUMMARY

Småskala agroforestry[1]-systemer udgør en stor del af ”træer udenfor skovene”. De er hovedsagelig plantede systemer, som genopretter eller genskaber skove på både private og offentlige marginale jordområder, hvor produktion af andre afgrøder ikke længere er biologisk eller økonomisk mulig. Selvom der er en stor variation i småskala agroforestry-systemer, er de fleste karakteriseret ved at have mange træer og arter og ved at producere landbrugs- og træprodukter til både eget forbrug og til salg. De sidste 10-20 år er systemerne i stigende grad blevet markedsorienterede. Lokale, nationale og internationale markeder bliver alle forsynet med produkter fra småskala agroforestry-systemer. Disse systemer producerer 90% af den globale produktion af kakao, 75% af gummiproduktionen, to tredjedele af kaffen, ca. 40% af palmeolien og 25% af teen. Småskala agroforestry systemer giver også vigtige miljøfordele, inklusive genoprettelse af jordens frugtbarhed, beskyttelse af vandressourcerne, lagring af CO_2, beskyttelse af biodiversiteten og genoprettelse af landskaber.

Denne afhandlings hypotese er, at småbønders agroforestry-systemer er levedygtige landbrugs- og naturforvaltningssystemer, som bidrager væsentligt til globale miljømæssige og lokale økonomiske mål. Afhandlingen understøtter hypotesen gennem en analyse af globale og asiatiske tendenser for afskovning, befolkningsudvikling og behovet for skov- og træprodukter. Potentialet for småskala agroforestry-systemer til at udvide de regionale skovressourcer, producere skovprodukter og andre goder samt bidrage til den lokale velfærd på landet bliver diskuteret. Strategier for at transformere traditionelle småskala-systemer til markedsorienterede systemer bliver også berørt.

De fem artikler inkluderet i afhandlingen fremhæver småskala agroforestry-systemers kapacitet til at binde kulstof, deres egnethed til carbonprojekter, hvilke typer af teknisk bistand og hvilke betingelser der fremmer en vellykket udvikling af småskala projekter, hvordan genetisk mangfoldighed i agroforestry-systemer understøtter tilpasning til klimaændringer, og systemernes kapacitet til på samme tid at producere salgbart tømmer og andre landbrugsafgrøder.

Det meste af forskningen præsenteret i denne afhandling er udført i Indonesien og på Filippinerne. Resultaterne og konklusionerne kan imidlertid anvendes indenfor det brede spektrum af naturgeografiske og socioøkonomiske betingelser hvori småskala agroforestry-systemer findes, både i Sydøstasien og i resten af troperne. Diskussionen og vurderingerne i afhandlingen under-

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[1] Det er vanskeligt at finde en dækkende oversættelse af ”smallholder agroforestry”, og på dansk anvendes den engelske vending ofte. Her benyttes ”småskala agroforestry”, selv om en mere direkte oversættelse ville være ”småbonde- agerskovbrug”.

støttes af relevant litteratur, inkluderende forfatterens tidligere og nuværende forskning. Afhandlingens konklusion indeholder anbefalinger til fremtidigt arbejde for at styrke anerkendelsen af småskala træ-baserede systemer som vigtige bidragsydere til opfyldelse af globale miljømæssige og lokale økonomiske mål.

LIST OF PUBLICATIONS

This thesis is based on the work presented in the five papers listed below. In the body of the thesis, each paper - also called a study - is referred to by corresponding roman numerals.

I. **Roshetko JM**, Delaney M, Hairiah K, Purnomosidhi P. 2002. Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage? *American Journal of Alternative Agriculture* 17:138–148.

II. **Roshetko JM**, Lasco RD, Delos Angeles MD. 2007. Smallholder agroforestry systems for carbon storage. *Mitigation and Adaptation Strategies for Global Change* 12:219–242.

III. Dawson IK, Vinceti B, Weber JC, Neufeldt H, Russell J, Lengkeek AG, Kalinganire A, Kindt R, Lillesø JB, **Roshetko** JM, Jamnadass R. 2011. Climate change and tree genetic resource management: maintaining and enhancing the productivity and value of smallholder tropical agroforestry landscapes. A review. *Agroforestry Systems* 81:67–78.

IV. **Roshetko JM**, Mulawarman, Purnomosidhi P. 2004. *Gmelina arborea* - a viable species for smallholder tree farming in Indonesia? *New Forests* 28:207–215.

V. Bertomeu M, **Roshetko JM**, Rahayu S. 2011. Optimum pruning strategies for reducing crop suppression in a *Gmelina*-maize smallholder agroforestry system in Claveria, Philippines. *Agroforestry Systems* 83:167–180.

Papers I, IV, and V are specific research studies; papers II and III are broad review studies. The papers are organized in this order for the following reasons. Paper I provides a detailed study of smallholder homegarden systems and their potential for carbon storage. Paper II expands this work, comparing the carbon storage capacity of multiple smallholder agroforestry systems and addresses other key issues related to smallholder systems as viable options for carbon projects. Paper III is an overview of climate change and genetic resources issues, and the relevance of smallholder agroforestry systems to these issues. Paper IV evaluates the suitability of *Gmelina arborea* as a smallholder timber crop in Indonesia. Paper V studies the issue further by identifying that pruning in smallholder *Gmelina*-maize systems can enhance productivity and profitability. *Gmelina arborea* was chosen for studies IV and V because it is a fast-growing timber species, widely grown by farmers and industry in South and Southeast Asia (Roshetko 2001a).

1. INTRODUCTION

The global human population reached 7 billion on or about 31 October 2011, only 12 years after reaching 6 billion, and doubling since 1968. With an annual growth rate of 75 million, the population is projected to be 9 billion by 2046 (Worldometers 2011). Human population growth, and a corresponding increase in wealth, exerts pressure to convert forests to agricultural, industrial, and residential uses. It also increases the demand for food, fuel, wood fibre and other tree products, further intensifying the production pressure on the surviving forest systems. Simultaneously, these forest systems are expected to provide a diverse array of environmental services. Additionally, the United Nations Millennium Development Goals call for considerable per capita growth for the eradication of extreme poverty and hungry, while ensuring environmental sustainability (United Nations 2012). For the last twenty-five years, an expressed global challenge has been to sustain the provision of forest products and services in ways that "meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). Sustainability in this sense does not mean keeping things the same, but rather requires the constant development of new ideas and options to meet current needs and future challenges (van Noordwijk et al. 2008). Agroforestry systems that farmers develop with limited resources (land, capital and other inputs) to meet their families' livelihoods' needs are a major opportunity to advance the sustainable production of forest products and services.

Agroforestry is a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels (Mead 2004). Valuable environmental services provided by agroforestry include soil fertility replenishment, water catchment protection, carbon sequestration, biodiversity conservation and land rehabilitation (Garrity 2004, Idol et al. 2011). Agroforestry systems can be defined as landuse systems in which woody perennials are deliberately integrated with agricultural crops, animals or both, in some form of spatial arrangement or temporal sequence (Huxley and van Houten 1997). These systems are increasingly recognized as important options for smallholder livelihoods, with neutral-to-positive environmental impacts (Leakey 2010). Recent research shows that species-diverse agroforestry systems enable farmers to adapt better to climate change; the fruit, nut and berry trees in the systems are more tolerant than annual crops and expand food production and increase food security (Nguyen et al 2012). The last twenty years have witnessed an intensification and expansion of research relevant to smallholder agroforestry systems (Leakey et al. 2012). Zomer et al. (2009) estimated that over 1.2 billion people across the world practise some form of agroforestry, with approximately 560 million living in farm agroforestry landscapes, that is, those with more than 10% tree cover. Farmers are the dominate land managers in the developing world, producing food, tree products and environmental services from small landholdings (Tscharntke et al. 2012, Jackson et al. 2010).

'Agroforestation' refers to the establishment of smallholder agroforestry systems and implies land rehabilitation through the establishment of tree-farming systems and intensification of land management (II). Farmers develop and manage such systems by nurturing trees on their farms, pasture lands and homesteads. These tree-farming systems are efficient agricultural and natural resources production systems. A prominent component of 'trees outside the forest', smallholder tree-farming systems are primarily 'planted' systems that rehabilitate or reforest marginal farmlands where agricultural crop production is no longer biophysically or economically viable. These systems can also be used to reclaim degraded public lands that have been abandoned. Smallholder tree-farming systems include forest-like systems where selected species are integrated in natural and secondary forests. In these systems, farmers cultivate trees to diversify production; generate commodities for home consumption; enhance income through market sales; and reduce risk. Smallholder systems tend to contain multiple species, produce multiple products and are found in both rural and peri-urban areas (Roshetko et al. 2008a). In some locations, these systems are a major economic source of forest and tree products. In Kerala, India, smallholder systems provided 83% of the State's wood production and up to 90% of its fuelwood production (FAO 1998). Sri Lankan smallholder systems produced 73% of the nation's timber and 80% of its fuelwood (Gunasena 1999). Products produced in smallholder systems in Indonesia included rattan, forest honey, sandalwood, gaharu, damar, benzoin, cinnamon, cloves, nutmeg, candlenut, rubber, cacao, coffee, oil palm and tea (Dove 2004, de Foresta et al. 2003, Garcia Fernandez 2004, Rohadi et al. 2003, Sunderlin et al. 2000; DGEC 2012). The importance of smallholder systems will only increase as the global forest resource continues to shrink and human populations expand. Yet, smallholder systems are excluded from formal definitions; are lost in statistics; and are often overlooked in the legal and institutional frameworks of agriculture and natural resources (van Noordwijk et al. 2008). Additionally, smallholder systems could be more productive and profitable if the common barriers that limited their development were addressed in a systematic way.

This introduction emphasizes the contribution of smallholder tree-farming systems to environmental sustainability and local livelihoods. It first reviews trends globally and in Asia of regional deforestation, human population growth, and demand for forest and tree products, with an emphasis on South and Southeast Asia. Following that review, common tree-farming systems are described and their potential to produce forest and tree products and services discussed. Emphasis is placed on the potential of smallholder tree-based systems to expand regional forest resources and produce forest products and services as well as representing a major contribution to local livelihoods for rural communities. The enabling conditions, institutional support and policy support that facilitate the establishment of successful smallholder systems are reviewed. Strategies to transform traditional smallholder systems towards market-oriented systems that better serve environmental and economic goals are also discussed.

1.1 Forest loss, environmental degradation and a loss of forest services

The rate of global forest loss over the last 20 years is alarming. For the period 1990–2000, global annual deforestation rate was 16 million hectare; for 2000–2010, it was 13 million hectare. This alarming rate, likely under-reports the damage sustained by the global forest resource as forest degradation is not included. Forest cover has been reduced to slightly more than 4 billion hectare or 30% of the global land area. The two countries with largest loss of forest area over the 20 years were Brazil and Indonesia, which respectively lost 2.8 million and 1.2 million hectare/year, representing 0.5% and 1.1% annual loss of their forest area (FAO 2010). These changes primarily represent the loss of tropical forests to other land uses: conversions from diverse tropical ecosystems to annual agricultural systems, monoculture tree plantations, and cleared (but unutilized) landscapes. Fortunately, the rate of forest loss in both countries and across the globe has declined, a welcomed trend, but the rate is still far from sustainable. The rate of deforestation is somewhat offset by planting and the natural expansion (regeneration) of forests. Total net change in global forest area for 1990–2000 was a decline of 8.3 million hectare/year and for 2000–2010 was a decline of 5.2 million hectare/year, the difference with the deforestation figures given above being found in areas planted or naturally regenerated (FAO 2011). Efforts to plant forests and trees have gained momentum, with planted forests now representing 7% of total global resources. In the last 10 years, the total global area of planted forests increased by 5 million hectare (FAO 2010).

In Asia, the deforestation–afforestation trend has been mixed. Based on FAO data for the 1990–2000 period, the Asia-Pacific region lost forest cover at a rate of 700,000 hectare/year. However, in the last 10 years the trend has been reversed, with regional forest cover increasing by 1.4 million hectare/year (FAO 2011, FAO 2010). The reversal in regional deforestation was largely due to successful tree planting programs in China, India, Vietnam and Thailand. In the last 20 years, China has planted an amazing 35.2 million hectare of forests, India 4.5 million, Vietnam 2.5 million and Thailand 1.3 million. Sub-regional and national performance has varied significantly. East Asia and South Asia both show gains in forest cover during the last 10 years, while Southeast Asia and the Pacific continue to lose forest cover (Table 1). Countries which have experienced significant forest loss since 1990 are Indonesia (2.2 million hectare), South Korea (1.3 million), Mongolia (891,000), North Korea (398,000), Cambodia (444,000), Malaysia (149,000) and Sri Lanka (147,000) (Table 2). In most countries, these losses represent the conversion of natural forests. However, Malaysia has lost only planted forests whereas North Korea and Sri Lanka have lost both natural and planted forests. As with the global trend, the rate of forest loss in Southeast Asia is declining, with the rate during 2000–2010 being less than half that of 1990–2000 (FAO 2011). The biggest turnaround has been in the last five years. As recently as 2007, data indicated an annual forest loss of 2.7 million hectare in South and Southeast Asia (WRI 2005), a rate which exceeded the dire projections of the 1997 Asia-Pacific Forest Sector Outlook (Blanchez 1997). Successful tree planting programs and the protection of natural forests from conversion have reversed that trend. Asian countries where the rate of forest loss is not declining are Mongolia and North Korea. In Indonesia, the rate of forest lost has greatly declined, but annual forest loss is still high (100,000 hectare of primary forests and 30,000 hectare of planted forests).

Table 1. *Forest areas in Asia and the Pacific, 1990–2010.*

	Area (1000 ha)			**Annual change (1000 ha)**		**Annual change %**	
Sub-region[1]	**1990**	**2000**	**2010**	**1990–2000**	**2000–2010**	**1990–2000**	**2000–2010**
East Asia	209,108	226,815	254,626	1762	2781	0.81	1.16
South Asia	78,163	78,098	80,039	-7	221	-0.01	0.28
SE Asia	247,260	223,045	214,063	-2422	-898	-1.03	-0.41
Pacific	198,744	198,381	191,384	-36	-700	-0.02	-0.36
Asia-Pacific	**733,364**	**726,339**	**740,383**	**-703**	**1404**	**-0.10**	**0.19**
World	**4,168,399**	**4,085,063**	**4,032,905**	**-8334**	**-5216**	**-0.20**	**-0.13**

1) **East Asia:** China, North Korea, Japan, Mongolia, South Korea
South Asia: Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
SE (Southeast) Asia: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Vietnam
Pacific: American Samoa, Australia, Cook Islands, Micronesia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru,, New Caledonia, New Zealand, Niue, Norfolk Island, Northern Marina Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands
Source: FAO 2011

Table 2. *Forest area of South and Southeast Asia by country, 1990–2010*[1]*.*

	Forest Area (1000 ha)			**Annual Change (1000 ha)**		**Annual Change %**	
	1990	**2000**	**2010**	**1990–2000**	**2000–2010**	**1990-2000**	**2000–2010**
South Asia							
Bangladesh	675	707	673	3.2	-3.4	0.22	-0.23
Bhutan	414	415	416	0.1	0.1	0.00	0.00
India	21,417	22,868	25,912	145.1	304.4	0.23	0.47
Maldives	0	0	0	0	0	0	0
Myanmar	3,586	3,888	4,180	30.2	29.2	0.10	0.09
Nepal	431	590	569	15.9	-2.1	0.45	-0.06
Pakistan	234	296	340	6.2	4.4	0.39	0.27
Sri Lanka	499	418	352	-8.1	-6.6	-0.40	-0.34
Southeast Asia							
Brunei	314	289	266	-2.5	-2.3	-0.58	-0.57
Cambodia	833	535	391	-29.8	-14.4	-0.28	-0.14
Indonesia	Na	52,942	50,785	Na	-215.7	Na	-0.22
Laos	1,493	1,589	1,714	9.6	12.5	0.06	0.08
Malaysia	5,776	5,479	5,627	-29.7	14.8	-0.14	0.07
Philippines	1,163	1,188	1,213	2.5	2.5	0.03	0.03
Singapore	2	2	2	0	0	0.00	0.00
Thailand	9,394	9,837	10,712	44.3	87.5	0.25	0.48
Timor-Leste	29	43	43	1.4	0	0.19	0.00
Vietnam	1,351	2,237	3,592	88.6	135.5	0.77	1.09

[1)] Forest area includes primary forests, other natural forests, and planted forests.
Source: FAO 2011

Besides helping to reverse the loss of forest cover, planted forests are an important and efficient source of wood and other tree products. In 2000, forest plantations accounted for approximately 5% of global forest cover, with industrial forest plantations accounting for only 3% but supplying 35% of global roundwood (FAO 2000a). By reducing production pressure, planted forests may have a tempering effect on the rate of natural forest loss. While established for diverse reasons, tree plantations generally have limited species diversity and frequently are monocultures of exotic species. Such systems are inferior to natural forests in supporting many forest services: biodiversity and habitat conservation, genetic conservation, ecological resilience, water and soil conservation, and carbon storage (Xu 2011, van Noordwijk et al. 2008, van Weerd and Snelder 2008, Roshetko et al. 2007a, Roshetko et al. 2007c, Murdiyarso et al. 2002, Lamb 1998, Michon and de Foresta 1995). Planting species inappropriate for site conditions, or planting any trees on a drought-stressed site (of either natural or anthropogenic origin), can negatively impact ecological services (Xu 2011).

Additionally, in many cases forest plantations are a main cause of natural forest conversion and loss (Xu 2011, Barr et al. 2004, ARD 2004, Forester et al. 2004, Sheng and Cannon 2004), thus being a direct cause of natural forest, biodiversity and carbon stock loss. This may be occurring in Vietnam, which has planted 2.5 million hectare of trees in the last 20 years, but lost 304,000 hectare of natural forests in the same period. As with commercial logging of natural forests, tree plantations provide less social and livelihoods' services to rural communities than community-managed forests and agroforestry systems (Tomich et al. 1998).

Moreover, forest plantations have not been equally successful across the region: efforts to promote plantations regularly fail to achieve the expected targets and results (Moestrup 1999, Lasco et al. 2001, Snelder and Lasco 2008, Barney 2008). This includes areas where timber is 'cleared' for plantation development, providing short-term economic returns for investors, without plantations being established (Barr et al. 2004, Sheng and Cannon 2004). Thus, forest plantations are a paradox. They are an important and efficient source of wood and non-wood products but are also a main cause of forest conversion and the loss of environmental services provided by these natural systems.

The decrease in natural forest area is associated with a loss of forest services, which are not provided in equal quality or quantity by a similar area of planted forests. This is alarming as most of the world's population resides in Asia (Worldometers 2011). Decreases in natural forest and accompanying accelerated shortages of forest products and services will affect both rural and urban populations throughout the region.

An important environmental service provided by forest is carbon storage and climate change mitigation. The Intergovernmental Panel on Climate Change's Third Assessment Report concluded that there was strong evidence that human activities have affected the world's climate (IPCC 2001). The rise in global temperatures has been attributed to emissions of greenhouse gasses, notably carbon dioxide. Indonesia is the third largest emitter of greenhouse gasses (WB et al. 2007, Lasco et al. 2004). Tropical forests have the largest potential to mitigate climate change amongst the world's forests through conservation of existing carbon pools (for example, reduced impact logging), expansion of carbon sinks (for example, reforestation, agroforestry), and substitution of wood products for fossil fuels (Brown et al. 1996, 2001). In tropical Asia, it is estimated that forestation, agroforestry, regeneration and avoided deforestation activities have the potential to sequester 7.50, 2.03, 3.8–7.7 and 3.3–5.8 Pg C respectively between 1995 and 2050 (Brown et al. 1996).

1.2 Population growth, economic development and demand for forest products

While the forest base will decrease, human populations and economic development will grow, increasing the demand for, and consumption of, forest and wood products throughout Asia and the rest of the world. In 1995, South and Southeast Asia were home to, respectively, 1,109 million (23% of the world's population) and 437 million (9%) (ADB 2004). By 2010, the human populations of the regions had grown to 1,598 million and 593 million, respectively, with their propositional share of the global population remaining steady (United Nations 2010). These rates of growth are similar to those projected for 2010 by an FAO social and economic study (Chipeta et al. 1998).

