Graham, Victoria F. (2017) ***Opportunities for REDD+ to minimise forest carbon emissions and mitigate climate change in Southeast Asia.*** **MPhil thesis, James Cook University.**

Opportunities for REDD+ to minimise forest carbon emissions and mitigate climate change in Southeast Asia

A Thesis submitted by

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DipSc; GradDip Res; James Cook University

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in March 2017

for the degree of Master of Philosophy

in the College of Science and Engineering

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Author Declaration

The material contained within this thesis is the original work of the author and has not been published or written by another person, except unless where otherwise acknowledged. The contribution of others to jointly published works has been clearly stated. Oscar Venter, Alana Grech and Susan Laurance contributed substantially to this work.

Oscar Venter contributed to the formulation of ideas, the design of this study, shared spatial data and provided editorial and financial assistance. Susan Laurance provided general direction, editorial and financial assistance and assisted with the formulation of ideas. Alana Grech provided GIS support, access to resources, editorial and financial assistance and assisted with the formulation of ideas. Bill Laurance provided financial assistance for travel to field sites in Southeast Asia. Data was kindly provided by Sassan Saatchi of the California Institute of Technology.

Throughout this candidature, I was supported by an Australian Postgraduate Award from the Australian Government Department of Industry, Innovation, Science, Research and Tertiary Education. The project costs of this research were funded by the Skyrail Rainforest Foundation and the College of Marine and Environmental Sciences at James Cook University, Cairns. The Australian Research Council supported Susan Laurance with a Future Fellowship and Oscar Venter through a Discovery Grant and DECRA Fellowship.

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Acknowledgments

This project was supervised by Oscar Venter, Alana Grech and Susan Laurance and supported by numerous academic staff members. First and foremost, I would like to thank my advisory team collectively, for giving me so much of their valuable time and being a constant source of support. I am grateful for the opportunity to work with each of you. I am especially grateful to Oscar Venter for initiating this research and to Susan Laurance for encouraging me to pursue this cross-disciplinary area of conservation science and economics. I am extremely grateful to Alana Grech for stepping into an associate advisory role when I relocated to Sydney and for being an outstanding role model and mentor.

I would like to thank Leanne Shillitoe and Debbie Berry for being my ‘go to’ people and always being willing to help, Tony Page and Will Edwards for providing me with employment opportunities and the Graduate Research School for guidance. I thank Liz Tynan for her invaluable workshops on academic writing that greatly improved the quality of my written work. I will never forget her pertinent advice that an academic dissertation is NOT a ‘who-dunnit’. Thank you to Bill Laurance for generously funding my travel to Southeast Asia and connecting me with relevant researchers in the field.

Thank you to my writing group, especially Michelle Redman-MacLaren and Yvonne Drazic, for sharing their time and providing encouragement and support. Thank you to Alice Hughes for training me in ARC GIS. I thank my postgraduate peers, office mates and university friends for their motivation and assistance during challenging times, especially Meira Mizrahi and Michelle McIntyre for being true friends.

To Sue Laurance, thank you for taking me under your wing and for mentoring and encouraging me. You have been a constant source of support and a positive influence throughout my years at JCU. Not only did you guide me academically, you also opened up many doors for me and for that I am eternally grateful.

Thank you to Alana Grech for teaching me how to think spatially and for technical support in ARC GIS. Your vast knowledge of GIS, support and mentoring have helped me tremendously to complete my masters remotely from Sydney. I am incredibly grateful for the opportunities you have given me and for your career guidance and mentoring.

To my primary advisor, Oscar Venter, thank you for introducing me to REDD+ and for steering me into this new and exciting area of cross-disciplinary research. It has been a steep but thrilling learning curve and given me insight into an area of research that has truly engaged me and will do for many more years. You have been an outstanding mentor and advisor and I am extremely grateful for the opportunity to work with you.

Finally, thank you to my parents, Robin and Alan, for your unwavering love and support in all of my pursuits, especially as an adult returning to study, and to my sister, Bec, for your friendship and counselling, and to my closest friends; Fi, Grant, Niki, Simone and Suzie for keeping my spirits high throughout this journey.

Statement on the Contribution of Others

Research Funding

Australian Postgraduate Award (stipend for two years)	$50,784
Skyrail Rainforest Foundation	$2,890
College of Marine and Environmental Sciences	$2,400
Professor William Laurance	$10,353

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Dr Alana Grech

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The anonymous reviewers and handling editors of my published chapters

Use of infrastructure external to JCU

Macquarie University (Department of Environmental Sciences) provided me with an office space

Contributions to published papers

Graham and Venter developed the research questions. Graham collected and analysed the data and wrote the paper. Analytical assistance was provided by Grech and Venter. All co-authors provided editorial input.

Abstract

Tropical forests are large reservoirs of carbon, containing around half of the carbon stored in forests worldwide. Annual gross tropical deforestation is estimated at over 100 million hectares for the period 1990-2010, which contributed ~15% of total anthropogenic carbon emissions over that period. In recognition of the substantial emissions resulting from deforestation and forest degradation in the tropics, global agreements have emerged to incentivise the maintenance of carbon stocks in standing forests. Indonesia is one of the world's largest sources of net carbon emissions from land-use change. Most tropical forests are in developing countries, where trees themselves, along with non-timber forest products, represent a valuable natural resource for local communities.

A prominent international financial mechanism for supporting emissions reduction targets in developing countries is REDD+ (for Reducing Emissions from Deforestation and forest Degradation plus conserving, sustainably managing forests and enhancing forest carbon stocks). The mechanism channels monetary incentives to nations that preserve or enhance tropical forest carbon stores. REDD+ offers multiple benefits; by providing a degree of protection for threatened forests and attracting new streams of international investment. As with all policies, the financial and political support for REDD+ will depend on it being cost-effective, therefore, drawing attention to the financial competitiveness of different options for reducing emissions, could increase political support.