Current annual population growth rates for individual countries in South and Southeast Asia ranged between 0.7% in Thailand and Myanmar; 1.8% in Pakistan, Nepal, Bhutan and Brunei; 2.1% in Timor-Leste; and 3.5% in Singapore (United Nations 2010). Gross national income (GNI) per capita in the regions in 2005 varied from US $270 in Nepal through US $430 in Cambodia and Laos to US $2,720 in Thailand and US $4,970 in Malaysia (ADB 2006). Increases in GNI per capita between 2000 and 2005 varied from 17% in Nepal and Bhutan to 35% in Thailand, 62% in India and Vietnam, and125% in Indonesia (ADB 2006). The gross domestic products (GDP) of most South and Southeast Asian countries are estimated to have grown at annual rates of 5–8% between 2010 and 2012 (CIA 2012). At such growth rates, Chipeta et al. (1998) projected that the size of the middle classes of Asia's developing economies (excluding Japan) would double or triple in the first decade of the new millennium, numbering 0.8 to 1 billion people and forming a middle-class market equal to or surpassing that of the US and Europe combined (Naisbitt 1995 in Chipeta et al. 1998). Population growth and expansion of middle classes with greater disposable incomes will increase the demand and consumption of forest products, which in turn will be reflected in expanded global trade of these products.

According to the FAO (2005), major Asian forest products traded in international markets included industrial roundwood (59 million m^3 with 14% for export markets), wood-based panels (35 million m^3; 46% exports), sawnwood (32 million m^3; 25% exports), paper and paperboard (32 million m^3; 35% exports), and pulp for paper (16 million m^3; 17 % export). The production and trade of forest products vary greatly across countries: Indonesia is the greatest producer of industrial roundwood, wood-based panels and paper/paperboard (Table 3, based on 2002 data); India is the greatest producer of sawnwood; and Malaysia is the largest volume exporter of industrial roundwood.

The relationships between population and economic growth and the demand, consumption, and trade of forest products are complex, with various other factors playing significant roles as well. Developing a good overview of the subject requires comparing various, potentially confusing, data sources. Data for these factors for the same period (1990–2002) shows that Indonesia and Laos experienced enormous growth in population and per capita GNI, and realized net gains in terms of the financial value of their forest product trade (Table 3). Malaysia, Cambodia and Myanmar, while all experiencing population and per capita GNI growth, showed substantial decreases in net financial gain from forest product trade during the same period. The differences in trade trends can be explained in terms of access and availability (abundance or scarcity) of harvestable forest resources; the relative contribution and financial value of processed forest products; and changes in national economies. Most countries in the region experienced a decrease in forest product trade between 2000 and 2002 (Table 3). Bhutan and Vietnam even changed from forest-product exporters to forest-product importers. These changes can likewise be explained by an increasing financial value of imported forest products and a decreasing value of exported forest products, suggesting a mounting shortage of locally produced forest products (Table 3). The export of forest products in most South and Southeast Asian countries accounted for less than 1% of 2000–2002 GDP. The exceptions being Indonesia, with forest products exports accounting for 3.3% of GDP; Malaysia (3.2%); and Laos (2.6%) (WRI 2005).

Woodfuel (fuelwood and charcoal) production is the greatest among forest products in terms of volume in Asia (782 million m^3 in 2002 for countries in South and Southeast Asia, see Table 4). However, woodfuels are produced primarily for local consumption, with only 22,480 m^3 of woodfuels (8%) traded internationally (FAO 2005). During 1990–2002, the per capita use of woodfuels declined in countries with higher GNI levels: Indonesia, Malaysia, Philippines, Sri Lanka and Thailand. During the same period, the use of fuelwoods grew in the lower GNI countries: Bhutan, India, Laos and Myanmar (tables 3 and 4). Through 2005, relative trends in woodfuel consumption in those countries remained the same, with the exception of the Philippines where consumption increased. Overall fuelwood consumption slightly decreased in South and Southeast Asia (FAO 2010, FAO 2011). While fuelwood use varies both between and within Asian countries, it is a common and important energy source not only for rural and urban low-income households but also for higher income households (FAO 2003a).

Table 3. *Trends in population growth, per capita Gross National Income (GNI) and average net annual trade in forest products for various South and Southeast Asian countries.*

Country/region	**Population[1] (million)**		**Annual % population growth[1]**	**GNI/capita[a] (US $)**		**Average annual net trade in forest products [b, 4,,5] (US $,000)**	
	1990	**2005**	**2000–2005**	**2000[2]**	**2005[3]**	**1990–1992**	**2000–2002**
Bangladesh[#]	108.7	137.0	1.4	380	470	-17,581	-75,872
Bhutan[#]	0.7*	0.8	2.4	510	600*	7,119	-876
Cambodia*	8.6	13.8	1.9	290	430	41,705	7,374
India[#]	835.0	1107.0	1.7	450	730	-547,290	-865,449
Indonesia^	179.4	219.9	1.3	570	1280	3,170,812	3,909,903
Lao PDR*	4.1	5.6	1.4	290	430	33,951	45,114
Malaysia^	18.1	26.1	2.2	3390	4970	2,737,487	1,907,737
Myanmar*	40.8	55.4	2.0	n.a.	n.a.	291,461	231,529
Nepal[#]	18.1	25.3	2.3	230	270	-3,960	-1,514
Philippines^	60.9	85.2	2.1	1030	1320	-134,026	-495,568
Sri Lanka[#]	16.3	19.7	1.3	890	1160	-76,625	-86,884
Thailand*	55.8	64.8	0.8	2010	2720	-1,074,407	-301,270
Vietnam*	66.0	83.1	1.4	380	620	85,163	-117,044
Asia	1415.4	1848.7	n.a.	n.a.	n.a.	-14,208,400	-19,568,974

[1] Source: ADB 2006

[2] Source: ADB 2004

[3] Source: World Bank 2007 at http://siteresources.worldbank.org/DATASTATISTICS/Resources/GNIPC.pdf

[4] Source: FAOStat 2007, Earthtrends Data Tables: Forest Production and trade 2005 at http://earthtrends.wri.org/datatables/index.php?theme=4

[5] Source: World Resources Institute 1994; FAO 2005

[*] 2002 data

[a] GNI per capita (formerly GNP per capita) is the gross national income, converted to US dollars using the World Bank Atlas method, divided by the midyear population. GNI is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad.

[b] Refers to the aggregate of all forest products, including industrial roundwood, fuelwood and charcoal, sawnwood, wood-based panels, wood pulp (including recovered paper), and paper and paperboard (see also Table 3); a negative trade value refers to a net expenditure derived from a net import of forest products whereas a positive value refers to a net income derived from a net export of forest products.

[#] average of 1989–1991 consumption data

__Table 4.__ Trends in volumetric woodfuel consumption, net trade in industrial roundwood, and production of major forest products for various South and Southeast Asian countries.

Country / region	**Consumption[a] of woodfuels (,000 m^3)**		**Net trade in industrial roundwood[b] (,000 m^3)**		**Production of industrial roundwood (,000 m^3)**		**Production of sawnwood (,000 m^3)**		**Production of wood-based panels (,000 m^3)**		**Production of paper and paperboard (,000 m^3)**	
	1990[c]	**2002**	**1990[c]**	**2002**	**1990[c]**	**2002**	**1990[c]**	**2002**	**1990[c]**	**2002**	**1990[c]**	**2002**
Bangladesh[#]	30,061	27,763	-87	3	882	575	79	70	8	9	95	46
Bhutan[#]	1,254	4,348	4	0	278	134	33	31	12	32	-	-
Cambodia*	5,366	9,737	56	-	681	125	79	5	2	37	-	0
India[#]	250,089	300,564	-1,118	1,990	24,421	19,308	17,460	7,900	442	645	2,202	3,973
Indonesia^	141,017	82,556	1,245	(322)	26,804	32,997	9,549	6,500	8,837	12,635	1,432	6,995
Laos*	3,827	5,899	20	(63)	367	392	66	182	10	13	-	-
Malaysia^	8,719	3,228	20,125	(4,762)	41,219	17,913	8,684	4,594	2,071	6,803	283	851
Myanmar*	17,785	35,403	669	(877)	5,065	5,539	436	381	15	20	11	42
Nepal[#]	17,661	12,728	4	0	583	1,260	470	630	-	5	9	13
Philippines^	33,447	13,328	-276	433	5,019	3,079	845	154	455	620	212	1,056
Sri Lanka[#]	8,364	5,774	0	0	674	694	12	61	10	22	17	25
Thailand*	34,585	20,250	-1,444	688	3,154	7,800	1,123	288	340	705	868	2,444
Vietnam*	24,154	26,547	262	39	4,816	4,183	782	2,950	40	40	67	384
Asia	817,437	782,395	49,527	43,312	254,245	222,563	104,587	61,157	27,515	58,768	56,357	97,823

Source 1990 data: WRI 1994
Source 2002 data: FAO 2006

a) woodfuel consumption equals woodfuel production for all countries listed suggesting no international trading in woodfuels

b) positive values represent a net income derived from export of the product in question whereas negative values represent a net expenditure derived from net import of the product

c) annual average of 1989–1991 data

Within South and Southeast Asia, there is a trend towards lower trade of unprocessed (or partially processed) forest products such as industrial roundwood and sawnwood (see Table 4) and a higher production and trade of processed forest products such as wood-based panels, paper and paperboard. The demand for all forest products, whether processed or not, is significant and is projected to remain so and increase, from the local to international levels, with a growing number of countries being unable to meet their domestic demand, whether from a shortage of local resources or shift in economic base. This projection emphasizes the urgent need to expand the regional forest base, a process that should include afforestation, reforestation, and the establishment of other tree-based systems not normally included in forest system classifications, such as smallholder agroforestry systems (Roshetko et al. 2008a).

1.3 Other sources of tree products and services

SUSTAINABLE MANAGEMENT OF FORESTS

As discussed above, planted forests (plantations) can be efficient systems for producing wood fibre. But compared to the natural forests they replace they do not provide the quality and quantity of services and products required by human society's growing needs. Additionally, the time lag between plantation establishment (tree planting) and tree product harvesting (even for fast-growing species) is counted in years. Thus, the pressure on natural forests will likely become worse before it becomes better. To minimize production pressure, efforts must be made to conserve the shrinking natural forest resource through sustainable management: 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biological diversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national and global levels, and that does not cause damage to other ecosystems' (FAO 2000b).

There remains debate regarding the potential of sustainable management of forests. Rice et al. (1997) argued that sustainable forest management focused on perpetual yields of multiple services and products provides lower returns and damages forests more than conventional timber harvesting. Pearce et al. (2003) acknowledged that sustainable forest management was less profitable than conventional logging but performed better in terms of carbon storage and biodiversity conservation. The latter suggests sustainable forest management has high prospects in safeguarding forests and meeting society's multiple demands as values attached to forests and associated services rise over time. An analysis of various landuse systems demonstrated that sustainable community-based management provided superior biodiversity, carbon storage and rural social/livelihood services compared to commercial logging (Tomich et al. 1998). Another global study found that commercial logging was a common cause of forest conflict, with local communities set against companies and government agencies (ARD 2004, Forester et al. 2004). Commercial logging frequently usurped legal local traditional rights and was the major cause of forest degradation in many areas (Lasco et al. 2001, Mittelman 2001, ARD 2004, Barr et al. 2004, Wulan et al. 2004, Forester et al. 2004, Sheng and Cannon 2004).

While sustainable forest management cannot counter-balance the loss of natural forests, it is the only viable option to conserve that dwindling resource, enabling natural forests to provide the environmental services that they are uniquely positioned to supply—biodiversity conservation, soil and water conservation, and carbon storage—and contribute strongly to healthy ecosystems, multiple socioeconomic benefits, and support of social/livelihoods' services to poor rural communities. Sustainable forest management, however would need to be combined with other sources of tree services and products (Roshetko et al. 2008a).

SMALLHOLDER TREE-FARMING SYSTEMS

In this thesis, the term 'smallholder tree-farming systems' is interchangeable with 'smallholder agroforestry systems'. Depending on local needs or opportunities, smallholder systems may focus on tree crops, agricultural crops, livestock or a combination of the three. These various systems will differ greatly in size, species components, tree density, tree longevity, and management intensity (II). A shortage of local forest resources is often the catalyst of spontaneous expansion of smallholder agroforestry systems. This type of farmer-led, spontaneous, smallholder tree-farm development has been documented in Bangladesh (Byron 1984), Sri Lanka (Gunasena 1999), Philippines (Pasicolan and Tracey 1996, Schuren and Snelder 2008, FAO 1993, Magcale-Macandog et al. 1999), Kenya (Scherr 1995, Place et al. 2005) and Indonesia (Michon and Bompard 1987). In addition, proximity to urban centres creates high demand for timber, fruit and other forest products and stimulates spontaneous smallholder agroforestry. This is particularly true for areas far from the extractive forest frontier and/or with farms large enough to support tree crops in addition to seasonal cash crops. In other situations (for example, in central and eastern Java), the (temporary) migration of young people to cities results in extensification of land use with tree farming as a form of a 'living saving account' (Roshetko et al. 2008a). Under these conditions, smallholder farmers see tree farming as a means of diversifying their production, reducing risk, and building assets to enhance family incomes and security (I, II, Schuren and Snelder 2008). As opposed to forest plantations and other public-planted forests discussed above, smallholder tree-farming systems provide an array of tree and forest products and services, including support of local livelihoods.

Smallholder tree-farming systems may originate from natural forests that have been altered in composition or structure by local people, tree-based systems established on agricultural or fallowed land, or a combination of both. There are examples of forest degradation being deflected by the establishment of smallholder tree-farming systems that avoid the more serious stages of environmental degradation (de Jong et al. 2001). In these situations, good markets for tree products, such as fruits, resins and latex, have allowed a transition of substantial areas of Southeast Asian forests into 'agroforests', a land use that combines 'planted trees' with forest flora and fauna, either retained or naturally regenerated vegetation (de Jong et al. 2001, Michon and de Foresta 1990, 1995). Similarly, through the production of tree products and services on farms, smallholder agroforestry systems have been identified as a means of reducing pressure on and conserving natural forests (de Foresta et al. 2004, Scherr and McNeely 2008, Strandby-Andersen et al. 2008, Jamnadass et al. 2010). Farmers in Sumatra who cultivated agroforestry systems relied less on wood supplies harvested from the natural forest than those without agroforestry systems (Murniati et al. 2001). Dawson et al. (2013a) recently published a review paper on smallholder agroforestry's contribution to tropical tree diversity. This aspect of smallholder agroforestry systems is referred to as 'conservation through use'.

Smallholder farmer tree-planting systems are generally successful on their own terms. Smallholders have limited time and financial resources. The trees they plant represent a conscious investment for which other options have been forfeited. Farmers generally restrict plantings to the number of trees that can be maintained and integrate tree-growing with their crop and animal production activities. The management practices undertaken to assure good food crop yields cultivation, weed control and fertilization also benefit their trees. The available land, labour and other resources are allocated according to the farmer's objectives. Because landholdings are small, farmers can select the farm niches most appropriate for tree production. The combination of limited resources, small individual plantings, and intimate familiarity with the planting site result in high tree survival and good growth rates. Smallholder tree-growing activities benefit from intensive management over limited areas and vested self-interest: the desire of the farmer to profit from their investment of time and resources (Roshetko et al. 2008a).

Besides supporting family livelihoods, smallholder agroforestry systems also make a significant contribution to national economies and global trade. The five major global tree commodities are oil palm, coffee, rubber, cacao and tea, with an export value of roughly US $60 billion in 2009 (FAO Trade Statistics in Dawson et al. 2013b). Indonesia is a major producer of all five commodities. In 2011, smallholders produced most of the coffee and cacao in Indonesia, 80% of the rubber, 39% of the oil palm, and 26% of the tea (Table 5; DGEC, 2012). Compiling data from diverse sources, with various definitions of 'smallholder', Dawson et al. (2013b) reported that globally smallholders are responsible for 90% of cacao production, more than two-thirds of coffee production, up to three-quarters of rubber production, and 75% and 50% of tea production in Sri Lanka and Kenya, respectively.

Smallholders with diverse, risk-averse farms that include a significant tree component could be efficient producers of other tree commodities in the future. As described above, their tree-farming systems have high potential to yield both wood and non-wood products and play an important role in the reforestation of degraded lands. Smallholder tree-farming systems have the potential to be one component of a general poverty alleviation strategy for agrarian-based, poor rural communities (II, Krol 1992, Michon and Mary

1994, Snelder 2008). Although the potential of tree-farming systems for poverty alleviation has not been fully exploited and the extent to which these systems can alleviate poverty and enhance food security is poorly documented, the importance and potential of the systems will continue to rise, particularly with the continued development of market economies and rural infrastructure (I).

Table 5. *Smallholder production of oil palm, coffee, rubber, cacao and tea in Indonesia, 2011.*

	Smallholder area (,000 ha)	% of total area	Smallholder production (,000 ton)	% of total production
Oil palm	3,315	42	7,774	39
Coffee	1,255	96	679	96
Rubber	2,935	85	2,104	80
Cacao	1,641	94	828	92
Tea	56	46	40	26

Note: Figures are based on historical records, current trends and preliminary data for 2011
Source: Director General of Estate Crops, Department of Agriculture, 2012

1.4 Organization of the thesis

This thesis is organized into six main sections. This first section reviewed the trends in global and regional deforestation, human population growth, and demands for forest and tree products as well as the contribution of smallholder tree-farming systems to environmental sustainability and local livelihoods. The following section states the hypothesis of the thesis, the objectives of the five papers included in the thesis and the relationship between these papers. The third section summarizes the objectives, materials and results of the five papers. The fourth section is a synthesised discussion of the results of the papers. The fifth section provides an overall conclusion to the thesis. The sixth section is a description of future work required to further recognize and consolidate the importance of smallholder tree-based systems and further test the hypothesis of the thesis. The thesis is supported by a review of literature, including other work completed by the candidate. Copies of the five papers are provided after the References.

2. OBJECTIVES OF THE THESIS

The hypothesis of this thesis is that smallholder tree-farming systems are viable agricultural and natural resources management systems that contribute significantly to global environmental goals and local economic objectives. The general validity of the hypothesis is supported by the thesis introduction, which demonstrates smallholder tree-based systems i) provide considerable tree cover and environmental services which are threatened by global trends in forest loss; and ii) support the livelihoods of millions of smallholder farm families through the production of tree and agricultural products for home use and market sale.

The hypothesis is further tested through the objectives of the five papers included in the thesis that illustrate smallholder systems' capacity for carbon storage, appropriateness for carbon projects, and capacity to produce marketable timber simultaneously with agricultural crops. There are specific objectives of each paper.

1) Generation of carbon stock inventory data for representative Indonesian homegarden systems to demonstrate that smallholder agroforestry systems can serve global environmental goals by targeting them for increased carbon storage.
2) Identification of the types of agroforestry systems that are appropriate for carbon storage, the types of technical assistance that will enhance smallholder agroforestry systems, and the types of enabling conditions that favour smallholder benefits and carbon project success.
3) Evaluation of the issues of 'additionality', 'leakage', and 'permanence'[2] from the point of reference of smallholder agroforestry systems and carbon projects.
4) Identification of 'genetic-level' responses by trees to environmental changes in the specific context of smallholder agroforestry systems and how that knowledge can be translated into action to better manage tree genetic resources on smallholding farms for more productive and sustainable environmental management.
5) Evaluation of the cultivation and utilization of *Gmelina arborea* as a viable species for smallholder tree farms in Indonesia.

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[2] *Additionality* requires that carbon stocks accrued to a carbon sequestration project are 'additional' to those that would occur without the project. *Leakage* is the loss of carbon, primarily as woody biomass, in non-project areas due to changes in landuse practices resulting from activities within the project area. *Permanence* concerns the longevity and stability of a carbon stock. The carbon stocks in any landuse system, although theoretically permanent, are potentially reversible through human activities and environmental change, including climate change.

6) Investigation of the effect of various pruning regimes on *Gmelina arborea* growth and associated maize yield and their implications for the financial returns of smallholder timber production systems.

Papers I and II focus on smallholder systems for carbon storage and, respectively, the first and second objectives listed above. Both papers also address the third objective, the issues of additionality, leakage, and permanence from the point of reference of smallholder agroforestry systems and carbon projects. Paper III concentrates on the fourth objective, the importance of tree genetic resources and their management for the adaptation of smallholder agroforestry systems to climate change. The issues covered in these three papers are also relevant to a broader set of global environmental goals—reforestation, land rehabilitation, biodiversity conservation, or other environmental services—as well as rural development in general. Similarly, while papers IV and V focus on the establishment and management of *Gmelina arborea* as a timber crop for smallholders (objectives 5 and 6), the management issues discussed are equally relevant to other timber species and smallholder agroforestry tree crops in general, such as cacao, coffee, rubber, fruits, spices, medicines or a combination of such crops.

All five papers and six objectives are applicable to the wide range of biophysical and socioeconomic conditions under which smallholder agroforestry systems are operated in Southeast Asia. Examples from literature and the candidate's past and continuing work are cited to support this assertion. The thesis ends with a description of future work required to recognize the importance of smallholder tree-based systems and further test the hypothesis.