REDD+ has received widespread support and at the same time suffered much criticism since its inception in 2005. In particular, the economic viability of REDD+ depends on whether the financing it generates is sufficient to off-set lost revenues from extractive activities, which in Southeast Asia includes highly profitable logging and oil palm production. The general consensus from the literature is that REDD+ will be of limited utility for reducing emissions from oil palm because the revenues from converting forest into oil palm far outweigh the revenues from trading the carbon credits on voluntary markets. However, by focusing almost exclusively on reducing emissions from oil palm expansion into forested areas, these papers have overlooked potentially

more cost-effective strategies for REDD+. To better allocate REDD+ resources, it is important to consider both activities that reduce emissions as well as activities that sequester carbon. It is equally as important to consider the spatial context in which projects are implemented, as costs and carbon incentives vary according to site specific factors. If restoring and sustainably managing forests offer cheaper avenues for reducing forest-based emissions, they could significantly alter the uptake of REDD+ within Southeast Asian nations and its role in global emissions reductions.

The primary goal of my thesis was to inform policy-makers regarding financially appropriate ways forward for REDD+ in Southeast Asia, by applying quantitative tools to compare the range of opportunities for reducing forest carbon emissions cost-effectively. The objectives underpinning this thesis were to (1) estimate the average per unit costs and carbon benefits of a wide range of REDD+ strategies in Southeast Asia; and, (2) estimate the mitigation costs and scope of these strategies in Indonesia using spatially-explicit costs and benefits. This approach allowed me to compare the cost-effectiveness of different strategies and highlight key opportunities (both strategies and locations) for REDD+.

Oil palm and timber are two of the most economically important land use activities in Southeast Asia. The expansion of oil palm and timber plantations contributed to 36% (5.3Mha) of forest loss in Indonesia between 2000 and 2010; hence plans to protect forests through REDD+ commonly target these two industries. REDD+ is perceived to be economically unviable due to the high costs of projects that target oil palm and timber production. However, REDD+ promotes other means of conserving forest carbon stocks, such as: (1) employing sustainable forest management to reduce degradation during logging; (2) conserving forest carbon stores by improving the management of protected areas; and (3) enhancing terrestrial carbon stores through reforestation. In Chapter 2, I reviewed REDD+ projects currently being deployed in Southeast Asia to determine if projects primarily reduce emissions from logging and oil palm, or pursue alternative strategies. I then conducted cost-benefit analyses to comparatively assess a subset of REDD+ strategies. I found a high level of variation in the cost of reducing emissions between strategies, ranging from $9 to $75 per tonne of avoided carbon emissions. The strategies that focused on reducing forest degradation and promoting forest regrowth were the most cost-effective ways of reducing emissions and were used in over 60% of projects.

The tendency in the literature to focus on average costs of reducing forest-based emissions across large land areas may be further overestimating the costs of REDD+. Mitigation costs and carbon benefits can vary according to site-specific characteristics; therefore, spatially-explicit information should be used to accurately assess costs, benefits and targets for REDD+ resources. In Chapter 3, I estimated the spatially-explicit cost-effectiveness of protecting, restoring and sustainably managing tropical forests across Indonesia. I found that when spatial variation in costs and benefits was considered, low-cost options emerged even for the two most expensive strategies: protecting forests from conversion to oil palm and timber plantations. This analysis demonstrated that no single strategy could reduce emissions at low-cost across Indonesia, but that there are cost-effective locations for all strategies.

In summary, this research was designed to comparatively evaluate the financial competitiveness of a broad range of strategies for REDD+ and inform policy-makers on how to distribute REDD+ resources efficiently in Southeast Asia. It revealed two novel and important insights. First, that achieving carbon benefits through REDD+ can be much less expensive than recognised in the literature. This is owing to strategies such as reforestation, reducing illegal deforestation in protected areas and sustainable forest management, which represent cost-effective strategies for investment and have considerable scope for implementation. Second, the two most expensive strategies, avoiding further deforestation in oil palm and timber concessions, offered multiple very low-cost locations for reducing carbon at under $7 per tonne. This is owing to high variation in the costs and benefits at different sites. I was able to achieve my objectives by using quantitative tools from economics and spatial information science. Targeting cost-effective opportunities for conserving tropical forest carbon stores, which are identified in this thesis, will foster greater political support and funding for climate mitigation in Southeast Asia and support developing countries to balance the trade-offs of economic development and reducing forest-based emissions.

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Publications associated with this thesis

Publications

Graham V, Laurance S G, Grech A, McGregor A and Venter O 2016 A comparative assessment of the financial costs and carbon benefits of REDD+ strategies in Southeast Asia *Environmental Research Letters* **11** 114022 (Chapter 2)

Graham V, Laurance S G, Grech A and Venter O 2017 Spatially explicit estimates of forest carbon emissions, mitigation costs and REDD+ opportunities in Indonesia *Environmental Research Letters* **12** 044017 (Chapter 3)

Conference Presentations

Graham V and Venter O 2014 *The upside of REDD+: A cost-benefit analysis of REDD+ strategies in Southeast Asia* 51st Annual Meeting of the Association for Tropical Biology and Conservation 20-24th of July 2014, Cairns, Australia.

Graham V 2017 *Three cheap ways of reducing forest carbon emissions in tropical Asia* 28th International Congress for Conservation Biology, 23-27 July 2017, Cartagena, Colombia.

Chapter 1

Introduction

In wilderness is the preservation of the world

Henry David Thoreau (1817-1862)

1.1 Background

Ecosystem services, including photosynthetic production of oxygen, the provision of food and water, soil formation and crop pollination are integral for human survival. Despite their importance for supporting all forms of life, ecosystem services are being rapidly depleted as they are seldom valued like other commodities, in monetary units. There is also a lack of information on their financial value and a belief that we are entitled to these services free of charge, which limits our willingness to pay for them. In this chapter, I discuss the important carbon storage function of forests and explain why tropical forests play a key role in global climate mitigation efforts. I then debate the economic challenges in reducing emissions in the developing region of Southeast Asia and finally propose REDD+ as a cost-effective tool for supporting carbon mitigation efforts in the region. At the end of this chapter, I provide an outline of the content, objectives and structure of this thesis.

1.2 The role of tropical forests in mitigating climate change

Global climate change is one of the most complex and urgent threats facing our society. Every year for the past three consecutive years, record-breaking high temperatures have been experienced globally with 2016 now the warmest year on record (Steffen *et al.* 2016). As the evidence base of human's influence on climate change builds, it is now widely understood that unprecedented concentrations of carbon dioxide (CO_2), methane and nitrous oxide in the atmosphere that are resulting from rises in energy production, agricultural output and industrial activity, are trapping heat in the lower atmosphere (IPCC 2014). Anthropogenic greenhouse gas (GHG) emissions increased by 22 $GtCO_2$-eq yr^{-1} from 1970 to 2010 and are rising at a rate of 2.2% per annum (IPCC 2014). In

2015, parties to the United Nations Framework Convention on Climate Change held in Paris (COP 21) agreed on a target to limit global warming in this century to well below 2°C and as close to 1.5°C as possible to pre-industrial levels (UNFCCC 2015). This target is highly ambitious as the current trajectory of global temperature increases are in the range of 1.4°C to 4.8°C under baseline scenarios (RCP6 and RCP8.5) without emissions constraints. It will also take considerable time to achieve as fossil fuel burning accounts for the majority of emissions and moving to alternative energy sources could be slow (Houghton *et al.* 2015).

Short-term emissions reductions can be achieved from protecting, restoring and better managing tropical forests, which could reduce half the carbon emissions required to limit atmospheric warming to 2°C and the carbon benefits would be relatively fast (Houghton *et al.* 2015; UNFCCC 2015). Consequently, it is widely understood that global agreements to limit climate change must include policies to reduce emissions from land use in the tropics. Tropical forests contain around half of all carbon stored in terrestrial vegetation and their destruction accounts for ~15% of anthropogenic carbon emissions (Harris *et al.* 2012; Houghton 2013; Watson 2000). Around 9 million hectares of tropical forest cover were lost every year since 1990, representing the largest loss in any forest type for the period (FAO 2015). Deforestation causes a net flux of carbon to enter the atmosphere from the loss of above- and below-ground biomass, while forest degradation releases carbon as well as reduces the ability of forests to sequester carbon (Melillo *et al.* 1996). Consequently, international climate agreements to reduce GHG emissions include incentivising the protection and enhancement of forest carbon stocks, in recognition of the substantial level of emissions resulting from agriculture, forestry and other land use in the tropics (FAO 2014a).

As most remaining primary forests are in tropical regions (FAO 2015), conservation efforts must consider the entrenched development challenges characteristic of tropical economies, including low incomes and slow technological advances in agriculture (Sachs 2001). Poverty, corruption and unsustainable human population growth are socio-economic challenges that have impeded conservation initiatives in the past and also present significant barriers to future conservation outcomes (Koh and Sodhi 2010; Sodhi *et al.* 2004; Sodhi *et al.* 2010). Many communities in the tropics rely on timber and non-timber forest products directly as a main source of livelihood or for income, therefore, carbon mitigation efforts in developing countries should safeguard carbon-rich forests, but not further disadvantage poor communities by completely restricting access to forests, or prohibiting use of their products. These are two important factors that shape policies to protect tropical forests in developing economies.

1.3 Addressing the drivers of deforestation in Southeast Asia

Southeast Asia (Figure 1.1) - comprising Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste and Vietnam - is undergoing higher relative rates of deforestation than any other tropical region (Achard *et al.* 2002). The contribution of global net emissions from land-use change in the tropics is estimated at 1.1 ± 0.3 Gt C yr^{-1} attributable to the following carbon sources: converting forests (71%), loss of soil carbon (20%), forest degradation (4%), the 1997–1998 Indonesian fires (8%) minus sinks (−3%) from regrowth (Achard *et al.* 2004). Globally, Indonesia is one of the largest sources of carbon emissions from deforestation (Baccini *et al.* 2012). As of 2010, less than half (236 million hectares) of the original forests of Southeast Asia remained (FAO 2011; Stibig *et al.* 2014). If the current pace of deforestation continues, the region will lose almost three quarters of its forest cover this century (Achard *et al.* 2002) and up to 42% of its biodiversity (Brook *et al.* 2003). The region overlaps with four of the world's 25 biodiversity hotspots identified as supporting high levels of endemic species facing intense threat from land conversion (Mittermeier *et al.* 1999; Myers *et al.* 2000; Sodhi *et al.* 2004). Compounding the problem for Indonesia, deforestation that has occurred on peatlands, particularly in Borneo (Langner *et al.* 2007), has led to wildfires that contribute significantly to annual national emissions (Baccini *et al.* 2012). For example, emissions from peat fires during the 1997 El Nino year were equivalent of 13-40% of annual global emissions from fossil fuels (Page *et al.* 2002). Although this was a particularly bad year for peat fires, it illustrates the magnitude of such an event.

Deforestation of Southeast Asian forests is driven by a range of threats. The most notable driver is plantation agriculture, which in the 1980's accounted for 20% of deforestation in the region, but by 2000 accounted for 60% of deforestation (Rudel *et al.*

2009). International demand for tropical timber and oil palm are driving this trend. First, Southeast Asia is the world's largest producer of tropical timber (Berry *et al.* 2010), with timber production in Borneo higher than both tropical Africa and Latin America combined (Cleary *et al.* 2007). Second, over 80% of the world's oil palm (*Elaeis guineensis*) is grown in Southeast Asia (Koh and Wilcove 2007), with production highest in Indonesia (FAO 2011). Human population growth, forest fires, insecure land tenure and overexploitation of wildlife are other drivers of deforestation (Sodhi *et al.* 2004).