3. OBJECTIVES, OVERVIEWS AND RESULTS OF PAPERS

3.1 Carbon stocks in Indonesian homegarden systems: can smallholder systems be targeted for increased carbon storage? *American Journal of Alternative Agriculture* 17:138–148 (Study I).

Forest-based landuse systems—natural forests, forest plantations, and agroforestry systems—sequester and store carbon dioxide through the carbon in their biomass. By promoting landuse systems which have a higher carbon content than an existing plant community, net gains in carbon stock (hence, sequestration) can be realized. The most significant increases in carbon storage can be achieved by moving from lower-biomass landuse systems (for example, grasslands, agricultural fallows and permanent shrublands) to tree-based systems. However, because many efforts to achieve increased forest carbon storage may have negative implications for the rural poor, options that support human livelihoods deserve special attention.

Indonesia provides an attractive environment for carbon investment. There are over 8.5 million hectare of *Imperata* grasslands in Indonesia (Garrity et al. 1997). Originally forests, these lands include pure grasslands, cyclic fallows and shrublands, and are acknowledged to be underutilized. There is clear interest, at both governmental and smallholder farmers' levels, to convert some of these lands to more productive land uses, including tree-based systems (Tomich et al. 1997). Homegardens are a common agroforestry system adopted by smallholders in many parts of Indonesia. These species-rich, tree-based systems usually occupy lands immediately surrounding the dwellings and are used to produce a diverse array of food and other products. Traditionally intended to produce goods mainly for home consumption, the advent of rural infrastructure and market economies has made homegardens more commercially oriented. Homegarden production now commonly serves both household and market demand, providing families with much-needed income (Krol 1992, Michon and Mary 1994).

Simultaneously, homegardens, and other tree-rich, smallholder systems, offer potential for carbon storage because of their high woody biomass. The question raised by the paper was whether the role of smallholder agroforestry systems could be expanded to serve global environmental goals by targeting them for increased carbon storage? The objective of the study was to generate carbon stock inventory data for homegarden systems in Lampung province, Sumatra, Indonesia. Study results were compared to carbon stock data for other landuse systems in Sumatra (Tomich et al. 1998).

The study was conducted in three villages in Pakuan Ratu district in Lampung province, Sumatra, Indonesia. Soils were well-drained, deep (>1–1.5 m), acidic and of low fertility. Elevation was less than 100 m above sea level, mean annual temperature was 28 °C, varying between 22 and 33 °C. Annual rainfall averaged 2200–2500 mm, with 5–6 months greater than 200 mm and 1–4 months less than 50 mm. At the study site, most families owned a 0.25 hectare homegarden. The species' composition of local homegardens included trees that produced fruit, vegetables, spices, oil, medicines, other non-wood products and timber; and annual crops such as vegetables, cassava, corn and rice for home consumption. The other major landuse classes in the area were sugarcane plantations, commercial cassava, other agricultural crops, *Imperata* grasslands and degraded secondary forests.

Nineteen homegardens were included in the study. Homegardens were selected if the landowner gave permission, and both structure and species present were considered typical of local homegardens. Homegardens were excluded if they contained 50% or more of i) annual crops (vegetables, cassava, maize, rice, etc.); or ii) one market-oriented tree crop (for example, coffee (*Coffea robusta*), coconut (*Cocus nucifera*) and/or *sengon* (*Paraserianthes falcataria*)). Homegardens that contained 25% or more of fish pond or rice paddy were also excluded. The carbon monitoring system used in this study quantified the carbon stocks in landuse systems using forestry and agroforestry inventory principles and practices (MacDicken 1997, Delaney and Roshetko 1999). The system quantified carbon sequestered by measuring changes in four main carbon pools over time or comparing the carbon in these four pools with other landuse options. Main carbon pools were aboveground biomass, litter, herbaceous material and soil. The system was very similar to the methods used to quantify carbon stocks in other Sumatran landuse systems (Hairiah et al. 1999, Palm et al. 1994). Details regarding plot installation, measurements, and estimations of aboveground biomass are provided in the full paper (I).

Homegarden ages varied from 12 to 17 years, with an average of 13 years. Total carbon per homegarden ranged from 56 to 174 Mg C ha^{-1} with an average of 107 Mg C ha^{-1} (I, Table 1). Tree biomass (aboveground plus roots) and soil accounted for 98% of these carbon stocks (41% and 57%, respectively). Aboveground carbon in the homegardens varied from 6.3 to 84.0 Mg ha^{-1}, with an average of 35.3 Mg ha^{-1} with a coefficient of variation (CV) of 60%. Soil carbon varied from 10.4 to 103.7 Mg ha^{-1}, with an average of 60.8 Mg ha^{-1} (CV of 32%). The remaining 2.2% of the carbon stock was in the litter (1.9%) and herbaceous (0.3%) pools. The homegardens were diverse, containing 45 tree species. A total of 597 trees were sampled, with an average of 34 per homegarden (2–3 plots/homegarden). The species, their predominance in the homegardens, and their primary uses are given in Table

3 (I). Eighty percent of the species in the homegardens provided primarily non-wood products or services: fruits, vegetables, spice, oils, medicines, resins and soil improvement. Coincidentally, these species also accounted for 80% of the trees surveyed and 73% of the tree biomass (I, tables 2 and 3). Twenty percent of the species in the homegardens, representing 20% of the trees sampled and 27% of the tree biomass, were grown primarily for timber and wood production (I, tables 2 and 3). These species can also produce non-wood products or services, but these products and services were of secondary importance.

The carbon content of homegardens compares favourably with that of mature agroforests, secondary forests, young rubber agroforests, *Imperata* grasslands, and cassava systems: five common landuse systems in the study area (Hairiah 1997). The carbon storage in homegardens was 58 times greater than in *Imperata* systems and had 1.5 times more carbon than young rubber agroforests. However, both mature agroforests and secondary forests contained higher carbon stocks compared to homegardens because the trees in these systems were older than the trees in homegardens with an average of 30 years compared to 13 years.

3.2 Smallholder agroforestry systems for carbon storage. ***Mitigation and Adaptation Strategies for Global Change*** **12:219–242 (Study II).**

During the Third Conference of Parties (COP 3) of the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol was drafted. This was the first international agreement to place legally binding limits on greenhouse gas emissions from developed countries (UNFCCC 1997). The Protocol entered into effect on February 2005, providing flexible mechanisms to meet carbon emissions reduction obligations. The most relevant mechanism for developing countries was the Clean Development Mechanism (CDM) found in Article 12, which allowed Annex 1 (developed) countries to meet their carbon reduction quota via activities in developing countries.

During the COP 6 in 2000, parties to the convention approved the inclusion of ‘sinks’ (land use, land-use change and forestry (LULUCF) projects for the first commitment period but limited them to reforestation and afforestation only. The rules and modalities for LULUCF projects were finalized in 2003 during COP 9 (UNFCCC 2003, Decision 19/CP9).

Carbon credits obtained through the CDM were called ‘certified emission reductions’ (CERs). To qualify for CERs under the Kyoto Protocol, reforestation and afforestation activities had to be directly induced by humans. As many efforts to achieve increased forest carbon storage may have negative implications for the rural poor, options that supported human livelihoods deserved special attention.

Addressing this concern, the CDM provided opportunities for investors seeking CERs to invest in developing countries for the dual mandate of reducing greenhouse gas emissions and contributing to sustainable development. Similarly, the World Bank initiated the Community Development Carbon Fund and the BioCarbon Fund to link the enhancement of local livelihoods with carbon investment projects. Tree-based carbon sequestration projects were eligible for the CDM and World Bank funds.

Globally, the greatest potential area for expanding agroforestry practices and other forms of landuse intensification is in areas considered ‘degraded’ at the margins of the humid tropics, such as many secondary forest fallows, *Imperata* grasslands, and degraded pastures (Sampson and Scholes 2000). It is estimated that a total of 10.5×10^6 ha could be placed under agroforestry yearly, if enabling government policies such as those described by Fay et al. (1998) and Tomich et al. (1998) would be put into place.

Economic and financial analyses of agroforestry systems with potential for CDM in Indonesia were encouraging (Ginoga et al. 2004, 2005). For example, in *Gliricidia sepium* tree farms, carbon payments encouraged landholders to adopt less intensive practices since net revenues were higher (Wise and Cacho 2005). In the Philippines, carbon sequestration through *Paraserianthes falcataria*-based agroforestry systems was found to be less costly than pure tree-based systems, suggesting that agroforestry systems were the more attractive option (Shively et al. 2004).

Southeast Asia contains vast areas of degraded and underutilized lands that could be used for carbon investment. Best estimates indicate that there are 35×10^6 ha of *Imperata* grasslands in Southeast Asia (Garrity et al. 1997). Originally forests, these lands now include pure grasslands, cyclic fallows and shrublands, and are acknowledged to be underutilized. There is clear interest, at both the governmental and smallholder farmer levels, to convert some of these *Imperata* grasslands and other degraded lands to more productive land uses, including tree-based systems (I, Tomich et al. 1997).

The establishment of agroforestry systems on underutilized sites would sequester carbon and could prevent further deforestation by providing on-farm sources of tree products (Sanchez 1994, Schroeder 1994). Agroforestry is one means by which smallholder farmers could benefit from carbon investment projects (CIFOR 2000, Sampson and Scholes 2000, Smith and Scherr 2002). Smallholder agroforestry systems maintain high tree densities and may contain high carbon stocks. On a per area basis, tree-rich smallholder systems accumulate a significant amount of carbon, equalling the amount of carbon stored in some secondary forests over similar time periods (I, Tomich et al. 1998).

Their ability to address smallholder livelihoods' needs, provide tree and forest products needed by society and simultaneously store large quantities of carbon make tree-rich smallholder agroforestry systems possible prototypes for CDM-type projects. Individual types of agroforestry systems differ greatly as do the conditions under which each type is appropriate. A set of guidelines is needed to help identify the type of agroforestry systems and conditions that are most promising for CDM-type projects. The paper addresses the: types of agroforestry systems appropriate for carbon storage; types of enabling conditions that favour smallholders' benefits and project success; type of technical assistance that can enhance smallholder agroforestry systems; and the topics of additionality, leakage, and permanence from the point of reference of smallholder agroforestry systems.

3.3 Climate change and tree genetic resource management: maintaining and enhancing the productivity and value of smallholder tropical agroforestry landscapes: a review. *Agroforestry Systems* 81:67–78 (Study III).

Anthropogenic climate change caused by greenhouse gas emissions is altering the mean, range and seasonality of a series of climatic variables, resulting in rapid temperature increases, significantly different rainfall patterns and a greater frequency of extreme weather events in many regions (IPCC 2007). Negative effects will disproportionately impact on the poor and will exacerbate current inequalities between high- and low-income nations. For example, a 2 ˚C warming could result in permanent reductions in gross domestic product of 4% or more in Africa, a region that already suffers from extreme poverty (World Bank 2009). In the absence of appropriate mitigation and adaption measures, there is a significant danger that climate change—together with other interrelated challenges such as high human population growth, fuel scarcity, deforestation, soil degradation and biodiversity loss—may result in catastrophic impacts (EC 2008, FAO 2006, Malhi et al. 2009).

Agroforestry—the practice of integrating trees with annual crop cultivation and other farm activities—is an approach adopted by millions of smallholders to meet their needs for essential resources of food, medicine, timber, fuel, fodder and market commodities, and provides valuable environmental services such as soil fertility replenishment, water catchment protection, carbon sequestration, biodiversity and habitat conservation, and landscape restoration (Garrity 2004, Idol et al. 2011, Roshetko et al. 2007c, Martini et al. 2012). When an active tree-planting culture exists in rural communities, hundreds of indigenous tree species can be found conserved *circa situm* in farmland (Acharya 2006, Kindt et al. 2006). A diversity of local and exotic trees and crops can improve the resilience of agricultural systems to environmental change if constituent species respond differently to disturbances (I, Kindt et al. 2006, Steffan-Dewenter et al. 2007).

In addition, by providing alternative sources of products, tree cultivation has the potential to take pressure off extractive harvesting from natural forests, contributing to *in situ* conservation, limiting deforestation and reducing greenhouse gas emissions, and fixing carbon in farmland (I, II, Jamnadass et al. 2010, Nair et al. 2009). Agroforestry is therefore seen as a key means of 'climate-smart' development. Understanding how to maximize the productivity of trees in agricultural landscapes under anthropogenic climate change is therefore essential in proactive management (World Bank 2009). In addition, in the context of climate change and other global challenges that will result in the loss of natural forests, in the coming decades farmland will play an increasingly important role in conserving the biodiversity of tropical trees (Simons et al. 2000). This is because not only are *in situ* options limited, but alternative *ex situ* methods of conservation—in which species are stored as seed or as growing plants in 'formal' gene banks—are generally not practical for tropical trees. This is due to a range of factors, including the number of taxa involved, frequent seed recalcitrance, specific associations with microorganisms that must be maintained for proper growth, and the prohibitive expense and time required to regenerate species with long generation intervals (Kindt and Lengkeek 1999).

Initial agroforestry-based responses to climate change can be envisaged as involving compositional adjustments between constituent tree species within farming systems. In this scenario, as climate changes, less well-performing species on farmland are replaced by other trees that are already present at low densities within systems and which are better-suited to new conditions (that is, the relative abundance of different species in the landscape changes, and certain existing species in farmland may be lost; Lengkeek et al. 2005a, b).

Compositional shifts to combat anthropogenic climate change will, however, be required beyond the level of species assemblages, and further crucial measures will involve maintaining, enhancing and better-managing tree genetic resources at an intra-specific level within farm landscapes. It is these interventions that are the focus of this essay. The paper reviews current knowledge on 'genetic level' responses by trees to environmental change (for example, Aitken et al. 2008, Vinceti et al. 2009), in the specific context of how that knowledge can be translated into action for the particular case of smallholder agroforestry systems in the tropics. The paper contributes to a wider discussion of how to better manage tree genetic resources on smallholder farms for more productive and sustainable practices (Dawson et al.

2009), in order to allow rural communities to face the range of pressing challenges to production that they are currently confronted with, of which climate change is one among many factors. It first considers germplasm translocation in agroforestry systems as a response to climate change; second the issue of local genetic adaptation; and third the role of plasticity in species' performance. In the context of climate change, germplasm-based interventions needed to deal with the constraints faced by farmers in tree planting are summarized in Table 1 (III).

3.4 *Gmelina arborea*: a viable species for smallholder tree farming in Indonesia? *New Forests* 28:207–215 (Study IV).

Across Indonesia, there are 15.1 million hectare (4.5% of the country) of degraded land in need of rehabilitation (MOF, 2001). There is interest by both the government and farmers to convert some of these lands to more productive use, including tree crops (I, Tomich et al. 1997). Smallholders cultivate 1–5 hectare of land and often practise tree farming to generate income. They traditionally cultivate a wide range of tree species in mixed agroforestry systems, with timber production as a common objective. Farmers' species preferences largely depend on household needs and markets (Yuliyanti and Roshetko 2002). However, farmers and non-government organizations (NGOs) that support them have little access to quality tree germplasm (Roshetko 2001b) or control over the tree species made available to them. Scientists or extension services generally make the decisions: screening new species in on-station trials or from available literature and evaluating them according to biophysical criteria (Franzel et al. 1998), without considering markets. Farmer-designed trials and participatory evaluations are important ways to strengthen farmers' role in the species' selection and technology development process for their specific biophysical and socioeconomic conditions.

The World Agroforestry Centre (ICRAF) and Winrock International, through the support of the Indonesia Forest Seed Project funded by Danida, initiated a project to enhance the tree-planting activities of farmers and NGOs by i) increasing availability and use of quality tree seed; and ii) strengthening technical awareness and skills of farmers and NGOs regarding tree germplasm collection and management. Project activities included surveys and participatory appraisals; training courses and workshops; distribution of quality tree seed; production and distribution of appropriate documents to farmers and NGOs; and establishment of farmer-designed demonstration trials. This paper summarizes results and observations from those activities that are relevant to the planting and utilization of *Gmelina arborea* by smallholder farmers in Indonesia.

A survey was distributed to 120 NGOs and similar organizations to identify priority species, germplasm pathways, capacities and needs for enhancing smallholder agroforestry systems. A second survey of the 140 known tree seed suppliers in Indonesia was conducted to determine the species for which seed were available, source and quality of the seed, and dynamics of the formal tree seed sector. Farmer demonstration trials (FDTs) were designed by researchers and farmers for farmers' specific biophysical and socioeconomic conditions (Roshetko et al. 2005). Farmers managed the trials, with advice from researchers or NGO staff. Researchers provided farmers and NGOs with practical guidelines for trial evaluation. This type of trial was an effective means to identify farmers' species preferences and tree management skills, stimulate farmers' innovation, and assess species' performance under farm conditions (Franzel et al. 1998). The evaluation of biophysical data was not a main objective of this type of trial, but may be possible. Seven FDTs that included *Gmelina* were established. The data from two of those trials, which were replicated and managed under a uniform design, are presented in the paper.

The trial sites in Karamabura, Sumbawa and Manamas, Timor, were characterized by steep slopes (30–45°), low precipitation (700–1000 mm/year), long dry seasons (7–9 months/year), clay loam soils with limited potential for annual crop production, and pre-existing unmanaged grasslands. Trial species included short-rotation species—*G. arborea*, *Paraserianthes falcataria* and a *Eucalyptus* hybrid (*E. urophylla x E. grandis*)—and long-rotation species: *Swietenia macrophylla* and two sources of *Tectona grandis* (a clone and a local landrace). A private company donated seedlings of the *Eucalyptus* hybrid and the *T. grandis* clone; seed of the other species originated from Central Java. At each site, three replications per species where established at 3 x 3 m spacing. The number of trees planted per species varied. Each trial was about 1 hectare in size and contained approximately 1100 trees. Under supervision of NGO staff, in accordance with project guidelines, farmers recorded tree survival and randomly selected 10 trees per replication to measure height and basal diameter or diameter at breast height (dbh). Height and diameter means were compared using Tukey's test (HSD) based on individual tree data.

Thirty-five percent of the NGO surveys were returned. Results identified 39 priority species, including multipurpose trees, fruit species, estate crops and timber species. *Gliricidia sepium, Leucaena leucocephala* and *Calliandra calothyrsus* were identified as priority species by 74%, 48% and 43% of respondents, respectively. Priority timber species were *S. macrophylla* (30% of respondents), *T. grandis* (26%) and *P. falcataria* (26%). *Gmelina arborea* was identified by 8% of respondents, primarily in Nusa Tenggara were the trials where established. Access to seed was identified as a universal problem. No respondents had direct access to improved quality seed. Respondents collected or purchased 75% of their seed from local sources of unknown genetic or physiological quality. The remaining 25% was donated by development organizations, technical agencies, or universities. NGO staff, farmers and local seed dealers were unfamiliar with proper seed collection guidelines.

Thirty-one percent of the seed dealer surveys were returned. Seed of *T. grandis, S. macrophylla* and *P. falcataria* were stocked by 57% of dealers; *G. arborea* by 45%; and *G. sepium, L. leucocephala* and *C. calothyrsus* by 36%. Of the dealers who supplied *G. arborea* seed, 45% were located in Wonogiri, Central Java, or Ponorogo, East Java (separated by only 75 km); another 35% collected *G. arborea* seed from stands of Wonogiri–Ponorogo origin. Most of the *G. arborea* dealers (85%) collected seed predominantly from industrial or farm plantations of undocumented origin. Large quantities of this undocumented seed were sold to various customers throughout the country. Only three dealers (15%) collected seed from seed production areas or seed stands, all of which were located in South or East Kalimantan. The seed from these sources were primarily sold to the forestry industry and government agencies.

Growth and survival data for the trials are presented in Tables 1 and 2 (IV). The survival of most species was 81 to 100%; survival of *G. arborea* averaged 99.5%. The survival of *P. falcataria* was only 61%. Of the short-rotation species, *G. arborea* showed superior height and diameter growth during the initial 6-month period. After 21 months, both *P. falcataria* and the *Eucalyptus* hybrid demonstrated greater height growth. Of the long-rotation species, the *T. grandis* clone demonstrated superior height and diameter growth after 21 months, followed by local *T. grandis* (land race) and *S. macrophylla*, respectively.

3.5 Optimum pruning strategies for reducing crop suppression in a *Gmelina*-maize smallholder agroforestry system in Claveria, Philippines. *Agroforestry Systems* 83:167–180 (Study V).

For the past three decades, the integration of fast-growing timber trees in smallholder farming systems has been promoted in the Philippines to diversify farm output and produce timber for household use and sale. As a result, smallholder timber is now an important source of raw materials for the local timber industry and income for smallholders. A unique advantage of smallholder tree production is the practice of intercropping, where the management practices associated with annual crop production (annual soil cultivation, weeding and fertilizer application) improves tree survival and growth (Kapp and Beer 1995, Garrity et al. 1997). Intercropping trees with annual crops also provides direct financial benefits by reducing tree establishment and management costs by half compared to tree plantations (Nissen et al. 2001, Jordan et al. 1992).