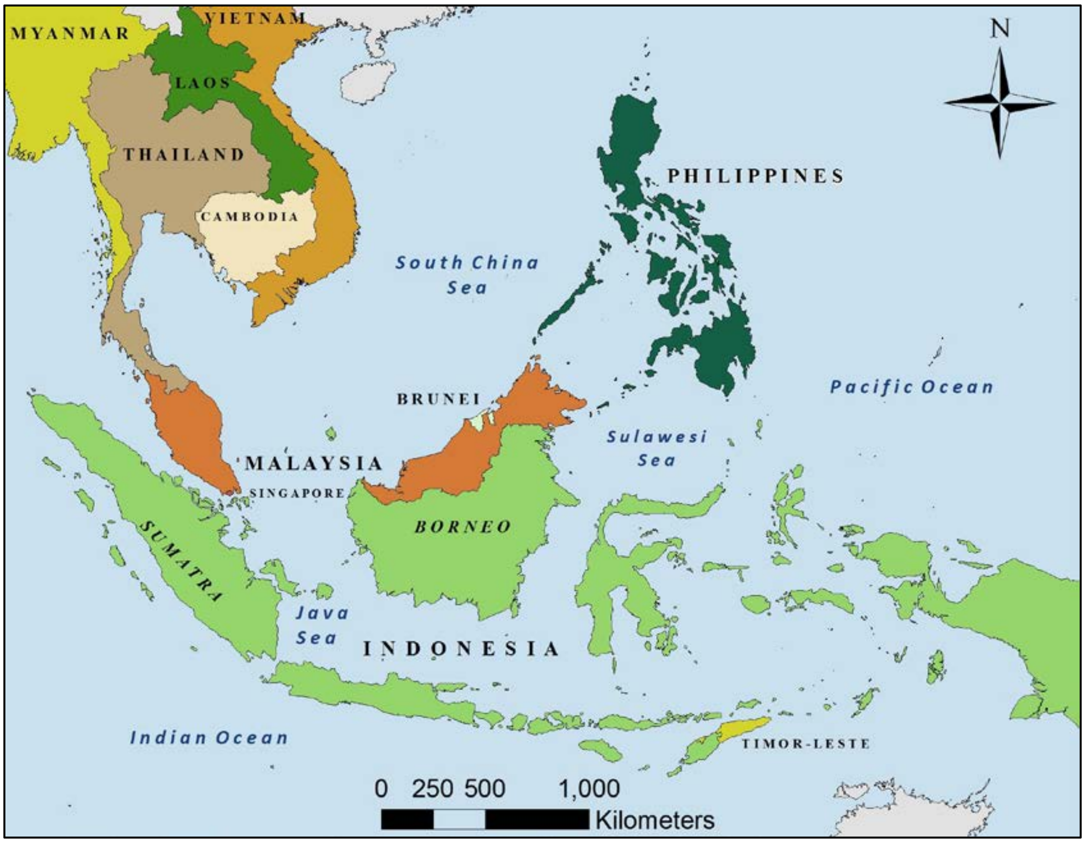

Figure 1.1 Map of the study region of Southeast Asia with country names.

Protected areas are the most widely used conservation initiative to protect ecosystems and biodiversity (Jenkins and Joppa 2009) and are integral to achieving global biodiversity targets, such as protecting 17% of terrestrial areas by 2020 (CBD 2011). In Southeast Asia, protected areas cover 38.5 million hectares, which equates to 9% of total land or 18% of forested area (FAO 2011). While in terms of sheer size this is impressive, many of these parks are not maintaining stable levels of forest cover, owing to threats from illegal logging, agricultural encroachment and clearing for small scale oil palm (Curran *et al.* 2004; Gaveau *et al.* 2007). On the Indonesia island of Sumatra, over 35% of protected areas experienced forest loss greater than 1% per annum from 1990 to 2000 (Gaveau *et al.* 2009). Sustainable forest management is another widespread type of forest protection that imposes less restrictions on human activity than protected areas, which can ban all extractive human use depending on their classification (Dykstra and Heinrich 1996). Sustainably managed forests often permit reduced-impact logging (RIL) activities, that adhere to guidelines aimed to reduce wastage and collateral damage during logging activities while still allowing timber extraction to occur (Putz *et al.* 2008a). Forests logged according to RIL principles have been found to lose less initial carbon and recover faster than conventionally-logged forests by applying techniques such as directional felling and protecting water courses (Pinard and Putz 1996). Finally, damage that has already occurred due to deforestation and forest degradation can be somewhat reversed by reforestation, where forests and their carbon stores, are assisted or allowed to recover in areas that are degraded or cleared (Chazdon 2008). The restoration of tropical forests reduces net anthropogenic carbon emissions by accruing carbon in tree biomass and soils (Elias and Lininger 2010; Silver *et al.* 2000).

1.4 Cost-effective ways to minimise forest carbon emissions in Southeast Asia

Addressing the threats to tropical forests incurs considerable expense and an investment shortfall can hinder the success of environmental policies (James *et al.* 1999). Mechanisms for incentivising environmental conservation by linking financial markets to environmental services aim to resolve this shortfall. Payments for Ecosystem Services (PES) are a type of market-based instrument that provide economic incentives (e.g. carbon credits) to stakeholders (e.g. landowners) for retaining and improving the size or quality of natural forests, resulting in improvements to ecosystem services, such as water quality or carbon storage (Engel *et al.* 2008). The most prominent international financial mechanism for conserving tropical forests in developing countries is REDD+ (for Reducing Emissions from Deforestation and forest Degradation plus conserving, sustainably managing forests and enhancing forest carbon stocks; Agrawal *et al.* 2011).

REDD+ facilitates monetary incentives to nations that preserve or enhance the carbon storage function of natural forests (Agrawal *et al.* 2011). The mechanism is recognised as a promising means of reducing rates of deforestation in tropical nations and mitigating carbon emissions cost-effectively (Eliasch 2008).

REDD+ was first officially proposed in 2005 by a group of 15 developing countries led by Papua New Guinea and Costa Rica known as the Coalition for Rainforest Nations (CRN; www.rainforestcoalition.org; Laurance 2007). When REDD+ was more formally discussed in 2007 at the COP13 in Bali, it was solely concerned with emissions from deforestation (RED) and only later grew to include forest degradation (becoming REDD). In 2008, the idea of including the conservation, sustainable management and enhancement of forest carbon stocks was discussed and REDD "+" was introduced (Agrawal *et al.* 2011). This was an important developmental milestone as it opened up two important activities: (1) improving the management of protected areas by channelling funds to employ more staff and purchase equipment; and (2) promoting the regeneration of degraded forests. By 2010, it was recognised that REDD+ needed some sort of protection against perverse outcomes for local forest-dependent communities and biodiversity, resulting in the inclusion of 'safeguards' in the Cancun agreements (UNFCCC 2011) and later refined in Paris in 2015. Indonesia has become the global leader in REDD+ readiness and demonstration projects (Cerbu *et al.* 2011). Since its inception, REDD+ has received significant international support. The UN Collaborative Programme on Reduced Emissions from Deforestation and Degradation in Developing Countries (www.un-REDD+.org) has provided early financial support for the initiative through multi-donor trust funds to support capacity building. The trust funds are largely from Norway, who has already committed over US$100 million (Venter and Koh 2011). The Forest Carbon Partnership Facility (FCPF, www.forestcarbonpartnership.org), with the World Bank as trustee, has also committed US$200 million in readiness activities to fund training and monitoring activities (Venter and Koh 2011).

The mechanism has also attracted a large amount of criticism towards its model of governance and process of measuring, reporting and verifying (MRV) carbon reductions. Among the most significant risks are corruption, additionality (paying to reduce emissions that would not have occurred under the business-as-usual scenario), permanence (emissions reduced now that are offset by increased emissions in the future) and leakage (emissions reduced in one location that are shifted to another location without the same controls; Venter and Koh 2011). A well-documented social challenge of the mechanism is community opposition, which is discussed further in Chapter 4. Other operational challenges are how to measure carbon reductions to ensure that only 'real' carbon reductions are being incentivised (Fearnside *et al.* 2014). Both methods that are commonly applied to carbon accounting have flaws. A historical approach, that assumes past rates of deforestation will continue, favours countries shifting from high to low deforestation and therefore has the risk of encouraging intensified deforestation prior to REDD+ implementation. Simulated models have also encountered distortions in measuring emissions reductions, as modelled predictions of future land cover change have been shown to have very high error rates, particularly when regional trend data is applied to small local sites (Fearnside *et al.* 2014; Pontius *et al.* 2008). This thesis focuses on the economic challenges of REDD+. To function as a market-based instrument, the financial compensation (offset payment) must be large enough to cover the foregone profits from the extractive markets they replace; known as the opportunity cost, but also compensate for lost social and environmental benefits (Fletcher *et al.* 2016; Stern 2008). A widespread economic risk is that REDD+ may become unviable if the payments do not cover the opportunity costs of deforestation-dependent activities, such as converting tropical forests to oil palm or timber plantations (Butler *et al.* 2009).

Numerous studies have subsequently assessed the mitigation costs of reducing emissions from oil palm concessions and logging in Asia and drawn comparisons against carbon prices on voluntary and compliance markets, rendering the mechanism uncompetitive with these highly lucrative activities (see Butler *et al.* 2009; Fisher *et al.* 2011a; Ruslandi *et al.* 2011; Venter *et al.* 2009). However, in the first decade of REDD+ readiness and demonstration activities, the majority of finance has been pledged by bilateral and multilateral agreements, from governments such as Norway and institutions including the World Bank - not through carbon markets as initially proposed (Fletcher *et al.* 2016). Though oil palm and logging contributed to ~3.4 million hectares of forest loss in Indonesia between 2000 and 2010, they accounted for only a quarter (23%) of total forest loss (Abood *et al.* 2015), indicating the majority of deforestation is driven by other threats that may be cheaper to address. Further, when REDD+ expanded its scope to include forest degradation and the enhancement of carbon stocks, it opened up a range of new opportunities for which the costs and benefits have not been broadly assessed, but may be cheaper.

Environmental threats, as well as the carbon benefits and costs of implementing conservation strategies are influenced by the spatial context in which they occur (Pagiola and Bosquet 2009). Site-specific factors, including terrain, distance to markets and soil type (Gibbs *et al.* 2007; Pagiola and Bosquet 2009) influence the costs and benefits of conservation strategies. Therefore, spatial-targeting can identify opportunities for cost-effective forest conservation through REDD+ (Bateman *et al.* 2015; Smit *et al.* 2013; Venter *et al.* 2012). For example, spatial analysis revealed that by expanding oil palm production in Indonesia on degraded land that is highly suitable for cultivation, oil palm production could be doubled, and with minimal losses to forest carbon stocks and biodiversity (Koh and Ghazoul 2010). In this thesis, I use spatial analysis to identify locations of high cost-effectiveness for reducing emissions across Indonesia.

1.5 Thesis Objectives

The primary goal of my thesis is to assess the economic viability of REDD+ in Southeast Asia. I will expand on previous studies that focused predominantly on the mitigation costs of reducing emissions from industrial oil palm, by incorporating strategies that reduce illegal deforestation in protected areas and reduce forest degradation and enhance forest-carbon stocks, such as: (a) implementing RIL; and (b); enhancing terrestrial carbon stores through reforestation and peat restoration. The two objectives underpinning this thesis are to: (1) identify the types of REDD+ strategies most prominent in Southeast Asia and estimate their associated average costs and carbon benefits; and, (2) estimate the mitigation costs of prominent REDD+ strategies and their scope for implementation in Indonesia using spatially-explicit costs and benefits.

Objective 1: Identify the types of REDD+ strategies in Southeast Asia and estimate their associated average costs and carbon benefits.

Numerous papers have compared the financial viability of REDD+ against large-scale oil palm plantations in Southeast Asia (see Butler *et al.* 2009; Fisher *et al.* 2011a; Ruslandi *et al.* 2011). These papers have generally concluded that REDD+ will be of limited utility for reducing emissions from oil palm expansion into forests because the revenues from converting forest into oil palm outweigh the revenues from selling the carbon credits on voluntary carbon markets. By focusing solely on reducing emissions from oil palm expansion into forested areas, these papers have overlooked potentially more cost-effective strategies for REDD+. In Chapter 2, I re-examined this question by reviewing existing REDD+ projects in Southeast Asia to determine if they primarily aim to reduce emissions from the oil palm sector or pursue alternative strategies. I used cost-benefit analyses to estimate the average cost of reducing emissions for each strategy that has publicly available financial cost and carbon benefit data, to comparatively assess the financial competitiveness of a broad range of options for REDD+.

Objective 2: Estimate the mitigation costs of REDD+ strategies and their scope for implementation across Indonesia using spatially-explicit costs and benefits.

Industrial concessions have expanded rapidly in Indonesia over the past 40 years, but vast amounts of forest remain that are allocated for conversion but yet to be cleared. Quantifying the potential carbon emissions from development plans is useful to assess the trade-offs of economic development. Also, the optimal approach to allocating REDD+ resources should consider the heterogeneity of costs and benefits across space, which vary based on site-specific factors including terrain, distance to markets and soil type (Gibbs *et al.* 2007; Pagiola and Bosquet 2009). The absence of spatially explicit analyses on the costs and benefits of REDD+ is a major limitation to the successful implementation of targeted and specific strategies. In Chapter 3, I used spatial analysis to quantify the carbon emissions that will occur from planned development in Indonesia in oil palm, timber and logging permits by mapping a range of heterogeneous factors, including: land classification, forest cover and above-ground biomass. I then quantified the carbon emissions resulting from deforestation within protected areas.