However, intercropping with timber trees frequently reduces understorey crop production as a result of competition for both above- and belowground resources (Ong et al. 1996). With few exceptions, the timber species commonly promoted for farm forestry were reported to depress yields of associated annual crops, which generally require full sunlight (Leiva and Borel 1994, Okorio et al. 1994, Ahmed 1989, Malik and Sharma 1990, Saxena 1991). In the humid tropics where soil water and nutrients are freely available, and fertilizer use is common, light availability is often the most limiting factor to production of understorey annual crops (Ong et al. 1996). Branch pruning effectively reduces light interception by trees, thus prolonging the period of intercropping (Watanabe 1992, Miah 1993, Gonzal 1994). Farmers often practise intensive branch pruning to reduce tree–crop competition as well as to improve tree shape (IV; Bertomeu 2004). While intensive pruning benefits understorey crop production, it may reduce the profitability of tree farming by reducing tree growth and final timber yields (Smith 1962, Miah 1993, Gonzal 1994).

On-farm trials were conducted in Claveria, Philippines, to investigate the effect of pruning on maize yield, tree growth and farmers' financial returns. Soils in Claveria were deep oxisols, clays to silty clay loams, with pH of 3.9−5.2, low available phosphorus, low cation exchange capacity, high aluminium saturation and low exchangeable potassium (Magbanua and Garrity 1988). Annual rainfall is 2500 mm with a short dry season from March to April (Kenmore and Flinn 1987). Temperatures vary from 28.6 °C to 21.3 °C. The average farm size was 2.5–3 hectare, comprised of two or more parcels. Maize was the dominant crop, cultivated twice a year or in rotation with cassava or upland rice. Typically, a rainy season crop was planted in May, followed by a dry season crop in September or October.

The trial was established in a randomized, complete block design with four treatments and four replications, established on two farms (two replications per farm). Treatment plots were 300 m^2 (15 x 20 m) containing three lines of *Gmelina* planted at 1 x 10 m (1000 trees per hectare) with 16 trees per line (48 trees per plot), and 15 rows of maize planted for six cropping seasons in each of the 10 m-wide alleys. Four pruning intensities were tested: 1) T_1 (control): retaining a live crown ratio (LCR) of 60–70%; 2) T_2: retaining a LCR of 40–50%; 3) T_3: retaining a LCR of 30–40%; and 4) T_4: retaining a LCR of 20–30%. Maize grain yields were measured row by row for each cropping season. Dbh and total tree height were measured twice a year until trees were 42 months old. The financial net benefits of the maize-*Gmelina* agroforestry system under the four pruning regimes were assessed by land expectation value and net returns to labour. Further details regarding site characteristics, trial establishment, trial management, data collection and analysis are provided in the full paper (V).

Compared to the first year (crop 1 and 2), maize production in the third year (crop 5 and 6) was substantially reduced at both sites due to competition from *Gmelina*. Crop 1 was around 50% larger than crop 5 at both sites, whereas crop 2 was 30–34% higher at site 1 and 37–54% higher at site 2 than crop 6. This reduction in maize production as trees grew occurred in all treatments, being most pronounced under T_4. Differences in grain yield between T_1 and T_4 were clearly significant after the first year (except in crop 6 at site 2). In the second year (crop 3 and 4), maize grain yield under T_4 was around 23–52% higher at site 1 and 20% higher at site 2 than under T_1. In the last year (crop 5 and 6), maize grain yields in T_4 at both sites were 30–40% greater than under T_1 (V; Table 3). Throughout the trial, the pattern of maize grain yields across alleys conformed to a bell-shaped curve, with yields differing significantly ($p < 0.05$) between pruning regimes and with distance from the tree line (V; Table 4). The bell-shaped curve became less pronounced with time. During the first year, yields under pruning regime T_4 were generally greater compared to other treatments; differences were irregular, probably due to the variability of soil conditions within the trial sites. Only the yield of the first maize row under T_4 (398 g lm^{-1}) was significantly different from that of T_1 (272 g lm^{-1}). In the first year, differences in grain yield between T_4 and T_1 ranged 5–14% in rows 7 and 9 (centre of the alley) up to 32% in row 1. Under all pruning regimes, grain yields from the rows next to the trees (rows 1 and 15) were significantly different from yields in the middle alleys (rows 5 to 10). Maize grain yield under each pruning treatment showed that the wet season crop was consistently greater than that of the dry season crop (V; Table 5). In the first year, no statistical differences ($p < 0.05$) in maize grain yields were detected. As trees grew, grain yield under T_4 became significantly greater ($p < 0.05$) compared to those under T_1. The cumulative difference in grain yield between T_1 and T_4 over the six cropping seasons was 3.58 t ha^{-1}.

Tree diameter increment was greatest under pruning regime T_1 and least under T_4 (V; Fig. 1). The effect of pruning on tree diameter increment was statistically significant ($p < 0.001$) only in site 1 during the 18–24 month and 30–36 month periods (V; Table 6). At site 2, trees under T_1 consistently showed greater diameter increment than all other treatments. However, differences were not statistically significant, probably due to variable soil conditions within the sites. This assumption was supported by analysis that demonstrated the site–treatment interaction at site 2 was highly significant (V; Table 6). Pairwise comparisons of treatment means showed that the difference in mean annual increment (MAI) between T_1 and T_4 was statistically significant at both sites and in all periods except at site 1 during the 36–42 month period. Comparisons between T_2 and T_4 showed that differences in MAI were significant only at site 1 during the 18–24 and 30–36 month period, and at site 2 during the 36–42 month period (V; Table 6).

Diameter MAI was greatest for trees under moderate pruning (T_1). At site 1, diameter MAI was 4.6 cm for pruning regime T_1, 4.5 cm for T_2, 4.1 cm for T_3 and 3.8 cm for T_4. At site 2, diameter MAI was 5.4 cm for pruning regime T_1, 4.9 cm for T_2, 4.8 cm for T_3 and 4.4 cm for T_4. Mean maize grain yield was highest under the T_4 pruning regime, with an average difference between T_1 and T_4 of 0.56 ton ha^{-1} at site 1 and 0.63 ton ha^{-1} at site 2 (V; fig. 2 and 3). There was no significant difference in tree height increment between treatments throughout the trial period. There was, however, a significant difference ($p < 0.001$) in tree height increment between sites, with site 1 having a greater increment, probably as a result of differences in soil properties. No significant difference was found in stem shape between treatments. About 50% of the trees assessed over all treatments had crooked stems, around 46% had medium stem shape, whereas only 4% were rated as excellent in shape.

The results of the financial assessment showed that for a 15% discount rate, moderate tree pruning regimes (T_1 and T_2) were more profitable than intensive pruning regimes (T_3 and T_4) if the difference in average dbh at the end of the rotation was 2 cm (11% difference in timber yield) (V; Table 7). However, in all scenarios pruning regime T_4 showed the highest returns to labour, indicating that higher maize yields compensated for lower timber yields. The return to labour for T_1 (at a 15% discount rate) would be equal to that of T_4, only if dbh at harvest for T_4 was 24 cm (a difference of 6 cm), which is equivalent to a timber yield of 50 m^3 ha^{-1}. The results of this study, however, did not evidence such a large difference in dbh between trees under T_1 and T_4.

4. INTEGRATING DISCUSSION

4.1 Generation of carbon-stock inventory data for representative Indonesian homegarden systems to demonstrate that smallholder agroforestry systems can serve global environmental goals by targeting them for increased carbon storage (Objective 1).

Smallholder tree farming systems are diverse. They vary greatly in size, species components, tree density, tree age (size), longevity, and management intensity (of both the tree and annual crop components). Depending on local needs and opportunities, systems may focus on tree crops, agricultural crops, livestock, or a combination. Homegardens are a common smallholder system found throughout the tropics (Fernandes and Nair 1986, Nair 1989). Study I demonstrated that, depending on tree density, the aboveground biomass (primarily trees) of young homegarden systems (average age 13 years) contained an equivalent of 260–1180 trees ha^{-1}, which was, on average, 33% of the total carbon in the system. A study in an area neighbouring the Study I site reported that the tree biomass of 30-year-old agroforests and secondary forests accounted for 60–65% of total carbon and tree biomass while 120-year-old natural forests accounted for 80% (Tomich et al. 1998). In terms of carbon sequestration, systems with young trees, like the homegardens in Study I, continued to accumulate carbon steadily for a long time. The carbon content of homegardens in Study I compared favourably with that of five other common landuse systems in the area: mature agroforests, secondary forests, young rubber agroforests, *Imperata* grasslands, and cassava systems (Hairiah 1997). The homegardens contained 34.7 Mg C ha^{-1} more (58 times greater) than *Imperata* systems and 21 Mg C ha^{-1} more (1.5 times) than young rubber agroforests. Mature agroforests and secondary forests contained higher carbon stocks than homegardens, by 66 Mg C and 51 Mg ha^{-1}, respectively, owing to the young trees in the homegardens. As homegarden systems grow older, their carbon stocks can be expected to equal or surpass those of similarly aged other systems. Like other agroforestry systems, homegardens also provide food, other products, and income for farm families (Fernandes and Nair 1986, Nair 1989).

4.2 Identification of the types of agroforestry systems that are appropriate for carbon storage, the types of technical assistance that will enhance smallholder agroforestry systems, and the types of enabling conditions that favour smallholder benefits and carbon-project success (Objective 2).

Study II expanded the focus of Study I to include all smallholder agroforestry systems. Based on the characteristics stated in the second sentence of the previous paragraph, smallholder systems were grouped into the following eight categories: agroforests, tree gardens, plantations, improved fallows, rows or scattered trees, livestock systems, community forests, and assisted natural regeneration. This classification is similar to the landuse systems suggested for carbon project appraisals by other authors (Smith and Scherr 2002, MOE 2003). A description of each smallholder agroforestry system category and characteristics are given in Table 6. The classification in Study II emphasizes tree density, longevity of the tree component, and products from the systems. Not all smallholder agroforestry systems hold the same potential for carbon storage. Systems with greater tree density and longer maximum age of the tree component have greater carbon storage capacity or potential. Agroforests, tree gardens, plantations, and community forests generally have high tree density and longevity of the tree component. An analysis of literature (I, Tomich et al. 1998, van Noordwijk et al. 2002) yielded the following indicative carbon stock potential: 350 Mg ha^{-1} for agroforests, forest tree gardens, and community forests (age +60 years); 300 Mg ha^{-1} for timber plantations (+40 years); 240–280 Mg ha^{-1} for homegarden systems (+60 yrs); 200 Mg ha^{-1} for rubber gardens (+30 yrs); 190 Mg ha^{-1} for rubber plantations (+25 yrs); 180 Mg ha^{-1} for oil palm plantations (+20 yrs); 160 Mg ha^{-1} for coffee gardens (+25 yrs); 100 Mg ha^{-1} for coffee plantations (+25 yrs). Studies I and II noted that systems of the same age and tree density may have lower carbon stocks if they contain a significant number of low-biomass, but economically important, species such as banana and coconut. The analysis found that scattered-tree systems and livestock systems have low potential for carbon storage. Improved fallows, intercropping and assisted natural regeneration are transient systems that can be used to establish tree-based, smallholder agroforestry systems and thus might be part of a carbon investment strategy rather than a target system themselves.

Most smallholder farmers prefer systems that produce a variety of both wood and non-wood products as a means of securing tree products for household use, generating income and limiting risk. Clearly most of the aboveground carbon stock in any smallholder agroforestry system is found in the tree component. Most non-wood products—fruits, vegetables, spices, oils, etc.—are harvested with negligible impact on the carbon stock of the system. In contrast, the removal of wood biomass, especially timber, has a significant negative impact on a system's carbon stocks. However, a limited amount of timber can be harvested from smallholder agroforestry systems and still achieve appreciable carbon sequestration. This is particularly true of smallholder systems that include a mix of tree species types. Analysis based on the smallholder systems of Study I demonstrated that 20–40% of the growing stock can be harvested for timber at year 20, while the system still accumulates additional carbon. The projections estimated aboveground carbon stocks of 236.1 and 199.7 Mg ha^{-1} for 20% and 40% timber harvests, respectively (Table 6). Those stocks are 231.6 Mg ha^{-1} (52.6 times) and 195.3 Mg ha^{-1} (44.4 times) greater than the carbon stock of the *Imperata* grasslands/agricultural fallow systems (4.4 Mg ha^{-1}) (Palm et al. 1999), which would be targeted for conversion to smallholder agroforestry in a carbon investment scheme. These projections are fair, as they are similar to the aboveground carbon stocks of 60-year-old community forests: 228–246 Mg ha^{-1}, assuming aboveground carbon is 65–70% of total carbon (Tomich et al. 1998). Actually, it is more likely that smallholders would employ periodic, rotational harvesting, maintaining higher carbon stocks than projected. This analysis demonstrated that smallholder systems can sequestrate carbon while also producing timber.

Besides the aboveground (tree) biomass, soils can also contain an appreciable amount of an agroforestry system's total carbon. Generally, the absolute amount of soil carbon stored in a system increases slowly with time. However, the portion of the system's total carbon stock in the soil decreases with time as the tree component grows. The original level of soil carbon is an important baseline that needs to be maintained, as a loss in soil carbon negatively affects a system's total carbon stock and soil health affects tree growth/productivity. Cleaning, weeding, burning and relocation of biomass are common management practices that lead to steady loss in soil carbon when practised to excess. Caution is required. Intercropping with annual crops should be limited to the first 1–3 years after the establishment of an agroforestry system and management practices should control soil erosion and maintain/return biomass to the soil. Model simulations indicate that these soil management practices can maintain, and possibly increase, soil carbon levels, soil nutrient levels and system sustainability (Wise and Cacho 2002).

Table 6. *Projection of aboveground carbon stocks for homegarden systems, assuming current (age 13 years) aboveground carbon stocks of 59 Mg ha^{-1}, with 60-year maximum age, and a timber harvest in year 20.*

Species component	Species % of homegarden	Current aboveground carbon stock (Mg ha^{-1})	Maximum/ current age (years)	Maximum aboveground carbon stock (Mg ha^{-1}) at 60 yrs
Example 1				
Non-timber species: Maximum age of 60 years	60	35.4	60/13	163.4
Timber species: Rotation age of 20 years	40	23.6	20/13	36.3
Total	100	59.0		199.7
Example 2				
Non-timber species: Maximum age of 60 years	80	47.2	60/13	217.9
Timber species: Rotation age of 20 years	20	11.8	20/13	18.2
Total	100	59.0		236.1

Study II showed that to achieve appreciable carbon storage, smallholders should convert low-biomass, underutilized landuse systems into agroforestry systems that maintain high tree density of species that are managed for long rotations and avoid the loss of soil carbon. It may also be beneficial to limit the number of low-biomass species, such as coconuts and bananas, but must be balanced with farmers' livelihoods and market objectives and opportunities.

Carbon is a new and mysterious product for smallholder farmers, even less tangible than other environmental services, such as watershed protection or biodiversity conservation. Farmers must feel confident that they will benefit from their efforts. The agroforestry systems developed to achieve carbon storage must be socially and economically viable independent of carbon payment and not be intended solely to provide society with carbon sequestration services. Agroforestry systems that provide tangible socioeconomic benefits are less likely to be converted to other landuse systems. The study recommended that farmers receive a carbon payment for tree cultivation to promote transparency as well as farmers' understanding of the services their agroforestry system provide. However, any income received from carbon payments should be treated as an additional return for the service. This approach would help protect smallholders from project or market failure. Within the domain of economically viable agroforestry systems, clear opportunity exists for smallholders to select management practices that lead to higher carbon stocks at the system level.

An analysis of carbon sequestration and watershed protection projects in Latin America by Grieg-Gran et al. (2005) determined that direct payment (cash income) for carbon services was important to family income. Compensation varied from up-front payments per hectare to annual payments per hectare for tree system maintenance, which could vary by system type. Smallholder families realized larger financial benefits from the sale of products, including timber, produced in the tree-based systems established through the projects. Assisting families with system establishment enhanced success. The authors recognized that in order for positive income and other benefits to occur, efforts were required to reduce smallholders' transaction costs, remove access and policy restrictions, and balance the interest of the project with those of participants. Other authors have also identified such concerns (Murdiyarso 2005, Boyd et al. 2007, Perez et al. 2007, Peskett et al. 2011). These issues are addressed below.

As described above and in the introduction, smallholder agroforestry systems are viable options for enhancement of livelihoods and carbon storage. However, they have not developed equally in all areas. There are number of factors that might restrict the development of smallholder agroforestry. Many farmers have little experience with intensive tree planting or marketing tree products and little access to technical information and germplasm. Besides a shortage of forests and market demand for tree products, the following factors have strong bearing on the successful development of smallholder agroforestry systems: i) secure land tenure and landuse conditions; ii) supportive policy conditions; iii) access to, and knowledge of, the management of quality germplasm; iv) tree management skills and information; and v) adequate market information and links (II, Roshetko et al. 2007b, Roshetko et al. 2004b). The first two factors, i.e. land tenure and policy support, are basic enabling conditions required to facilitate the development of smallholder systems and are discussed below under *stable and enforceable rules and access to land and trees*.

The other three factors of quality germplasm, tree management and market links are technical issues that can be effectively addressed at the local level by government extension agencies, non-government organizations, farmers' organizations and/or individual farmers, once the enabling conditions are satisfied (Roshetko et al. 2007b). Scientific research is an important means to compile and generate specific tree management technology for smallholders' conditions and could not be generated by farmers. Examples include studies on the alder-based cardamom agroforestry systems in eastern Himalaya, India (Sharma et al. 2008); how to convert *Imperata* grasslands, which develop from fallowed agriculture land and degraded forests; and smallholder tree-farming systems in Indonesia and the Philippines (de Foresta and Michon 1997, van Noordwijk et al. 2008).

Also, efforts should be made to link smallholders with sources of quality tree germplasm and technical support to effectively manage agroforestry systems, including farmers' nurseries (Simons et al. 1994, Harwood et al. 1999, Gunasena and Roshetko 2000, Tolentino et al. 2001). This should include the implementation of training activities, links with effective institutional technical support, and the development of a cadre of 'farmer specialists'. Training and participatory nursery development are proven methods of building farmers' awareness, leadership, and technical skills, as well as independence regarding germplasm quality, production and management capacity (Koffa and Roshetko 1999, Koffa and Garrity 2001, Carandang et al. 2006, Roshetko et al. 2008b). Specifically, the development of farmer-to-farmer extension capacity is an important step towards helping local communities to create viable smallholder agroforestry systems (Roshetko et al. 2007b, Roshetko et al. 2012). Finally, as farmers generally have poor understanding of, and links to, markets (Hammett 1994, Arocena-Fransico et al. 1999, Roshetko and Yuliyanti 2002, Holding-Anyonge and Roshetko 2003, Tukan et al. 2006, Fonsah et al. 2008), the development of accessible markets for tree products is a vital to the evolution of successful smallholder systems (Scherr 1999 and 1995, Potter and Lee 1998, Landell-Mills 2002, Fonsah et al. 2008).

Smallholder investment in trees is one component of their overall landuse and livelihoods' systems. They are not likely to be solely interested in carbon storage for public benefit. Additionally, some efforts to achieve increased carbon storage in landuse systems may have negative implications for rural residents, particularly the poor, by restricting access to land or binding communities to long-term landuse management practices that do not meet their socioeconomic needs. Starting with the initial findings of Study I, Study II reviewed relevant literature—including lessons learned from other environmental service projects, tree-based development projects and timber outgrower schemes—to identify the enabling conditions that favour benefits for smallholders from carbon projects: integrated planning and project design; establishing clear, stable and enforceable rules of access to land and trees; managing high transaction costs; and ensuring dynamic flexibility for co-generating other environmental services. A summary of the analysis of each factor is provided below.

Integrated planning and project design: adequate food security, off-farm employment, sufficient household labour, higher education levels, land access, supportive policies and lower risks have all been correlated to successful tree-planting activities. Efforts should be made to identify the community's development priorities, particularly those related to agricultural productivity, even if formal priorities do not exist. A project might not be able to assist with infrastructure, health care or education but it should be aware of those issues, avoid being an impediment and, if possible, provide direction to possible support. Providing support to strengthen community institutions and leadership can be achieved through agroforestry activities. That type of community capacity building may be the most significant contribution to the development of viable smallholder agroforestry systems.