1.6 Thesis Outline

This thesis consists of a series of chapters that are formatted for publication in peer-reviewed journals. Figure 1.2 illustrates the structure of this thesis, chapter-by-chapter. Authorship of the published chapters (Chapters 2 and 3) is shared with my advisory committee and is detailed in the front pages. Oscar Venter, Susan Laurance and Alana Grech contributed to the formation of ideas, the development of methods, interpretation of the results, training and funding. Andrew McGregor contributed to editing the Chapter 2 manuscript. Because each chapter is written for publication in a style suitable for the individual journal, there are minor style and formatting differences between chapters though these have been minimised. Multiple governments, research and aid organisations contributed information either in the form of economic data or spatial information. I have identified the custodians of economic and spatial information with relevant citations where applicable. I created all of the figures and tables in this thesis, unless detailed otherwise.

Chapter 1 introduces the role of Southeast Asian forests in mitigating climate change and discusses the challenges associated with funding this through REDD+.

In **Chapter 2,** I use quantitative tools to comparatively assess the financial costs and carbon benefits of prominent REDD+ strategies in Southeast Asia. This chapter is published in *Environmental Research Letters* (Graham *et al.* 2016). The outputs of this chapter are designed to guide policy-makers and implementing bodies on the financial competitiveness of REDD+ strategies in Southeast Asia. I conducted the analysis and wrote the chapter.

In **Chapter 3,** I use spatial analysis to identify cost-effective opportunities and locations for REDD+ across Indonesia. Oscar Venter and Alana Grech assisted with the development of the methods and the application in ARC GIS. This chapter is published in *Environmental Research Letters* (Graham *et al.* 2017). I conducted the analysis and wrote the chapter.

Chapter 4 synthesises the outputs of previous chapters, highlights the key opportunities for REDD+ identified in this thesis and discusses their management implications and finally recommends directions for future research. I wrote the chapter.

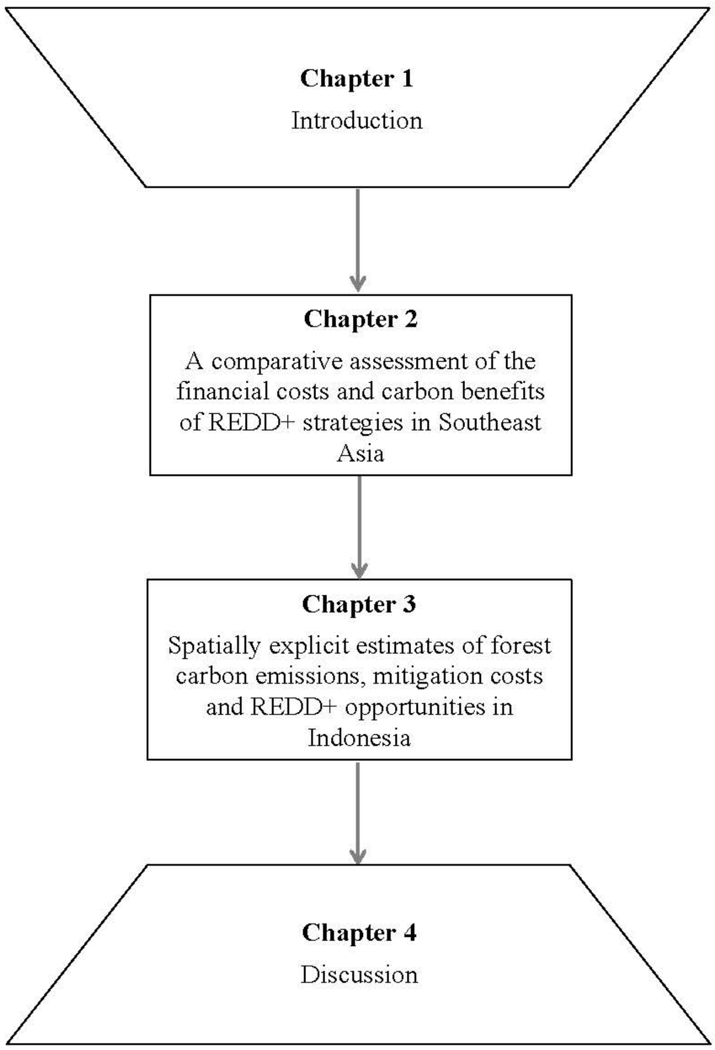

Figure 1.2 Chapter structure of thesis.

Chapter 2

A comparative assessment of the financial costs and carbon benefits of REDD+ strategies in Southeast Asia[1]

2.1 Abstract

In this chapter, I comparatively assess the financial costs and carbon benefits of prominent REDD+ strategies deployed in Southeast Asia. Firstly, I conduct a review of REDD+ projects in the region from online databases to identify the most commonly employed strategies for reducing emissions through REDD+. Then, I collate estimates from the scientific literature and government reports on the costs and benefits of a subset of these strategies to assess their cost-effectiveness for reducing emissions. I found that REDD+ projects primarily deployed seven main strategies: (1) reducing deforestation from oil palm, (2) reducing deforestation from timber plantations, (3) reducing deforestation from community threats (such as subsistence agriculture), (4) improving the management of protected areas to reduce fires and illegal logging, (5) employing RIL techniques to reduce wastage and collateral damage during log-harvesting operations, (6) moving oil palm permits to degraded land with suitable growing conditions ('permit swaps'), and (7) reforestation (including afforestation and peat restoration). I found the cost of reducing emissions ranges from $9 to $75 per tonne of avoided carbon emissions. The strategies focused on reducing forest degradation and promoting forest regrowth are the most cost-effective ways of reducing emissions and are used in over 60% of REDD+ projects. By comparing the financial costs and carbon benefits of a broader range of strategies than previously assessed, I highlight the variation between different strategies and draw attention to opportunities where REDD+ can achieve maximum carbon benefits cost-effectively.

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[1] Graham V, Laurance S G, Grech A, McGregor A and Venter O 2016 A comparative assessment of the financial costs and carbon benefits of REDD+ strategies in Southeast Asia *Environmental Research Letters* **11** 114022

2.2 Introduction

Southeast Asia has the highest rate of forest loss in the tropics, with 11 Mha (10%) of forest cover lost between 2000 and 2010 (Miettinen *et al.* 2011). The destruction of tropical forests contributes to ~15% of anthropogenic CO_2 emissions (van der Werf *et al.* 2009) and is a major cause of biodiversity declines (Laurance 1999). The most promising international financial mechanism for conserving tropical forests in developing countries is REDD+ (for Reducing Emissions from Deforestation and forest Degradation in developing countries plus conservation of forest carbon stocks, sustainable management of forests, and enhancement of forest carbon stocks; Venter and Koh 2011). REDD+ is often portrayed as providing a win–win scenario in Southeast Asia; as it directs large flows of international finance towards reducing forest carbon emissions, which benefits forest communities, ecosystems and the climate.

REDD+ has received widespread international support since it was proposed in 2005. Financial support for the mechanism totalled US $7.3 billion by 2015, including pledges of over US $2 billion to Indonesia alone (for real-time tracking of REDD+ expenditures see: Forest Trends Association 2016). Criticism of REDD+ covers a multitude of economic, social, ecological and governance issues (Agrawal *et al.* 2011; McGregor 2010). For instance, the economic viability of REDD+ depends on whether the finance it generates is sufficient to off-set lost revenues from alternative land-use activities, which in Southeast Asia can include timber extraction, oil palm concessions and smaller-scale agricultural encroachment (Venter and Koh 2011). There are concerns that the program may result in 'fortress conservation' in which the priorities of international investors are privileged over those of local forest users and that new forms of intimate exclusions will be experienced at the local-scale (Howson and Kindon 2015). Corruption, community opposition (Eilenberg 2015; Lounela 2015), and poor knowledge and communication (Howell 2015) are all governance issues that have stymied project development. Important ecological considerations include the carbon-biodiversity trade-offs of REDD+ activities. For example, afforestation is beneficial for carbon, but can have negative impacts on biodiversity (Bremer and Farley 2010). Although attention has been drawn to the trade-offs between carbon, biodiversity and community livelihoods (Newton *et al.* 2016), information is scarce on how these outcomes differ between the type of strategy employed.

In this chapter, I focus on the economic challenges, particularly in terms of the costs associated with different REDD+ strategies in Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste and Vietnam (Figure 1.1), as economic feasibility can influence the success of a project from infancy. Recent research has drawn comparisons of the financial incentives from REDD+ against large-scale oil palm plantations in Southeast Asia (Butler *et al.* 2009; Fisher *et al.* 2011a; Irawan *et al.* 2011; Ruslandi *et al.* 2011; Venter *et al.* 2009). For example, Fisher *et al.* (2011a) estimate that converting a hectare of forest into oil palm in Sabah, Malaysia earns ~$24,000 over 25 years, which equates to ~$170 per tonne of emitted carbon—a price that is unlikely to be met through REDD+ financing given the low price of carbon. The consensus from Fisher *et al.* (2011a) and Ruslandi *et al.* (2011) is that REDD+ will be of limited utility for reducing emissions from oil palm because the revenues from converting forest into oil palm far outweigh the revenues from trading the carbon credits on voluntary markets (Butler *et al.* 2009).

However, by focusing solely on reducing emissions from oil palm expansion in forests, such research can overlook potentially more cost-effective strategies for REDD+. To optimally allocate REDD+ resources, it is important to consider both activities that reduce emissions as well as activities that sequester carbon (van Kooten *et al.* 2009). Alternative options for REDD+, other than limiting oil palm expansion, include sustainable forest management practices (Putz *et al.* 2008a, Griscom 2009), investing in protected areas to improve their management and reduce illegal forest loss (Scharlemann *et al.* 2010) and forest restoration (Alexander *et al.* 2011; Silver *et al.* 2000). These strategies provide alternative models for pursuing REDD+ that may be more financially attractive to Southeast Asian nations.

In this chapter, I provide the first broad comparison of the financial costs and carbon incentives associated with different REDD+ strategies in Southeast Asia. I initially identify what types of strategies are most common in Southeast Asia before estimating their cost-effectiveness, measured as the cost of reducing one tonne of carbon, of a subset of REDD+ strategies for which financial cost and carbon benefit data are publicly available. The research is designed to emphasise and assess the variety of REDD+ strategies being employed in order to inform policy and decision-makers regarding the most financially appropriate ways forward.

2.3 Materials and Methods

There were two distinct stages to this review: 1) the assessment of a sample of REDD+ projects being planned or implemented in Southeast Asia; and 2) the collation of cost and benefit estimates of the main strategies adopted by REDD+ projects. The cost and benefit data are hypothetical estimates drawn from the literature and were not sourced from REDD+ projects.

REDD+ project review

An inventory of forest carbon projects was compiled by searching online REDD+ databases that were known to the authors or were found by searching the internet for "REDD+ databases" (Conservation International; Forest Carbon Asia; Forest Carbon Portal; Forest Climate Centre; Institute for Global Environmental Strategies; The REDD Desk; and Verified Carbon Standard). All projects that were either planned or implemented (regardless of whether they were still operational) as of March 2016 were initially added to the list. I refined the list by applying the selection criteria displayed in Figure 2.1. Reforestation and afforestation projects that were not classified as REDD+ projects were excluded during this stage. The purpose of the project review was to identify the main strategies used by the projects sampled, not to conduct a comprehensive review of REDD+ projects in the region, therefore projects without information on the strategy were excluded. As a result, 57 projects met the selection criteria and no projects were identified in Myanmar, Timor-Leste, Singapore or Thailand. In this thesis, a 'project' refers to a site (e.g. Heart of Borneo), while a 'strategy' refers to the approach adopted at a site to reduce emissions or promote sequestration by forests. The proponents were divided into the following four categories: government, non-governmental organization (NGO), private company, and research institution.