Establishing clear, stable and enforceable rules and access to land and trees: secure land/tree tenure and supportive policies are prerequisite for the development of spontaneous or project-based smallholder tree farming systems. Farmers' tree-planting activities are based on vested self-interest. Therefore, without guaranteed rights broad-scale establishment of smallholder agroforestry systems will not occur. Tenure rights must be part of a wider process that addresses communities' development needs and not just as a 'carrot' to encourage people to plant trees. Developing supportive tenure and policy conditions requires broad-based negotiations that include participation from local, regional and national governments, the private sector and community organizations.

Managing high transaction costs: most community-oriented tree-planting and carbon projects involve various types of partners and large numbers of farmers. The objectives and activities of the project, as well as the responsibilities and benefits of each party, should be clear and determined through negotiation. Project terms should be equitable, realistic and formalized. Communication should be open. Such projects are likely to have high transaction costs due to i) making information accessible to multiple partners; ii) facilitating and/or enforcing agreements; and iii) implementing monitoring systems. To help manage high transaction costs, the authors suggested that smallholder-oriented projects be combined with other development or research activities as a means of expanding the required funding base. What combination of financial resources is required and how these resources are allocated to cover costs and incentives is best determined at project level. While these mechanisms are promising, however, to date there has been little experience of the implementation and operational costs of smallholder-oriented carbon projects (Tomich et al. 2002). The subsequent challenge is to gain experience in the operation of smallholder-oriented projects and develop mechanisms that reduce these costs.

Ensuring dynamic flexibility for co-generating other environmental services: the development of smallholder agroforestry systems generate tree products, carbon storage and other environmental services, such as biodiversity conservation and watershed conservation. These services generate benefits to different sectors of society and may warrant payments to reduce scarcity and ensure sustainability. Markets for these services remain in various stages of development and most are intended to benefit smallholders. Pro-poor payments for landscape amenities (for example, eco-tourism) and watershed services require the same enabling conditions that were discussed for carbon markets above. Hence, the design of tree planting and/or carbon projects needs to be flexible to allow for the generation of multiple products and services by the smallholder systems.

4.3 Evaluation of the issues of 'additionality', 'leakage' and 'permanence' from the point of reference of smallholder agroforestry systems and carbon projects (Objective 3).

Additionality, leakage and *permanence* are three issues relevant to the question of smallholder agroforestry systems for carbon projects. *Additionality* requires that carbon stocks accrued to a carbon project are 'additional' to those that would occur without the project. The following conditions indicate that the carbon accrued to smallholder agroforestry projects would be additional. As established in the introduction of this thesis, over the last 10 years Asia has begun to expand its forest cover. But this achievement is primarily due to the efforts of China, India, Thailand and Vietnam. Other countries in the region continue to lose forest cover; and have large areas of land in need of rehabilitation (FAO 2010, FAO 2011). Studies I and II and related work (Roshetko et al. 2007b, Roshetko et al. 2004b) established that a minimum threshold of technical support and enabling conditions are required to make smallholder agroforestation possible and that those conditions do not yet widely exist. Certainly, support that facilitates smallholder agroforestation of degraded lands would qualify for carbon credits.

Leakage is the loss of carbon, primarily as woody biomass, in non-project areas owing to changes in landuse practices resulting from activities within the project area. The conversion of low-biomass (carbon) degraded landscapes to smallholder agroforestry systems is not likely to cause significant leakage from other landscapes, particularly when degraded lands are common. For example, Study I argued that the rehabilitation of *Imperata* grasslands would not result in the loss of carbon elsewhere because those grasslands, and other degraded land, are currently underutilized and abundant. In fact, agroforestation of low-biomass ecosystems may provide 'negative leakage' by preventing deforestation or forest degradation through the establishment of on-farm sources of trees (Smith and Scherr 2002, Sanchez 1994, Schroeder 1994).

Permanence concerns the longevity and stability of carbon stock. Carbon stocks in any landuse system, although theoretically permanent, are potentially reversible through human activities and environmental change, including climate change (Brown et al. 2001). By comparison, the permanence of emission avoidance/reduction through the energy sector is not at risk. Study II established the advantages and disadvantages of carbon projects related to conservation, industrial forestry, and smallholder systems. Conservation projects were identified as permanent carbon storage protected by legal, political and social action. However, at the time of the study, averted deforestation projects were not eligible for carbon credits. Industrial forestry was acknowledged as reliably sequestering large quantities of carbon through woody biomass production, but their rotational establishment/harvesting production system was neither permanent nor additional. Smallholder systems were recognized as challenging owing to high transaction costs related to the large numbers of farmers who would be involved in any project and the services required to help those farmers develop viable agroforestry systems. Studies I and II contended that the tree-rich, diversified, economically oriented systems smallholders established provided secure livelihoods' benefits to communities. Additionally, smallholders' flexible land management practices were a strength that allowed farmers to adapt their agroforestry systems to fluctuating markets or other socioeconomic conditions. Tree cover might fluctuate at the farm level but at the community or project level tree cover would continue to expand under the supportive influence of the enabling conditions discussed above. As they are often established on degraded low-carbon landscapes, smallholder systems would continue to store and accumulate carbon for 20–50 years (Watson et al. 2000).

4.4 Identification of 'genetic level' responses by trees to environmental change in the specific context of smallholder agroforestry systems and how that knowledge can be translated into action to better manage tree genetic resources in smallholder farms for more productive and sustainable environmental management (Objective 4).

Studies in both temperate and tropic regions report the rate of migration required for plant species to keep up with the temperature and rainfall transformation caused by anthropogenic climate change greatly exceed the natural migration rates of plants (Pearson 2006, Malcolm et al. 2002). The conversion of forests to annual crop systems further impedes natural migration by creating barriers between fragmented forest populations. The reestablishment of trees in these agricultural landscapes reconnects these populations, enabling forest ecosystems to better respond to climate change (Bhagwat et al. 2008, Thuiller et al. 2008). Study III presents the case that agroforestry ecosystems facilitate the translocation of germplasm in ways not possible in natural ecosystems. 'Facilitated translocation' involves human movement of tree seed and seedlings, associated micro-organisms and animal pollinators from existing to new sites of human occupation (Guariguata et al. 2008, MacLachlan et al. 2007). In the past, human-facilitated translocation of germplasm occurred formally and informally, by individuals and organizations, but was frequently not well-documented. Fundamental to the use of human-facilitated translocation as a response to climate change is an understanding of global circulation models (GCMs) that predict temperature and rainfall transformation resulting from anthropogenic climate change. GCMs are complicated, with predictions differing between models. Combining these predictions with an understanding of current species' distribution will inform where and how species translocation should occur.

Three interventions that can assist with facilitating species' transformation are i) tree-species matching and genetic variation; ii) exchanging germplasm between countries; and iii) delivering site-matched germplasm to smallholders. There is significant variation among populations of any species, with locally sourced germplasm often performing well, as reported for *Gmelina* in Indonesia in Study IV. Most of our understanding of species' population-level performance under smallholder conditions has been generated in field trials that did not consider the effect of anthropogenic climate change. A small number of recent trials have been designed and established with climate change in mind (Sanou et al. 2007, Weber et al. 2008, Sotelo-Montes and Weber 2009). More of such trials are needed on a wider range of priority species, sampling germplasm from a wider environmental range, and sharing results with a broad set of partners across the range of priority species.

As we adjust to the geographic shift in future climate conditions, sharing not only information but germplasm will become increasingly necessary (Vinceti et al. 2009). Between-country sharing (translocation) of germplasm for research and production is becoming more difficult and costly as nations seek to conform to commitments under international conventions. New approaches will be required to facilitate translation of promising germplasm between nations.

At national levels, the formal tree germplasm sectors (including national tree seed centres) primarily link government agencies, research organizations, and the private plantation sector. Experience indicates that national tree seed centres and other institutes at the national level are ineffective at providing quality tree seed to farmers and local organizations (Harwood et al. 1999, Graudal and Lillesø 2007). An informal seed sector often evolves to serve local seed users/customers (Koffa and Roshetko 1999, Harwood et al. 1999, Roshetko et al. 2008b). Local seed sector enterprises are usually operated at low cost by farmers and effectively serve the needs of local communities (Muriuki 2005). Both the formal and informal seed sectors serve vital roles. To assure that site-matched germplasm of priority species is delivered to farmers and local organizations, it is necessary to develop effective mechanisms that link the national formal tree seed sector with local informal ones.

Study III recognizes that the testing and adaptation of local germplasm to changing environmental conditions is an alternative to translocation of genetic material. This option is based on the common finding that local germplasm often performs well, demonstrating adaptation (micro-evolution) to local environmental conditions. However, the study also acknowledges that on-farm tree populations commonly share a number of disadvantages related to local adaptation. Theoretically, populations with higher effective population size have a greater potential for local adaptation. Related characteristics include high census numbers, high genetic diversity, outcrossing breeding, high seed yields, and pollen and seed that can be dispersed over long distances. This is supported by the concept of ‘sustainagility’, where agrobiodiversity at the gene- and species-levels makes landscapes more adaptable to future climate change (Jackson et al. 2007, Jackson et al. 2010). Many on-farm tree populations have low genetic diversity compared to natural populations (Dawson et al. 2009) because they are composed of a limited number of trees originating from a single introduction of germplasm of a narrow collection (Lengkeek et al. 2005a, Kindt et al. 2006). A related problem can occur if the best seed is intensively harvested for other uses, resulting in limited natural regeneration (Raebild et al., 2011) from unselected seed which may represent undesirable genetic material. Additionally, from a breeding point of view, tree populations on individual farms are often isolated. These characteristics limit genetic diversity and lead to inbreeding. Concerns regarding the limited size of on-farm tree populations are further exacerbated by climate change, which effects the life cycles of both the tree populations and their pollinators (NRC 2007, Parmesan 2007, FAO 2008a). Fortunately, practical measures exist that can increase effective on-farm tree population size. Key recommendations include farmer-to-farmer seed exchange (Lengkeek 2003, Roshetko et al. 2004c, Mulawarman et al. 2004) and the distribution of tree seed of priority species of known quality genetic source. Additional recommendations are the protection and promotion of pollinators (FAO 2008a), protection and promotion of on-farm natural regeneration, and training of farmers in appropriate tree seed collection and management methods (Dawson et al. 2009, Mulawarman et al. 2003).

Another option is the utilization of tree species (varieties or provenances) of high plasticity that perform well under a broad range of environmental conditions without genetic change (Gienapp et al. 2008). Evidence suggests that over the last few centuries humans have selected and promoted relatively plastic exotic species that grew well under various biophysical and socioeconomic conditions (Koskela et al. 2009). Success in one or more locations resulted in those species being introduced and promoted to a greater number of locations. Examples of plastic tree species include *Gmelina arborea* (the focus of studies IV and V), various *Eucalyptus* species, and fast growing multiple-use leguminous genera *Acacia, Leucaena, Gliricidia* and *Calliandra*, all of which are widely planted and utilized outside their native range under various environmental conditions (Roshetko 2001a). Such species are likely to perform well in the varying temperature and rainfall conditions anticipated under global climate change scenarios. Many indigenous species are not likely to have evolved the genetic diversity to cope with climate change, as they have a restricted distribution with a narrow range of climates and have not adapted to a range of various conditions. Characteristics of many plastic exotic species are fast growth and high competitiveness for water, light and nutrients. They may be considered weeds, out-compete and threaten to displace indigenous species. The utilization of plastic exotic species as a means to adapt to climate change should be combined with efforts to identify and improve the plasticity of valuable indigenous species.

4.5 Evaluation of the cultivation and utilization of *Gmelina arborea* as a viable species for smallholder tree farming in Indonesia (Objective 5).

Gmelina arborea is easy to cultivate and widely grown in South and Southeast Asia. In Study IV, *Gmelina* was identified as a common component of government planting programs and industrial plantations in Indonesia, but not in smallholder systems. By contrast, *Gmelina* was widely and successfully planted by farmers in the Philippines at that time. In their agroforestry systems, smallholders in Indonesia commonly cultivated multiple species on 0.25–1.0 ha of marginal or degraded agriculture land. The tree component included timber, fruit, multipurpose species, and commodity crops (rubber, cacao, rubber etc). Annual crops were usually intercropped for 2–3 years after tree establishment. Subsequently, shade-tolerant crops might be cultivated in the understorey. Both long-rotation, premium-value timber and short-rotation timber species are planted by Indonesian smallholder farmers. *Paraserianthes falcataria* is a common short-rotation smallholder timber species in Indonesia (I, Manurung et al. 2005, Hariri et al. 2002). *Gmelina* also seems appropriate for smallholder agroforestry systems in Indonesia. However, Study IV found that *Gmelina* was not popular with farmers or NGOs and the *Gmelina* germplasm suppliers primarily target government agencies and the forestry industry. Experience with *Acacia mangium* indicated that *Gmelina* could become popular with farmers if trials demonstrated *Gmelina* performed well under farmers' conditions and if timber markets were to become accessible.

In the trials of Study IV, *Gmelina* demonstrated excellent survival and growth under farmers' conditions of low management and no fertilizer amendments on good-to-fair sites but performed poorly on degraded sites. This agreed with smallholder experiences in the Philippines (Bertomeu 2004). *Gmelina* performed well compared to *Paraserianthes falcataria* and a *Eucalyptus* hybrid, the other fast-growing, short-rotation timber species in the trial. *Gmelina* demonstrated better survival and diameter growth while the other species had better height growth. Farmers participating in the trials selected narrow tree spacing—4 x 2m to 3 x 3m, to make the most of their limited land resources. As trees grow, they need more space to maintain fast growth. However, participating farmers were reluctant to thin, instead preferring to plant at final density. Reluctance to thin trees was also identified with smallholder teak farmers in central Java (Roshetko and Manurung, 2009). A recommended solution to this dilemma is to plant alternating rows of fast- and slow-growing timber species, with short-rotation species harvested in 5–8 years and long-rotation species harvested after 20–30 years or longer. That recommendation fits the scenario suggested in Study II where smallholder systems would sequestrate carbon while also producing timber (see Table 6). Farmers started pruning branches at six months to improve stem form and decrease shading of companion crops. They were not concerned with effect of pruning on tree growth. Most farmers practised moderate pruning, reducing live crown ratio (LCR) to about 40%; some farmers practised heavy pruning, retaining LCRs of only 10%. Study V recommended light-to-moderate pruning (retaining LCRs of 40–70%) when timber production is the main objective, but more intensive pruning (retaining LCRs of 20–30%) for systems where timber is intercropped with annual crops. This is similar to pruning recommendations for smallholder teak production systems in Indonesia (Pramono et al. 2011). Heavy pruning that retains LCRs of 10% severely inhibits tree growth (Bertomeu 2004). Rotation age for *Gmelina* in Indonesia was reported to be 8–12 years for farmers (Yuliyanti 2000) and 7–10 years for industry (I). However, *Gmelina* can be marketed at 3–5 years if farmers need the money. Farmers can maximize profit by producing and selling sawn timber of *Gmelina*, as opposed to selling logs. The opposite is true of premium timber species like *Tectona grandis* (Holding-Anyonge and

Roshetko 2003, Yuliyanti 2000). Most smallholder-grown *Gmelina* timber and logs are sold in local markets.

Some trees in Study IV and neighbouring areas exhibited inferior stem form. This likely resulted from the use of inferior germplasm, as most *Gmelina* seed in Indonesia is collected without the use of collection guidelines (Roshetko et al. 2008b). In Indonesia, the survival and productivity of *Gmelina* is closely linked to seed source selection (Wijoyo 2001) with local landraces often performing well (Lauridsen et al. 1995). Study III also identified seed collection guidelines, seed source selection, and local landraces as important adaptation responses of tree genetic resources to climate change. Use of farmer demonstration trials (Roshetko et al. 2005) was an effective research approach that also increased farmers' participation and enhanced their knowledge. Farmer participants credited the trials with i) demonstrating the advantages of good quality germplasm; ii) expanding farmers' interest in tree farming; and iii) promoting farmers' innovations. This participatory trial approach could be combined with consideration of climate change, as suggested in Study III, to enhance the relevance of results to both farmers' needs and climate change scenarios. In a recent study Narendra et al. (2012) recommend that smallholder tree domestication efforts with *Gmelina* should focus on access to and dissemination of quality germplasm, silvicultural practices to improve tree growth and log quality, and planting models that integrate long- and short-rotation species.

4.6 Investigation of the effect of various pruning regimes on *Gmelina arborea* growth and maize yield and their implications on the financial returns of smallholder timber production systems (Objective 6).

As discussed previously, smallholder farmers are not solely timber producers. Their systems are managed for multiple objectives and yield multiple products. Food security and short-term income are priorities that normally take precedence over timber production. Thus, intercropping timber with annual crops is a suitable system for smallholders. Study V demonstrates that pruning can be an effective practice to increase productivity and profitability of maize-*Gmelina* systems by extending the intercropping period. However, as pruning can slow tree growth, diameter increment and timber yields, the level of pruning intensity practised is the paramount decision to be taken. Results from Study V provide evidence that while intensive pruning (LCR 20–30%) was beneficial for maize production, it may reduce timber yields below levels that are acceptable to farmers wishing to grow commercial timber. These results are consistent with those of others studies in the Philippines and Indonesia (Miah 1993, Gonzal 1994, Manurung et al. 2009), as well as the deductions from Study IV. The financial analysis in Study V shows that under intensive pruning, increases in grain yield compensated for reduced timber yields of up to 6% (1 cm difference in average diameter at breast height (dbh) at harvest). Based on projections, even if intensive pruning reduced dbh by 3 cm (16% in timber volume), combined returns to labour for maize and timber are greater than under moderate pruning intensity (LCR 60–70%). The analysis also showed that moderate pruning would provide the same returns to labour as intensive pruning only in the unlikely event that intensive pruning reduced final dbh by 6 cm compared to moderate pruning.

One reason many farmers do not practise pruning is the labour requirement. In Study V, the intensive pruning regime required 24 days ha^{-1}of labour more than moderate pruning. To be effective, pruning needs to be implemented during the cropping season, before the maize plants emerge. Availability of household labour is often low during that time, making it difficult to implement intensive pruning. An option that may overcome the labour needs associated with tree establishment and management is to plant at final or quasi-final spacing (250–400 trees/hectare). This option matches farmers' preferences and common practices, as reported in Study IV. Modeling of native timber trees intercropped with maize in the Philippines supports the concept of planting at wider spacing (Martin and van Noordwijk 2009). However, timber trees planted at wider spacing require more pruning labour as there are likely to be more and larger branches. Kerr and Morgan (2006), working with four temperate timber species planted at densities of 600 to 1,370 ha^{-1}, found that intensive pruning of trees planted at wider spacing did not improve timber quality. Another option for smallholder timber producers to reduce pruning labour is to select species that are less management intensive. A study on smallholder timber management in the Philippines showed that growing *Swietenia macrophylla* (mahogany) and *Eucalyptus deglupta* ('bagras') required considerably less labour compared to *Gmelina* (Bertomeu 2004). The study concluded that the narrow crown and smaller branches of mahogany and the straight stem and self-pruning habit of bagras were characteristics that reduced management requirements. When selecting a timber species for planting, the advantages of architectural characteristics must be balanced with market preferences and demand.

In the Philippines and Indonesia, smallholders have emerged as important timber producers for the local wood industry (Bertomeu 2008, Tukan et al. 2004, Rohadi, et al. 2011). However, common smallholder management practices result in small diameter and low quality timber, which have low market demand and value. Studies in both countries show that traders and processors are willing to pay smallholders a premium for better quality timber (Bertomeu 2008, Tukan et al. 2004, Roshetko et al. 2004a, Perdana et al.

2012). Therefore, managing for larger diameter, better quality timber is recommended for both short-rotation and long-rotation species (V, Pramono et al. 2011).

In commercial forestry, moderate pruning is recommended to improve tree form and reduce knots, increasing the yield and value of quality timber. In the case of smallholder agroforestry, where preference is given to food security and short-term income, intensive pruning is practised to increase annual crop yields without excessively reducing timber production. The question remains what pruning strategy yields quality timber that commands a higher market price. Results from Study V imply that frequent intensive pruning during the first 2–3 years of intercropping is compatible with the production of knot-free quality timber. The key to success is that pruning is properly implemented.

5. CONCLUSIONS

The work presented in this thesis demonstrates that smallholder tree farming systems are agricultural and natural resource management systems that contribute significantly to global environmental goals and local economic objectives. The key characteristics of smallholder systems that achieve those accomplishments and are emphasized in this thesis are significant carbon storage, diverse genetic and species components, and the production of products for home use and market sale.

While individual smallholder agroforestry systems are of limited size and by themselves store small amounts of carbon, on a per area basis smallholder systems accumulate significant amounts of carbon, equalling the amounts stored in other tree-based systems. Smallholder agroforestry systems greatly exceed the amount of carbon stored in degraded landscapes, fallowed agriculture land, and other low-carbon land-use systems, which they generally replace. Not all smallholder systems hold the same potential: from a carbon storage perspective, smallholder systems should maintain high tree density, contain species that attain large size, and be managed for long rotations. However, farmers' needs and objectives are of crucial importance. Most smallholders prefer systems that provide a mix of products to meet household needs and market demands. Smallholder systems must be economically viable independent of carbon payments. Income from carbon payments should be considered as an individual return for the carbon service.

As smallholders and smallholder communities often have limited links with support agencies and market entities, the success of their systems will often benefit from technical and marketing assistance. Many efforts to achieve increased landuse-based carbon storage could have negative implications on local livelihoods by restricting access to land, land management options or product use. To avoid such problems, the following conditions should readily exist at any carbon project site. Land and tree tenure rights should be recognized or available to local residents. Additionally, institutional and policy conditions should support the establishment and success of smallholder systems. Farmers should be interested in agroforestry systems, have obtained food security and have sufficient access to labour and technical inputs (germplasm, information, expert consultation, and training) to establish and manage viable agroforestry systems.

To promote its own success and the distribution of appropriate benefits to smallholders who participate, any carbon project should be designed and implemented in close collaboration with project staff, governments, smallholder farmers and independent local institutes. Objectives and activities, as well as responsibilities and benefits, of each partner should be determined through negotiation, not set unilaterally. The negotiation process must be participatory, transparent and agreeable to all parties. The terms of the project should be formalized but remain flexible to address potential conflicts. The project should not stand separate from other local activities but rather be integrated into the community's broader development plans. Concerns over the permanence of the carbon stocks in smallholder agroforestry systems are not different from those of other fixed-rotation landuse systems. However, it can be argued that multi-species, multi-product agroforestry systems that support the livelihoods of smallholders are likely to be more permanent than commodity-based landuse systems. Questions of additionality and leakage may also be positively addressed. As stated above, sensibly designed carbon projects will provide the minimum threshold of technical support, market assistance and enabling conditions to facilitate the development of viable, sustainable smallholder systems. Certainly, facilitating such success would qualify for carbon credits. As smallholder agroforestry systems are most often established on degraded lands or otherwise low-carbon landuse systems, the process is not likely to cause significant leakage elsewhere, particularly as degraded lands remain abundant. The single greatest hindrance to developing smallholder agroforestry systems as a carbon project is the high transaction costs related to working with large numbers of smallholder farmers. The challenge is to develop mechanisms to reduce these costs through multilateral assistance, funds from private trusts and governments. The development of such mechanisms further strengthens claims of additionality. Carbon projects may not make farmers rich but if properly implemented, they could enhance local livelihoods, assuring that smallholders do benefit from the project investment.

Smallholder agroforestry systems can facilitate effective tree genetic resource-based responses to climate change through germplasm translocation to maintain physiological matching; the use of a broad range of more plastic species and provenances can address variability in conditions and uncertainty (both biophysical and socioeconomic); and promotion of tree populations with broad genetic base can encourage local adaptation. As with carbon storage, for these measures to be successful, efforts need to be participatory and provide policy, technical, and market support to smallholders.

A special measure required to effectively utilize tree genetic resource diversity is for researchers to assist in the identification of the best-performing provenances or landraces, and for farmers to understand the intraspecific diversity of individual species. Additionally, as smallholder systems provide a diversity of both wood and non-wood products, there is potential to reduce the pressure on forests to provide these same products. As the world's forests continue to decrease, an increasing proportion of the tree and forest products used by the expanding human population will be produced in other tree-based landuse systems, including smallholder agroforestry systems. Thus, agroforestry systems represent ‘climate-smart’ options that improve productivity and flexibility in the agricultural landscape under anthropogenic climate change.

Timber is a common component of smallholder agroforestry systems that contributes to on-farm diversity as part of farmers’ overall livelihood systems. Besides providing sources of income and on-farm wood, smallholder timber production has become an important source of raw material for local forest industries. Smallholder timber production is also compatible with carbon storage and sequestration under scenarios of periodic rotational harvesting. As mentioned in the previous paragraph, it can also be among the ‘climate-smart’ options by reducing the production pressure on natural forests.

Gmelina arborea is a viable option for smallholder agroforestry systems. It is easy to propagate and grows well in combination with other tree species and agricultural crops under conditions of low management on fair to good sites, conditions which occur in many smallholder sites. The productivity and profitability of *G. arborea* can be improved through proactive silvicultural management. Pruning and thinning are particularly important to reduce competition between trees and when agricultural crops are included. When intercropped with light-demanding annual crops, intensive pruning (retaining LCR of 20–30%) of *Gmelina* trees before crop production can generate greater returns from the system than moderate pruning (LCR 60–70%). The increase in yields of annual crops resulting from reduced shading compensates for the labour costs associated with pruning and the detrimental effects of intensive pruning on tree growth. To maximise returns from the agroforestry system, LCRs of 20–30% should be maintained until grain yields fall below the break-even point, at which time intercropping should be discontinued and tree management should prioritize the production of quality timber. Depending on local market conditions, the recommended rotation age for smallholder *Gmelina* may vary from 7–12 years. Likewise, depending on market conditions, farmers may maximize profits by producing sawn timber for village markets or by selling logs to sawmills. Traders and processors are willing to pay a premium for better quality timber. So, managing for larger diameter, better quality timber is recommended. This includes pruning to improve tree form and increase knot-free wood, and thinning to increase diameter growth. Although evidence from the studies is limited, *Gmelina* seems to hold promise as one component of a smallholder system that integrates short-rotation and long-rotation timber species: with short-rotation species intended for local markets and premium-quality long-rotation species intended for more lucrative national markets.

To summarize, smallholder agroforestry systems hold great potential to contribute to global environmental goals and local livelihood objectives. Under conditions of secure land tenure, supportive government policies, technical and marketing support, and the other enabling conditions stated in this thesis, smallholders can and will cultivate a wide range of tree species as a component of efficient, integrated and risk-averse livelihoods and agroforestry systems, and will effectively respond to the increased demand for wood and other tree products. Additionally, tree-rich smallholder agroforestry systems also store significant quantities of carbon and provide many other environmental services, including soil fertility replenishment, water catchment protection, biodiversity conservation, intraspecific genetic conservation, reforestation, and reduction of production pressure on natural forests. To harness the potential of smallholder agroforestry systems a *paradigm shift* is required to recognize and support smallholder tree-farming systems as part of the solution to achieve global environmental goals and local economic objectives.

6. FUTURE PERSPECTIVES

Smallholder systems are under-recognized and should be prioritized for further research and support that both test and demonstrate the validity of the hypothesis. Research that builds on the studies presented in this thesis is recommended in this section. Some of that research has been recently published by the author and colleagues and some is currently underway.

A review of agroforestry system domestication has been published that illustrates how smallholder systems have evolved over the last 20 years and are making significant contributions to globally environmental goals and local economic development (Leakey et al 2012). A study that compiles and documents the value of trees and tree genetic resources to the livelihoods of rural communities was conducted by Dawson et al 2013b. Additionally, a review of the contributions of smallholder agroforestry systems to the conservation of tropical tree diversity in *circa situm*, *in situ* and *ex situ* conditions has been published (Dawson et al 2013a).

Related to tree germplasm, studies should be conducted on the evolution of household or group nurseries to become market-oriented commercial nurseries and the involvement of smallholder enterprises in national seed and seedling delivery systems. A broader study is also required on sustainable models of seed and seedling supply for agroforestry tree species. Work has begun on these topics with colleagues from Department of Geosciences and Natural Resource Management, Faculty of Scienc, University of Copenhagen.

Forest areas continue to decrease, while demand for tree and agricultural products increases with the expanding human population. There is a need to research understorey crop production as a means to increase food security, expand agricultural production in landscapes where available land is shrinking, and cope with climate change where temperatures may increase rapidly in some locations. The intensification of agricultural production in smallholder agroforestry landscapes is also required, including the effects of silvicultural practices on crop production. Initial work on vegetable agroforestry systems has been conducted and published in Indonesia (Roshetko et al. 2012).

Specific to smallholder timber production, research is needed to identify options to increase commercial yields by integrating short- and long-rotation species. Further research is required on the trade-offs of planting at final spacing, and intensities of thinning and pruning in both monocultural and intercropped plantations. Assessments of what impedes farmers from adapting effective silvicultural practices should be implemented. This would include long-term studies, through a full rotation, of integrated smallholder timber, agricultural and livestock production. Computer simulations of these dynamic, diverse systems should be conducted.

Finally, smallholder marketing systems should be researched. Rapid market appraisal methods appropriate for smallholder agroforestry products should continue to be developed and evaluated. Improving smallholder income generation through market integration, value-added processing and collective participation should be studied. That could include understanding market competition and smallholders' options to address competition. Market integration strategies to sustain commercial production and market links should be developed for various types of smallholder agroforestry products.

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8. REFERENCES

Acharya, KP. 2006. Linking trees on farms with biodiversity conservation in subsistence farming systems in Nepal. Biodiversity Conservation 15:631–646.

[ADB] Asian Development Bank. 2004. *Key indicators 2004: poverty in Asia: measurements, estimates, and prospects*. Manila: Asian Development Bank.

[ADB] Asian Development Bank. 2006. *Key indicators 2006: measuring policy effectiveness in health and education*. Manila: Asian Development Bank.

Ahmed P. 1989. Eucalyptus in agroforestry: its effects on agricultural production and economics. *Agroforestry Systems* 8(1):31−38.

Aitken SN, Yeaman S, Holliday JA, Wang T, Curtis-McLane S. 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications* 1:95–111.

[ARD] Associates in Rural Development. 2004. *Forest conflict in Asia: undermining development and security*. Jakarta: ARD, INC.

Arocena-Francisco H, de Jong W, Le QD, de Guzman RS, Koffa S, Kuswanda M, Lawrence A, Pagulon A, Rantan D, Widawati E. 1999. Working Group 1: external factors affecting the domestication of agroforestry trees (economics and policy). In: Roshetko JM, Evans DO, eds. *Domestication of agroforestry trees in Southeast Asia*. Forest, Farm and Community Tree Research Reports. Special issue 1999. Morrilton USA: Winrock International. p. 212–213.

Barney K. 2008. Local vulnerability, project risk, and intractable debt: the politics of smallholder eucalyptus promotion in Salavane Province, Southern Laos. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services*. Amsterdam: Springer Science + Business Media. p. 263–286.

Barr C, Resosudarmo IAP, Dermawan A, McCarthy JF, Moeliono M, Setiono B. 2004. *Decentralization of forest administration in Indonesia: implications for forest sustainability, economic development and community livelihoods.* Bogor, Indonesia: Center for International Forestry Research.

Bertomeu M. 2004. Smallholder timber production on sloping lands in the Philippines: a systems approach. Manila: World Agroforestry Centre (ICRAF).

Bertomeu, M. 2008. Can smallholder tree farmers help revive the timber industry in deforested tropical countries? A case study from southern Philippines. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services*. Amsterdam: Springer Science + Business Media. p. 177–191.

Bertomeu M, Roshetko JM, Rahayu S. 2011. Optimum pruning strategies for reducing crop suppression in a gmelina-maize smallholder agroforestry system in Claveria, Philippines. *Agroforestry Systems* 83:167–180.

Bhagwat SA, Willis KJ, Birks HJB, Whittaker RJ. 2008. Agroforestry: a refuge for tropical biodiversity? *Trends in Ecology and Evolution* 23:261–267.

Blanchez JL. 1997. *Asia Pacific forestry sector outlook study.* Working Paper No. APFSOS/WP/17. Bangkok: Food and Agriculture Organization of the United Nations, Forestry Policy and Planning Division, Regional Office for Asia and the Pacific.

Boyd E, Gutierrez M, Chang M. 2007. Small-scale forest carbon projects: adapting CDM to low-income communities. *Global Environmental Change* 17:250–259.

Brown S, Sathaye J, Cannel M, Kauppi P. 1996. Management of forests for mitigation of greenhouse gas emissions. In: Watson RT, Zinyowera MC, Moss RH, eds. *Climate change 1995: impacts, adaptations and mitigation of climate change: scientific-technical analyses. Contribution to Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*: Cambridge UK: Cambridge University Press. p. 775–797.

Brown S, Masera O, Sathaye J, Andrasko K, Brown P, Frumhoff P, Lasco R, Leach G, Moura-Costa P, Mwakifwamba S, Phillips G, Read P, Sudha P, Tipper R. 2001. Project-based activities. In: Watson B, Noble I, Bolin B, Ravindranath NR, Verardo DJ, Dokken DJ, eds. *Land use, land-use change and forestry. A special report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. p. 285–338.

Carandang WM, Tolentino Jr EL, Roshetko JM. 2006. Smallholder tree nursery operations in southern Philippines: supporting mechanisms for timber tree domestication. *Forests, Trees and Livelihoods* 16:71–83.

[CIA]. Central Intelligence Agency. 2012. *The World Factbook.* Washington DC: Central Intelligence Agency. Available from https://www.cia.gov/library/publications/the-world-factbook/fields/2003.html?

[CIFOR] Center for International Forestry Research. 2000. *Capturing the value of forest carbon for local livelihoods*. Bogor, Indonesia: Center for International Forestry Research.

Chipeta ME, Whiteman A, Brooks DJ. 1998. *Review of social and economic developments in the Asia-Pacific region with projections to 2010*. Asia-Pacific Forestry Sector Outlook Study Working Paper Series No: APFSOS/WP/49. Bangkok: Food and Agriculture Organization of the United Nations, Forestry Policy and Planning Division, Regional Office for Asia and the Pacific.

Dawson IK, Lengkeek A, Weber JC, Jamnadass R. 2009. Managing genetic variation in tropical trees: linking knowledge with action in agroforestry ecosystems for improved conservation and enhanced livelihoods. *Biodiversity and Conservation* 18:969–986.

Dawson IK, Vinceti B, Weber JC, Neufeldt H, Russell J, Lengkeek AG, Kalinganire A, Kindt R, Lillesø JB, Roshetko JM, Jamnadass R. 2011. Climate change and tree genetic resource management: maintaining and enhancing the productivity and value of smallholder tropical agroforestry landscapes. A review. *Agroforestry Systems* 81:67–78.

Dawson IK, Guariguata MR, Loo J, Weber JC, Lengkeek A, Bush D, Cornelius J, Guarino L, Kindt R, Orwa C, Russell J, Jamnadass R. 2013a. What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in *circa situm*, *in situ* and *ex situ* settings? A review. Biodiversity Conservation 22: 301-324.

Dawson IK, Leakey R, Place F, Clement CR, Weber JC, Cornelius JP, Roshetko JM, Tchoundjeu Z, Kalinganire A, Masters E, Orwa C, Jamnadass R (2013) Trees, tree genetic resources and the livelihoods of rural communities in the tropics. Thematic Study for the State of the World's Forest Genetic Resources. Food and Agriculture Organization of the United Nations, Rome, Italy

De Jong W, van Noordwijk M, Sirait M, Liswanti N, Suyanto. 2001. Farming secondary forests in Indonesia. *Journal of Tropical Forest Science* 13:705–726.

De Foresta H, Michon G. 1997. The agroforest alternative to Imperata grasslands: when smallholder agriculture and forestry reach sustainability. *Agroforestry Systems* 36:105–120.

De Foresta H, Michon G, Kusworo A, Levang P. 2004. Damar agroforest in Sumatra, Indonesia: domestication of a forest ecosystem through domestication of dipterocarps for resin production. In: Kustersand K, Belchers B, eds. *Forest products, livelihoods and conservation. Case studies of non-timber forest product systems.* Vol.1: Asia. Bogor, Indonesia: Center for International Forestry Research.

De Foresta H, Michon G, Kusworo A, Levang P. 2003. Damar agroforests in Sumatra, Indonesia. In: Kustersand K, Belchers B, eds. *Forest products, livelihoods and conservation. Case studies of non-timber forest product systems.* Vol.1: Asia. Bogor, Indonesia: Center for International Forestry Research.

Delaney M, Roshetko JM. 1999. Field test of carbon monitoring methods for homegardens in Indonesia. In: *Field tests of carbon monitoring methods in forestry projects*. Arlington USA: Winrock International.

Dove M. 2004. So far from power, so near the forest: a structural analysis of gain and blame in tropical forest development. In: Padoch C, Peluso N, eds. *Borneo in transition: people, forests, conservation and development.* Second edition. Oxford UK: Oxford University Press.

[DGEC] Director General of Estate Crops. 2012. *Commodities data.* Director General of Estate Crops, Department of Agriculture, Government of Indonesia. Available from http://ditjenbun.deptan.go.id/cigraph/index.php/viewstat/komoditiutama.

[EC] European Commission. 2008. *The economics of ecosystems and biodiversity. An interim report for the European Communities.* Cambridge, UK: Banson Production.

[FAO] Food and Agriculture Organization of the United Nations. 1993. *Patterns of commercial wood fuel supply, distribution and use in the city and province of Cebu, Philippines*. Bangkok: Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific.

[FAO] Food and Agriculture Organization of the United Nations. 1998. *Asia-Pacific forestry towards 2010: report of the Asia-Pacific forestry sector outlook study*. Bangkok: Food and Agriculture Organization of the United Nations, Forestry Policy and Planning Division.

[FAO] Food and Agriculture Organization of the United Nations. 2000. *Global forest resource assessment 2000*. Rome: Food and Agriculture Organization of the United Nations.

[FAO] Food and Agriculture Organization of the United Nations. 2000. *Asia-Pacific Forestry Commission: Development of National-Level Criteria and Indicators for the Sustainable Management of Dry Forests of Asia: Workshop Report.* RAP publication 2000/07. Bangkok: Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific.

[FAO] Food and Agriculture Organization of the United Nations. 2003a.*Wood energy information analysis in Asia*. Bangkok: Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific.

[FAO] Food and Agriculture Organization of the United Nations. 2003b. *Towards equitable partnerships between corporate and smallholder partners: relating partnerships to social, economic and environmental indicators*. Rome: Food and Agriculture Organization of the United Nations.

[FAO] Food and Agriculture Organization of the United Nations. 2005. *State of the world's forests 2005*. Rome: Food and Agriculture Organization of the United Nations.

[FAO] Food and Agriculture Organization of the United Nations. 2006. *Global forest resources assessment 2005: progress toward sustainable forest management.* FAO Forestry Paper 147. Rome: Food and Agriculture Organization of the United Nations.

[FAO] Food and Agriculture Organization of the United Nations. 2008a. *Rapid assessment of pollinators' status: a contribution to the International Initiative for the Conservation and Sustainable Use of Pollinators.* Global Action on Pollination Services for Sustainable Agriculture. Rome: Food and Agriculture Organization of the United Nations.

[FAO] Food and Agriculture Organization of the United Nations. 2010. *Global forest resources assessment 2010.* Rome: Food and Agriculture Organization of the United Nations.

[FAO] Food and Agriculture Organization of the United Nations. 2011. *State of the world's forests 2011*. Rome: Food and Agriculture Organization of the United Nations.

Fay C, de Foresta H, Sirait M, Tomich TP.1998. A policy breakthrough for Indonesian farmers in Krui damar agroforests. *Agroforestry Today* 10:25–26.

Fonsah EG, Roshetko J, Tukan J, Nugraha E, Manurung GS. 2008. Fruit and vegetable industry in Indonesia: production and limited access to market. *Journal of Food Distribution Research* 39(1):62–66.

Forester JJ, Kanaan R, Malley M, Roule T, Thomson J. 2004. *Conflict timber: dimensions of the problem in Asia and Africa*. Vol II: Asian Cases. Jakarta: Associates in Rural Development, Inc.

Fernandes ECM, Nair PKR. 1986. An evaluation of the structure and function of tropical homegardens. *Agricultural Systems* 21(4):279–310.

Franzel, S, Ndufa JK, Obonyo OC, Bekele TE, Coe R. 1998. Farmer-designed agroforestry trials: farmers' experience in western Kenya. In: Franzel S, Scherr S, eds. *Trees on the farm: assessing the adoption potential of agroforestry practices in Africa.* Wallingford, UK: Centre for Agriculture and Biosciences International Publishing. p. 111–123.

Garcia Fernandez C. 2004. Benzoin resin: scent from the Far East. In: Lopez C, Shanley P, eds. *Riches of the forest: food, spices, crafts and resins of Asia*. Bogor, Indonesia: Center for International Forestry Research; London: Department for International Development.

Garrity DP, Soekardi M, van Noordwijk M, de la Cruz R, Pathak PS, Gunasena HPM, Van So N, Huijun G, Majid NM. 1997. The *Imperata* grassland of tropical Asia: area, distribution and typology. *Agroforestry Systems* 36:3–29.

Garrity DP. 2004. Agroforestry and the achievement of the Millennium Development Goals. *Agroforestry Systems* 61:5–17.

Gienapp P, Teplitsky C, Alho JS, Mills JA, Merila J. 2008. Climate change and evolution: disentangling environmental and genetic responses. *Molecular Ecology* 17:167–178.

Ginoga K, Wulan YC, Lugina M. 2005. *Potential of agroforestry and plantation systems in Indonesia for carbon stocks: an economic perspective.* Working Paper CC14, ACIAR Project ASEM 2002/066. Available from http://www.une.edu.au/febl/Economics/carbon.

Ginoga K, Wulan YC, Djaenudi D. 2004. *Potential of Indonesian smallholder agroforestry in the CDM: a case study in the upper Citanduy watershed area.* Working Paper CC12, 2004. ACIAR Project ASEM 2002/066. Available from http://www.une.edu.au/febl/Economics/carbon.

Gonzal DR. 1994. Gmelina arborea–annual crop interactions in contour hedgerow systems for smallholder farm forestry. Thesis. Los Baños, the Philippines: University of the Philippines.

Graudal L, Lillesø J-PB. 2007. *Experiences and future prospects for tree seed supply in agricultural development support: based on lessons learnt in Danida-supported programmes, 1965–2005.* Copenhagen: Ministry of Foreign Affairs of Denmark.

Grieg-Gran M, Porras I, Wunder S. 2005. How can market mechanisms for forest environmental services help the poor? Preliminary lessons from Latin America. *World Development* 33(9):1511–1527.

Guariguata MR, Cornelius JP, Locatelli B, Forner C, Sánchez-Azofeifa GA. 2008. Mitigation needs adaptation: tropical forestry and climate change. *Mitigation and Adaptation Strategies for Global Change* 13:793–808.

Gunasena HPM. 1999. Domestication of agroforestry trees in Sri Lanka. In: Roshetko JM, Evans DO, eds. *Domestication of agroforestry trees in Southeast Asia.* Forest, Farm, and Community Tree Research Reports. Special issue 1999. Morrilton USA: Winrock International. p. 49–53.

Gunasena HPM, Roshetko JM. 2000. *Tree domestication in Southeast Asia: results of a regional study on institutional capacity*. Bogor, Indonesia: International Centre for Research in Agroforestry (ICRAF).

Hammett AL. 1994. Developing community-based market information systems. In: Raintree JB, Francisco HA, eds. *Marketing multipurpose tree species in Asia.* Proceedings of an International Workshop, Baguio City, Philippines, 6–9 December 1993. Bangkok: Winrock International. p. 289–300.

Hairiah K. 1997. *Final report: carbon stock in various land-use systems in Lampung and Jambi.* Bogor, Indonesia: International Centre for Research in Agroforestry (ICRAF).

Hairiah K, van Noordwijk M, Palm C 1999. Methods for sampling above- and below-ground organic pools. In: Murdiyarso D, Van Noordwijk M, Suyamto A, eds. *Modelling global change impacts on the soil environment.* IC-SEA Report No. 6/GCTE Working Document No. 28. Bogor, Indonesia: Southeast Asia Regional Centre for Tropical Biology; Global Change and Terrestrial Ecosystems; Impacts Centre for Southeast Asia. p. 46–77.

Hariri D, Mulawarman, Roshetko JM. 2002. Socio-economic characteristics of smallholder tree farmers in Gunung Kidul and Wonogiri districts, Indonesia. Bogor, Indonesia: International Centre for Research in Agroforestry (ICRAF); Arlington USA: Winrock International.

Harwood C, Roshetko JM, Cadiz RT, Christie B, Crompton H, Danarto S, Djogo T, Garrity D, Palmer J, Pedersen A, Pottinger A, Pushpakumara DKNG, Utama R, van Cooten D. 1999. Working Group 3: Domestication strategies and process. In: Roshetko JM, Evans DO, eds. *Domestication of agroforestry trees in Southeast Asia.* Forest, Farm, and Community Tree Research Reports. Special issue 1999. Morrilton USA: Winrock International. 217–225.

Holding-Anyonge C, Roshetko JM. 2003. Farm-level timber production: orienting farmers towards the market. *Unaslyva* 212(54):48–56.

Huxley P, van Houten H. 1997. *Glossary for agroforestry*. Nairobi: International Centre for Research in Agroforestry (ICRAF).

Idol T, Haggar J, Cox L. 2011. Ecosystem services from smallholder forestry and agroforestry in the tropics. In: Campbell WB, Lopes Ortiz S, eds. *Integrating agriculture, conservation and ecotourism: examples from the field*. New York: Springer. doi 10.1007/978-94-007-1309-3_5.

[IPCC] Intergovernmental Panel on Climate Change. 2001. *Climate change 2001: impacts, adaptation and vulnerability. Summary for policy makers and technical summary of the Working Group II Report*. Geneva: World Meteorological Organization; Nairobi: United Nations Environment Programme.

[IPCC] Intergovernmental Panel on Climate Change. 2007. *Climate change 2007. The fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Jackson LE, Brussaard L, de Ruiter PC, Pascual U, Perrings C, Bawa K. 2007. Agrobiodiversity. *Encyclopaedia of Biodiversity*. p. 1–13. Available from http://dx.doi.org/10.1016/B978-012226865-6/00572-9.

Jackson L, van Noordwijk M, Bengtsson J, Foster W, Lipper L, Pulleman M, Said M, Snaddon J, Vodouhe R. 2010. Biodiversity and agricultural sustainagility: from assessment to adaptive management. *Current Opinion in Environmental Sustainability* 2:80–87.

Jamnadass R, Dawson IK, Anegbeh P, Asaah E, Atangana A, Cordeiro N, Hendrickx H, Henneh S, Kadu CAC, Kattah C, Misbah M, Muchugi A, Munjuga M, Mwaura L, Ndangalasi HJ, Njau CS, Nyame SK, Ofori D, Peprah T, Russell J, Rutatina F, Sawe C, Schmidt L, Tchoundjeu Z, Simons T. 2010. *Allanblackia*, a new tree crop in Africa for the global food industry: market development, smallholder cultivation and biodiversity management. *Forests, Trees and Livelihoods* 19:251–268.

Jordan FC, Gajaseni J, Watanabe H, eds. 1992. *Taungya: forest plantations with agriculture in Southeast Asia*. Wallingford UK: Centre for Agriculture and Biosciences International.

Kapp GB, Beer J. 1995. A comparison of agrisilvicultural systems with plantation forestry in the Atlantic lowlands of Costa Rica. Part I. Tree survival and growth. *Agroforestry Systems* 32(3):207–223.

Kerr G, Morgan G. 2006. Does formative pruning improve the form of broadleaved trees? *Canadian Journal of Forestry Research* 36(1):132–141.

Kindt R, Lengkeek AG. 1999. Tree diversity on farm: use it or lose it. In: *Agricultural biodiversity conservation.* Proceedings of a workshop, Nairobi, Kenya, January 1999. Nairobi: Intermediate Technology Development Group East Africa. p. 75–85.

Kindt R, van Damme P, Simons AL, Beeckman H. 2006. Planning tree species diversification in Kenya based on differences in tree species composition between farms. I. Analysis of tree uses. *Agroforestry Systems.* 67:215–228.

Koffa SN, Roshetko JM. 1999. Farmer-managed germplasm production-diffusion pathways in Lantapan, Philippines. In: Roshetko JM, Evans DO, eds. *Domestication of agroforestry trees in Southeast Asia.* Forest, Farm, and Community Tree Research Reports. Special issue 1999. Morrilton USA: Winrock International. p. 142–150.

Koffa SN, Garrity DP. 2001. Grassroots empowerment and sustainability in the management of critical natural resources: the Agroforestry Tree Seed Association of Lantapan. In: Coxhead I, Buenavista G, eds. *Seeking sustainability: challenges of agricultural development and environmental management in a Philippine watershed*, Los Baños, Philippines: Philippine Council for Agriculture, Forestry and Natural Resources Research. p. 197–217.

Koskela J, Vinceti B, Dvorak W, Bush D, Dawson I, Loo J, Kjaer ED, Navarro C, Padolina C, Bordacs S, Jamnadass R, Graudal L, Ramamonjisoa L. 2009. *The use and movement of forest genetic resources for food and agriculture*. Background study paper no. 44. Rome: The Commission on Genetic Resources for Food and Agriculture, Food and Agriculture Organization of the United Nations.

Krol M. 1992. *Changing homegardens in upland Java: the effects of changing economic conditions on the use of Javanese homegardens: a case study in two villages of Gunung Kidul District, Java, Indonesia.* FONC Project Communication No. 4. Yogyakarta, Indonesia: Forestry/Nature Conservation Project, Faculty of Forestry, University of Gadjah Mada.

Lamb D. 1998. Large-scale ecological restoration of degraded tropical forest lands: the potential role of timber plantations. *Restoration Ecology* 6(3):271–279.

Landell-Mills N. 2002. *Marketing forest environmental services – who benefits?* Gatekeeper Series No. 104. London: International Institute for Environment and Development.

Lasco RD, Pulhin FB**,** Roshetko JM, Banaticia MRN. 2004. *LULUCF climate change mitigation projects in the Philippines: a primer*. Los Baños, Philippines: World Agroforestry Centre (ICRAF) Southeast Asia Regional Research Programme.

Lasco RD, Visco RG, Pulhin FB. 2001. Secondary forests in the Philippines: formation and transformation in the 20th century. *Journal of Tropical Forest Science* 13:652–670.

Lauridsen EB, Kaejer ED, Nissen M. 1995. *Second evaluation of a series of* Gmelina *provenance trials.* Humlebaek, Denmark: Danida Forest Seed Centre.

Leakey RRB. 2010. Agroforestry: a delivery mechanism for multi-functional agriculture. In: Kellimore LR, ed. *Handbook on agroforestry: management practices and environmental impact.* Environmental Science, Engineering and Technology Series. Hauppauge, USA: Nova Science Publishers. p. 461–471.

Leakey RRB, Weber JC, Page T, Cornelius JP, Akinnifesi FK, Roshetko JM, Tchoundjeu Z, Jamnadass R. 2012. Tree domestication in agroforestry: progress in the second decade. 145-173 pp. In: Nair PKR, Garrity DP, eds. The future of agroforestry. New York: Springer. 541 p.

Lengkeek AG. 2003. Diversity makes a difference: farmers managing inter- and intra-specific tree species diversity in Meru, Kenya. PhD Thesis. Wageningen, The Netherlands: Wageningen University.

Lengkeek AG, Jaenicke H, Dawson IK. 2005a. Genetic bottlenecks in agroforestry systems: results of tree nursery surveys in East Africa. *Agroforestry Systems* 63:149–155.

Lengkeek AG, Kindt R, van der Maesen LJG, Simons AJ, van Oijen DCC. 2005b. Tree density and germplasm source in agroforestry ecosystems in Meru, Mount Kenya. *Genetic Resources and Crop Evolution* 52:709–721.

MacDicken KG. 1997. A guide to monitoring carbon storage in forestry and agroforestry projects. Arlington USA: Winrock International.

Magbanua RD, Garrity DP. 1988. *Acid upland agroecosystems: A microlevel analysis of the Claveria research site*. In: Proceedings of the 1988 Acid Upland Research Design Workshop. Los Baños, the Philippines: International Rice Research Institute. p. 1–20.

Magcale-Macandog DB, Menz K, Rocamora PM, Predo CD. 1999. Smallholder timber production and marketing: the case of *Gmelina arborea* in Claveria, Northern Mindanao, Philippines. *International Tree Crops Journal* 10:61–78.

Malcolm JR, Markham A, Neilson RP, Garaci M. 2002. Estimated migration rates under scenarios of global climate change. *Journal of Biogeography* 29:835–849.

Malik RS, Sharma SK. 1990. Moisture extraction and crop yield as a function of distance from a row of *Eucalyptus tereticornis*. Agroforestry Systems 12(2):187−195.

Malhi Y, Aragao LEOC, Galbraith D, Huntingford C, Fisher R, Zelazowski P, Sitch S, McSweeney C, Meir P. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences USA* 106:20610–20615.

Manurung GE, Roshetko JM, Budidarsono S, Tukan JC. 2005. Dudukuhan: traditional tree farming systems for poverty reduction. In: van der Ploeg J, Masipiquena AB, eds. *The future of the Sierra Madre: responding to social and ecological changes.* Proceedings of the 5th International Conference on Environment and Development. Cagayan Valley Program on Environment and Development. Tuegarno, the Philippines: Golden Press. p. 90–110.

Manurung GE, Roshetko JM, Budidarsono S, Kurniawan I. 2008. Dudukuhan tree farming systems in West Java: how to mobilize self-strengthening of community-based forest management? In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services.* Advances in Agroforestry, vol 5. Amsterdam: Springer Science + Business Media. p 99-116.

Manurung GES, Roshetko JM, Anggakusuma D, Pramono AA, Heriansyah I, Fauzi A. 2009. *Smallholder teak-based farming management in Gunungkidul, Yogyakarta: current practices, obstacles and improvement options.* ACIAR Project Report. Bogor, Indonesia: World Agroforestry Centre (ICRAF).

Martin FS, van Noordwijk M. 2009. Trade-offs analysis for possible timber-based agroforestry scenarios using native trees in the Philippines. Agroforestry Systems 76(3):555–567.

Martini E, Roshetko JM, van Noordwijk M, Rahmanulloh A, Mulyoutami E, Joshi L, Budidarsono S. 2012. Sugarpalm (*Arenga pinnata*) for livelihoods and biodiversity conservation in the orangutan habitat of Batang Toru, North Sumatra, Indonesia: mixed prospects for domestication. *Agroforestry Systems* 86(3):401-417.

McLachlan JS, Hellmann JJ, Schwartz MW. 2007. A framework for debate of assisted migration in an era of climate change. *Conservation Biology* 21:297–302.

Mead DJ. 2004. Agroforestry. In: Forests and forest plants. Vol 1. *Encyclopedia of life science systems*. Oxford UK: EOLSS Publishers. p. 324-55.

Miah MDG. 1993. Performance of selected multipurpose tree species and field crops grown in association as affected by tree branch pruning. Thesis. Muñoz, the Philippines: Central Luzon State University.

Michon G, Bompard JM. 1987. Indonesian agroforestry: peasants' contributions to the conservation of natural forests and their resources. *Revue of Ecology* [*Revue d'Ecologie: La Terre et la Vie*] 42(1):3–34.

Michon G, de Foresta H. 1990. Complex agroforestry systems and conservation of biological diversity. 1. Agroforestry in Indonesia: a link between two worlds. *The Malayan Nature Journal.* Golden Jubilee issue. 45:457-473.

Michon G, de Foresta H. 1995. The Indonesian agro-forest model. In: Halladay P, Gilmour DA, eds. *Conserving biodiversity outside protected areas. The role of traditional ecosystems.* Gland, Switzerland: International Union for the Conservation of Nature. p. 90–106.

Michon G, Mary F. 1994. Conversion of traditional village gardens and new economic strategies of rural households in the area of Bogor, Indonesia. *Agroforestry Systems* 25:31–58.

Ministry of Environment. 2003. *National strategy study on CDM in the forestry sector*. Jakarta: Ministry of Environment, Government of Indonesia.

Ministry of Forestry. 2001. *Statistik kehutanan 2001*. Forestry statistics. Ministry of Forestry, Government of Indonesia. Available from http://www.dephut.go.id.

Mittelman A. 2001. Secondary forests in the lower Mekong subregion: an overview of their extent, roles and importance. *Journal of Tropical Forest Science* 13(4):671–690.

Moestrup S. 1999. The Indonesian forest seed project, 1998–2001. In: Roshetko JM, Evans DO, eds. Domestication of agroforestry trees in Southeast Asia. Forest, Farm, and Community Tree Research Reports. Special issue 1999. Morrilton USA: Winrock International. p 4-16.

Mulawarman, Roshetko JM, Sasongko SM, Iriantono D. 2004. Seed source establishment and management. In: Elevitch GR, ed. The overstory book: cultivating connections with trees. Second edition. Holualoa USA: Permanent Agriculture Resources. p. 368–377.

Mulawarman, Roshetko JM, Sasongko SM, Iriantono D. 2003. *Tree seed management: seed sources, seed collection and seed handling: a field manual for field workers and farmers.* Bogor, Indonesia: World Agroforestry Centre (ICRAF); Arlington USA: Winrock International.

Murdiyarso D, van Noordwijk M, Wasrin UR, Tomich TP, Gillison AN. 2002. Environmental benefits and sustainable land-use options in the Jambi transect, Sumatra, Indonesia. *Journal of Vegetation Science* 13:429–438.

Murdiyarso D. 2005. Sustaining local livelihoods through carbon sequestration activities: a search for a practical and strategic approach. In: Murdiyarso D, Herawati H, eds. *Carbon forestry: who will benefit?* Bogor, Indonesia: Center for International Forestry Research. p. 1–16.

Muriuki JK. 2005. Informal agroforestry tree seed quality and supply systems: a case of peri-urban Nairobi, Meru and western Kenya. MSc thesis. Nairobi: Kenyatta University.

Murniati, Garrity DP, Gintings AN. 2001. The contribution of agroforestry systems to reducing farmers' dependence on the resources of adjacent national parks: a case study from Sumatra, Indonesia. *Agroforestry Systems* 52:171–184.

Nair PKR. 1989. Food-processing trees in agroforestry systems. In: Nair PKR, ed. Agroforestry systems in the tropics. Dordrecht, The Netherlands: Kluwer Academic Publishers. p. 541–551.

Nair PKR, Kumar BM, Nair VD. 2009. Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science* 172:10–23.

Narendra BH, JM Roshetko, HL Tata, E Mulyoutami. 2012. Prioritizing Underutilized Tree Species for Domestication in Smallholder Systems of West Java. Small-scale Forestry DOI 10.1007/s11842-012-9227-x

Nguyen Q, Hoang MH, Oborn I, van Noordwijk M. 2012. Multipurpose agroforestry as a climate change resiliency option for farmers: an example of local adaptation in Vietnam. *Climate Change.* doi 10.1007/s10584-012-0550-1.

Nissen TM, Midmore DJ, Keeler AG. 2001. Biophysical and economic tradeoffs of intercropping timber with food crops in the Philippine uplands. *Agricultural Systems* 67(1):49–69.

[NRC] National Research Council. 2007. *Status of pollinators in North America.* Committee on the Status of Pollinators in North America, National Research Council. Washington DC: The National Academies Press.

Okorio J, Byenkya S, Wajja N, Peden D. 1994. Comparative performance of seventeen upperstorey tree species associated with crops in the highlands of Uganda. *Agroforestry Systems* 26(3):185−203.

Ong CK, Black CR, Marshall FM, Corlett JE. 1996. Principles of resource capture and utilization of light and water. In: Ong CK, Huxley P, eds. *Tree-crop interactions: a physiological approach.* Wallingford UK: Centre for Agriculture and Biosciences International. p. 73−158.

Palm C, Hairiah K, van Noordwijk M. 1994. Methods for sampling above and below ground organic pools for ASB sites. In: Murdiyarso D, Hairiah K, van Noordwijk M, eds. *Modelling and measuring soil organic matter dynamics and greenhouse gas emissions after forest conversion.* Proceedings of Workshop/Training Course, 8–15 August 1994. Bogor and Muara Tebo, Indonesia: ASB Indonesia Publication no. 1. p. 57–71.

Palm C, Woomer PL, Alegre J, Arevalo L, Castilla C, Cordeiro DG, Feigl B, Hairiah K, Kotto-Same J, Mendes A, Moukam A, Murdiyarso D, Njomgaang D, Parton WJ, Ricse A, Rodrigues V, Sitompul SM, van Noordwijk M. 1999. *Carbon sequestration and trace gas emissions in slash-and-burn and alternative land-uses in the humid tropics*. Final Report Phase II. Nairobi: ASB Climate Change Working Group, International Centre for Research in Agroforestry (ICRAF).

Parmesan C. 2007. Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology* 13:1860–1872.

Pasicolan P, Tracey J. 1996. *Spontaneous tree growing initiatives by farmers: an exploratory study of five case in Luzon, Philippines, in improving smallholder farming systems in* Imperata *areas of Southeast Asia.* Canberra: Australian National University; Laguna, the Philippines: South East Asian Regional Center for Graduate Study and Research in Agriculture.

Pearce D, Putz FE, Vanclay JK 2003. Sustainable forestry in the tropics: panacea or folly? *Forest Ecology and Management* 172: 229–247.

Perdana A, Roshetko JM, Kurniawan I. 2012. Forces of competition: smallholding teak producers in Indonesia. *International Forestry Review* 14(2):238–248.

Pearson RG, Dawson TP. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography* 12:361–371.

Perez C, Roncoli C, Neely C, Steiner JL. 2007. Can carbon sequestration markets benefit low-income producers in semi-arid Africa? Potentials and challenges. *Agricultural Systems* 94(1):2–12.

Peskett L, Schreckenberg K, Brown J. 2011. Institutional approaches for carbon financing in the forest sector: learning lessons for REDD+ from forest carbon projects in Uganda. *Environmental Science and Policy* 14:216–229.

Place F, Kristjanson P, Staal S, Kruska R, Wolff T de, Zomer R, Njuguna E. 2005. Development pathways in medium-high potential Kenya: a meso-level analysis of agricultural patterns and determinants. In: Pender J, Place F, Ehui S, eds. Strategies for sustainable land management in the East African highlands. Washington DC: International Food Policy Research Institute. doi.org/10.2499/0896297578.

Potter, L. and J Lee. 1998. *Tree Planting in Indonesia: Trends, Impacts and Directions*. CIFOR Occasional Paper No.18. Center for International Forestry Research (CIFOR), Bogor. Indonesia.

Pramono AA, Fauzi MA, Widyani N, Heriansyah I, Roshetko JM. 2011. Management of community teak forests: a field manual for farmers. Bogor, Indonesia: Center for International Forestry Research; World Agroforestry Centre (ICRAF); Forestry Research and Development Agency.

Raebild A, Hansen UB, Kambou S. 2011. Regeneration of *Vitellaria paradoxa* and *Parkia biglobosa* in a parkland in Southern Burkina Faso. *Agroforestry Systems*. doi 10.1007/s10457-011-9397-0.

Rice R, Gullison R, Reid J. 1997. Can sustainable management save tropical forests? *Scientific American* 276:34–39.

Rohadi D, Retno M, Widyana M, Azhar I. 2003. Case study of the production to consumption system of sandalwood in South Central Timor, Indonesia. In: Kusters K, Belcher B, eds. *Forest products, livelihoods and conservation: case studies of non-timber forest product systems*. Vol. 1: Asia. Bogor, Indonesia: Center for International Forestry Research; London: Department for International Development.

Rohadi D, Roshetko JM, Perdana A, Blyth M, Nuryartono N, Kusumowardani N, Pramono AA, Widyani N, Fauzi A, Sasono J, Sumardamto P, Manalu P. 2011. *Improving economic outcomes for smallholders growing teak in agroforestry systems in Indonesia*. Canberra: Australian Centre for International Agricultural Research.

Roshetko JM. 2001a. *Agroforestry species and technologies: a compilation of the highlights and factsheets published by NFTA and FACT Net 1985–1999.* Taiwan: Taiwan Forestry Research Institute and Council of Agriculture; Morrilton USA: Winrock International.

Roshetko JM. 2001b. *Strengthening germplasm security for NGOs and smallholders in Indonesia.* First Annual Report. Bogor, Indonesia: International Centre for Research in Agroforestry (ICRAF); Morrilton, USA: Winrock International.

Roshetko JM, Delaney M, Hairiah K, Purnomosidhi P. 2002. Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage? *American Journal of Alternative Agriculture* 17:138–148.

Roshetko JM, Yuliyanti. 2002. Pemasaran untuk hasil-hasil wanatani di tingkat petani. Marketing smallholder farmers agroforestry products. In: Roshetko JM, Mulawarman, Santoso WJ, Oka IN. *Wanatani di Nusa Tenggara. Prosiding Lokakarya Wanatani Se-Nusa Tenggara.* Agroforestry in Nusa Tenggara, Proceedings of a Workshop. Denpasar, Bali. Bogor, Indonesia: International Centre for Research in Agroforestry (ICRAF); Morrilton USA: Winrock International.

Roshetko JM, Mulawarman, Purnomosidhi P. 2004a. *Gmelina arborea*: a viable species for smallholder tree farming in Indonesia? *New Forests* 28:207–215.

Roshetko JM, Fay C, Budidarsono S, Tukan J, Nugraha E, Pratowo N, Manurung G. 2004b. Agroforestry innovations and livelihood enhancement in West Java. Final Report January 2003–September 2004. Bogor, Indonesia: World Agroforestry Centre (ICRAF); Indonesia Institute for Forest and Environment; Morrilton, USA: Winrock International.

Roshetko JM, Mulawarman, Iriantono D. 2004c. Kebun benih untuk petani and LSM: Memgapa dan bagaimana. Seed orchards for farmers and NGOs: why and how. *Gema Desa Hutan*, Special Supplement 2004, Benih untuk Rakyat.

Roshetko JM, Purnomosidhi P, Mulawarman. 2005. Farmer Demonstration Trials (FDTs): promoting tree planting and farmer innovation in Indonesia. In: Gonsalves J, Becker T, Braun A, Caminade J, Campilan D, De Chavez H, Fajber E, Kapiriri M, Vernooy R, eds. *Participatory research and development for sustainable agriculture and natural resource management: a sourcebook,* Laguna, the Philippines: International Potato Center; Ottawa: International Development Research Centre; Rome: International Fund for Agricultural Development. p. 384–392.

Roshetko JM, Lasco RD, Delos Angeles MD. 2007a. Smallholder agroforestry systems for carbon storage. *Mitigation and Adaptation Strategies for Global Change* 12:219–242.

Roshetko JM, Nugraha E, Tukan JCM, Manurung G, Fay C, van Noordwijk M. 2007b. Agroforestry for livelihood enhancement and enterprise development. In: Djoeroemana S, Myers B, Russell-Smith J, Blyth M, Salean IET, eds. *Integrated rural development in East Nusa Tenggara, Indonesia.* Proceedings of a workshop to Identify Sustainable Rural Livelihoods, Kupang, Indonesia, 5–7 April 2006. ACIAR Proceedings No.126. Canberra: Australian Centre for International Agricultural Research.

Roshetko JM, Martini E, Tarigan J, Manurung G, Budidarsono S, Wijaya K, Tukan JC, Kurniawan I, Galudra G, Nugroho DK, Ekadinata A, Dewi S, Harja D, Lusiana B, van Noordwijk M, Purba J. 2007c. *Agroforestry on the interface of orangutan conservation and sustainable livelihoods in Batang Toru (North Sumatra).* Working Paper 56. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program.

Roshetko JM, Snelder DJ, Lasco RD, van Noordwijk M. 2008a. Future challenge: a paradigm shift in the forestry sector. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services*. Amsterdam: Springer Science + Business Media. p. 453–485.

Roshetko JM, Mulawarman, Dianarto A. 2008b. Tree seed procurement–diffusion pathways in Wonogiri and Ponorogo, Java. *Small-scale Forestry* 7:333–352.

Roshetko, JM and Manurung GES. 2009. Smallholder teak production systems in Gunungkidul, Indonesia. Poster presented at the 2nd World Congress of Agroforestry, Nairobi.

Roshetko JM, Manurung GS, Kurniawan I, Dahlia L, Susila A. 2012. Intensifying vegetable production in smallholder agroforestry systems of West Java. *Acta Hort* 958: 59-66.

Sampson N, Scholes RJ. 2000. Additional human-induced activities. In: Watson B, Noble I, Bolin B, Ravindranath NR, Verardo DJ, Dokken DJ, eds. *Land use, land-use change and forestry. A Special Report of the Intergovernmental Panel on Climate Change*. Cambridge UK: Cambridge University Press. p. 157–245.

Sanchez PA. 1994. Alternatives to slash and burn: a pragmatic approach for mitigating tropical deforestation. In: Anderson JR, ed. *Agricultural technology, political issues for the international community*. Wallingford UK: Centre for Agriculture and Biosciences International. p. 451–480.

Sanou H, Korbo A, Tougani A, Rabiou A, Kambou S, Ouedraogo M, Diallo BO, Parkouda C, Ræbild A, Jensen JS. 2007. *Protocol for establishment of trials with baobab and tamarind within the SAFRUIT project.* Working Paper 21-2007. Hørsholm, Denmark: Forest and Landscape Denmark.

Saxena NC. 1991. Crop losses and their economic implications due to growing of Eucalyptus on field bunds: a pilot study. *Agroforestry Systems* 16 (3):231–245.

Scherr SJ. 1995. Economic factors in farmer adoption of agroforestry: patterns observed in western Kenya. *World Development* 23(5):787–804.

Scherr SJ. 1999. The economic context for agroforestry development: evidence from Central America and the Caribbean. *Outlook on Agriculture* 28(3):163–170.

Scherr SJ, McNeely JA. 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of ‘ecoagriculture’ landscapes. *Philosophical Transactions of the Royal Society B* 363:477–494.

Schroeder P. 1994 Carbon storage benefits of agroforestry systems. *Agroforestry Systems* 27:89–97.

Schuren SHG, Snelder DJ. 2008. Tree growing on farms in Northeast Luzon (The Philippines): smallholders' motivations and other determinants for adopting agroforestry systems. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services.* Amsterdam: Springer Science + Business Media. p. 75–97.

Sharma E, Sharma R, Sharma G, Rai SC, Sharma P, Chettri N. Values and services of nitrogen-fixing alder based cardamom agroforestry systems in the Eastern Himalayas. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services.* Amsterdam: Springer Science + Business Media. p. 393–409.

Sheng F, Cannon J. 2004. *The wrong conditions: a critique of structural adjustment in Indonesia's forestry sector.* Washington DC: Center for Conservation and Government, Conservation International.

Shively GE, Zelek CA, Midmore DA, Nelson TM. 2004. Carbon sequestration in a tropical landscape: an economic model to measure its incremental use. *Agroforestry Systems* 60:189–197.

Simons AJ, MacQueen DJ, Stewart JL. 1994. Strategic concepts in the domestication of non-industrial trees. In: Leakey RRB, Newton AC, eds. Tropical trees: the potential of domestication and rebuilding of the forest resources. London: HMSO. p. 91–102.

Simons AJ, Jaenicke H, Tchoundjeu Z, Dawson I, Kindt R, Oginosako Z, Lengkeek A, De Grande A. 2000. The future of trees is on farm: tree domestication in Africa. In: Krishnapillay B, Soepadmo E, Lotfy Arshad N, Wong A, Appanah F, Wan Chik S, Manokaran N, Lay Tong H, Kean Choon K, eds. *Forests and society: the role of research.* Sub-plenary sessions Vol. 1. Proceedings of the 21st IUFRO world congress, Kuala Lumpur, Malaysia, August 2000. Vienna: IUFRO Secretariat; Kuala Lumpur: Forest Research Institute Malaysia. p. 752–760.

Smith DM. 1962. *The practice of silviculture.* Seventh edition. New York: John Wiley and Sons Inc.

Smith J, Scherr S. 2002. *Forest carbon and local livelihoods.* Policy Report. Bogor, Indonesia: Center for International Forestry Research; Forest Trends.

Snelder DJ. 2008. Smallholder tree growing in Philippine back yards: homegarden characteristics in different environmental settings. In: Snelder DJ, Lasco RD, eds. *Smallholder tree growing for rural development and environmental services.* Amsterdam: Springer Science + Business Media. p. 37–74.

Snelder DJ, Lasco RD. 2008. Smallholder tree growing in South and Southeast Asia. In: Snelder DJ, Lasco RD, eds. *Smallholder tree growing for rural development and environmental services*. Amsterdam: Springer Science + Business Media. p. 3–33.

Sotelo-Montes C, Weber JC. 2009. Genetic variation in wood density and correlations with tree growth in *Prosopis Africana* from Burkina Faso and Niger. *Annals of Forestry Science* 66:e713 (online). Available from www.afs-journal.org.

Steffan-Dewenter I, Kessler M, Barkmann J, Bos MM, Buchori D, Erasmi S, Faust H, Gerold G, Glenk K, Gradstein SR, Guhardja E, Harteveld M, Hertel D, Hohn P, Kappas M, Kohler S, Leuschner C, Maertens M, Marggraf R, Migge-Kleian S, Mogea J, Pitopang R, Schaefer M, Schwarze S, Sporn SG, Steingrebe A, Tjitrosoedirdjo SS, Tjitrosoemito S, Twele A, Weber R, Woltmann L, Zeller M, Tscharntke T. 2007. Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. *Proceedings of the National Academy of Sciences USA* 104:4973–4978.

Strandby-Andersen U, Prado Cordova JP, Nielsen UB, Smith-Olsen C, Nielsen C, Sørensen M, Kollmann J. 2008. Conservation through utilization: a case study of the vulnerable *Abies guatemalensis* in Guatemala. *Oryx* 42:206–213.

Sunderlin WD, Resosudarmo IAP, Rianto E, Angelsen A. 2000. *The effect of Indonesia's economic crisis on small farmers and natural forest cover in the outer islands.* Occasional Paper 28(E). Bogor, Indonesia: Center for International Forestry Research.

Thuiller W, Albert C, Araujo MB, Berry PM, Cabeza M, Guisan A, Hickler T, Midgley GF, Paterson J, Schurr FM, Sykes MT, Zimmermann NE. 2008. Predicting global change impacts on plant species' distributions: future challenges. *Perspectives in Plant Ecology, Evolution and Systematics* 9:137–152.

Tolentino EL, Carandang WM, Roshetko JM. 2001. *Evaluation of smallholder tree farmers' nursery: quality stock production in support of the tree domestication program of the Philippines.* Los Baños, the Philippines: College of Forestry and Natural Resources, University of the Philippines; International Centre for Research in Agroforestry (ICRAF).

Tomich TP, Kuusipalo J, Metz K, Byron N. 1997. Imperata economics and policy. *Agroforestry Systems* 36:233–261.

Tomich TP, van Noordwijk M, Budidarsono S, Gillison A, Kusumanto T, Murdiyarso D, Stolle F, Fagi AM eds. 1998. *Alternatives to slash-and-burn in Indonesia. Summary report and synthesis of Phase II.* ASB Indonesia Report no. 8. Bogor, Indonesia: Alternatives to Slash and Burn Project; International Centre for Research in Agroforestry (ICRAF).

Tomich TP, de Foresta H, Dennis R, Ketterings Q, Murdiyarso D, Palm C, Stolle F, van Noordwijk M. 2002. Carbon offsets for conservation and development in Indonesia? *American Journal of Alternative Agriculture* 17:125–137.

Tscharntke T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J, Whitbread A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* 151:53–59.

Tukan CMJ, Roshetko JM, Budidarsono S, Manurung GS. 2006. Market chain improvement: linking farmers to markets in Nanggung, West Java, Indonesia. *Acta Hort.* 699: 429–438.

Tukan JCM, Yulianti, Roshetko JM, Darusman D. 2004. Pemasaran kayu dari lahan petani di Provinsi Lampung. Marketing timber from farmers' land in Lampung Province. *Agrivita* 26:131–140.

[UNFCCC] United Nations Framework Convention on Climate Change. 1997. *The Kyoto Protocol to the Convention on Climate Change*. Bonn: UNFCCC Secretariat.

[UNFCCC] United Nations Framework Convention on Climate Change. 2003. *Modalities and procedures for afforestation and reforestation project activities under the clean development mechanism in the first commitment period of the Kyoto Protocol*. FCCC/CP/2003/6/Add.2, 30 March 2004.

United Nations. 2010. *World Population Prospects, 2010 Edition.* Department of Economic and Social Affairs, Population Division, Population Estimates and Projections Section, United Nations. Available from http://esa.un.org/unpd/wpp/Sorting-Tables/tab-sorting_population.htm.

United Nations. 2012. *United Nations Millennium Development Goals* Available from http://www.un.org/millenniumgoals/bkgd.shtml.

Van Noordwijk M, Roshetko JM, Murniati, Delos Angeles M, Suyanto, Fay C, Tomich TP. 2008. Farmer tree planting barriers to sustainable forest management. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services.* Amsterdam: Springer Science + Business Media.. 429–451.

Van Weerd M, Snelder DJ. 2008. Human-altered tree-based habitats and their value in conserving bird and bat diversity in Northern Luzon, the Philippines. In: Snelder DJ, Lasco R, eds. *Smallholder tree growing for rural development and environmental services.* Amsterdam: Springer Science + Business Media. p. 347–377.

Vinceti B, Dawson I, Koskela J, Jamnadass R. 2009. Tree genetic resources: international interdependence in the face of climate change. In: Fujisaka S, Halewood M, Williams D, eds. *The impact of climate change in countries' interdependence on genetic resources for food and agriculture.* Background study paper no. 48. Rome: Commission on Genetic Resources for Food and Agriculture, Food and Agriculture Organization of the United Nations. p. 18–26.

Watanabe H. 1992. Tree-crop interactions in Taungya plantations. In: Jordan CF, Gajaseni J, Watanabe H, eds. *Taungya: forest plantations with agriculture in Southeast Asia*. Wallingford UK: Centre for Agriculture and Biosciences International. p. 32–43.

Watson B, Noble I, Bolin B, Ravindranath NR, Verardo DJ, Dokken DJ, eds. 2000. Summary for policymakers. In: *Land use, land-use change and forestry. A special report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge UK: Cambridge University Press.

[WB] World Bank, Department For International Development, Pelangi Energi Abdi Citra Enviro. 2007. *Indonesia and climate change: current status and policies***.** Washington DC: World Bank; London: Department for International Development; Jakarta: Pelangi Energi Abdi Citra Enviro.

Weber JC, Sotelo-Montes C. 2008. Geographic variation in tree growth and wood density of *Guazuma crinita* Mart. in the Peruvian Amazon. *New Forests* 36:29–52.

[WCED] World Commission on Environment and Development. 1987. *Our common future*. London: Oxford University Press.

Wijoyo FS. 2001. The benefits of tree improvement cooperatives to serve breeding and *ex situ* conservation programs of *Gmelina arborea*, Roxb. In: Thielges BA, Sastrapradja SD, Rimbawanto A, eds. In situ *and* ex situ *conservation of commercial tropical trees*. Yogyakarta, Indonesia: Faculty of Forestry, University of Gadjah Mada.

Wise R, Cacho O. 2002. *A bioeconomic analysis of soil carbon sequestration in agroforests*. Working Paper $CC0_2$. ACIAR Project ASEM 1999/093. Armidale: University of New England. Available from http:///www.une.edu.au/feb1/Econ/carbon.

Wise R, Cacho O. 2005. A bioeconomic analysis of carbon sequestration in farm forestry: a simulation study of *Gliricidia sepium*. *Agroforestry Systems* 64: 237–250.

World Bank. 2009. *World development report 2010: development and climate change.* Washington DC: World Bank.

Worldometers. 2011. *World population data*. Available from http://www.worldometers.info/world-population.

[WRI] World Resources Institute. 2005. *Earthtrends data tables: forest production and trade 2005.* Washington DC: EarthTrends, World Resources Institute. Available from http://earthtrends.wri.org/datatables/index.php?theme=4. Accessed 21 May 2007.

Wulan YC, Yasmi Y, Purba C, Wollenberg E. 2004. *Governance brief: an analysis of forestry sector conflict in Indonesia 1997–2003*. Bogor, Indonesia: Center for International Forestry Research.

Xu J. 2011. China's new forests aren't as green as they seem. *Nature* 477: 371. doi:10.1038/477371a.

Yuliyanti**.** 2000. *Analisis pemasaran kayu di Propinsi lampung.* Timber market analysis in Lampung Province. Bogor, Indonesia: Faculty of Forestry, Bogor Agricultural University.

Yuliyanti, Roshetko JM**.** 2002. *Karateristik sosio ekonomi rumah tangga petani dan pengaruhnya terhadap pilihan berusahatani tanaman pohon-pohonan oleh petani di Kecamatan Pakuan Ratu, Kabupaten Way Kanan dan Kecamatan Muara Sungkai, Kabupaten Lampung Utara, Propinsi Lampung.* Socioeconomic characterisitics of farm households and their influence on tree cultivation by farmers in Kecamatan Pakuan Ratu, Kabupatan Way Kanan and Kecamatan Muara Sungkai, Kabupaten Lampung Utara, Lampung Province. Bogor, Indonesia: International Centre for Research in Agroforestry (ICRAF); Arlington USA: Winrock International.

Zomer RJ, Trabucco A, Coe R, Place F. 2009. *Trees on farm: analysis of global extent and geographical patterns of agroforestry.* Working Paper 89. Nairobi: World Agroforestry Centre (ICRAF).

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III. Dawson IK, Vinceti B, Weber JC, Neufeldt H, Russell J, AG Lengkeek, Kalinganire A, Kindt R, Lillesø JB, **Roshetko JM**, Jamnadass R. 2011. Climate change and tree genetic resource management: maintaining and enhancing the productivity and value of smallholder tropical agroforestry landscapes. A review. *Agroforestry Systems* 81:67–78.

IV. **Roshetko JM**, Mulawarman, Purnomosidhi P. 2004. *Gmelina arborea* - a viable species for smallholder tree farming in Indonesia? *New Forests* 28:207–215.

V. Bertomeu M, **Roshetko JM**, Rahayu S. 2011. Optimum pruning strategies for reducing crop suppression in a *Gmelina*-maize smallholder agroforestry system in Claveria, Philippines. *Agroforestry Systems* 83:167–180.

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