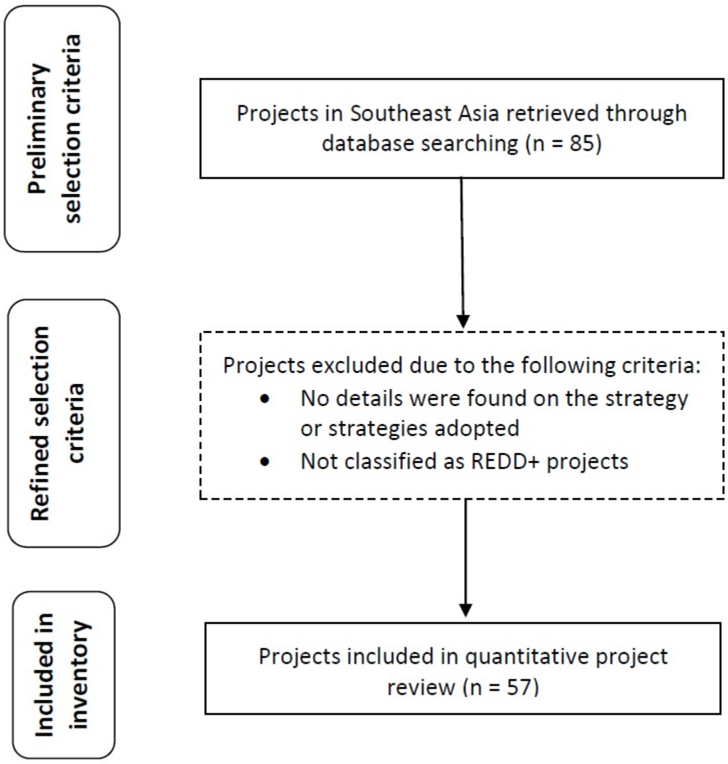

Figure 2.1 Flow chart showing the selection criteria used to generate the list of REDD+ projects in Southeast Asia as of March 2016. Dashed lines represent where the selection criteria were applied to exclude projects. A total of 57 projects were included in the final inventory.

Once an inventory of projects was compiled, I used proponent websites and project proposal documents to extract data on specific projects, including: name, geographic location, strategies adopted, area under management (hectares), proponents, planned duration, driver of deforestation and targeted or realised emissions reductions. Each planned or existing project was categorised into at least one of the strategies shown in Table 2.1 based on key terms identified in the project description. The strategy list was based on an initial literature search and modified as the review progressed, such as adding or deleting categories based on their prevalence. I assigned projects to more than one category if they adopted multiple strategies. For example, the Heart of Borneo project covers 16,800,000 ha, spans three countries, and adopts seven different strategies. I classified this project as three projects (to represent each country), each with seven strategies.

Table 2.1 List of strategies included in the REDD+ project inventory with a description of the strategy and the business-as-usual scenario against which it was assessed. In the literature, different cost components (opportunity costs, management costs and/or transaction costs) were estimated for different strategies. If cost data was available for the strategy, the cost components are listed.

REDD+ strategy	Description of strategy	Business-as-usual scenario	Costs estimated	Cost component
Oil palm	Buying land that was planned for oil palm development before it is cleared and protecting it from forest carbon loss.	Establish oil palm plantation	Yes	OC, TC
Timber	Buying land that was planned for timber plantations and protecting it from forest carbon loss.	Establish timber plantation	Yes	OC, TC
Community encroachment	Buying land that was planned for small-scale agriculture, rice and coffee plantations, risks development encroachment or other local threats and protecting it from forest carbon loss.	Establish small-scale agriculture	No*	
Protected areas	Investing in improved protected area management to prevent forest carbon loss through illegal clearing, logging and fire.	Continue current management plan	Yes	MC, TC
Reduced-impact logging	Promoting sustainable forest management practices, such as Reduced Impact Logging, in areas designated for logging, to reduce carbon lost during the logging process. Practices include reducing road and landing pad construction impacts, and reducing collateral damage to remaining trees during felling and extraction.	Conventional logging	Yes	OC, MC, TC
Permit swaps	Working with oil palm developers to retire oil palm permits in high carbon areas and identify alternative sites to establish plantations in low carbon degraded areas via oil palm 'permit swaps'.	Establish oil palm plantation	No*	
Reforestation	Identifying cleared or degraded land that is not being actively used for plantations or logging and restoring forests (and peat swamp forests) for carbon storage.	Land remains abandoned†	Yes	MC, TC

*The costs and benefits of the 'community encroachment' strategy were not estimated because they were considered to be too variable to capture with a single estimate. The 'permit swaps' strategy had insufficient cost and benefit data.

† I classify abandoned land in this chapter as degraded forest that is not being actively managed for plantations or logging by a person or corporation. However, land that appears abandoned is not always abandoned. In many areas insecure land tenure makes the task of identifying potential land for reforestation a considerable challenge. There are millions of hectares of degraded forest in Indonesia that are considered idle, which present a vast opportunity for improving carbon storage by promoting forest regrowth (Boer, 2012; Budiharta *et al.* 2014), but some of these areas that are close to villages are being actively worked by neighbouring communities. Methods for identifying degraded areas for plantations have been prescribed that utilise spatial information and community surveys (Gingold *et al.* 2012).

Cost-benefit analysis

The cost-benefit analysis focuses on the financial viability of different strategies for reducing emissions as one component influencing broader REDD+ discussions, while drawing attention to the social and ecological dimensions of these strategies, which are also important project outcomes. At this early stage in its development, all but the most advanced REDD+ nations are yet to develop national capacities for measuring and reporting on non-carbon benefits and safeguards (Vijge *et al.* 2016).

I used systematic search protocols (Moher *et al.* 2009) to collect financial cost and carbon benefit data for the strategies (Table 2.1) to directly compare their cost-effectiveness, as measured by the estimated financial cost of reducing one tonne of carbon emissions. The financial costs and carbon benefit data were collected from the respective bodies of literature, to provide representative estimates of the cost-effectiveness of REDD+ strategies. I searched for data in peer-reviewed books, journals, reports published by government and non-government agencies, using terms specific to each strategy (such as: 'costs' or 'carbon benefits' and 'reduced-impact logging') and examined the reference lists of suitable literature to locate further data. I included estimates from the 'grey literature' to ensure I collated multiple estimates for each strategy, as some strategies did not feature in the peer-reviewed literature. Once I identified all possible information sources, I removed studies that were duplicates (i.e. the published manuscript from an unpublished university thesis) or that were not in English. I further refined the list based on eligibility in meeting the following criteria: 1) the research was conducted in Southeast Asia - with the exception of the reforestation strategy as there was insufficient regional data so I expanded my search to tropical regions outside Southeast Asia; 2) the carbon emissions for reduced-impact logging (RIL) presented a 'before-after' scenario of RIL versus conventional logging (CL); and 3) the data was not for activities on peat soils (see 'Carbon benefits' section below for rationale). All remaining data sources were included in the review. Here I present a summarised version of the steps involved in calculating the costs and benefits; see Appendix 1 for more details.

Financial Costs

In this chapter, the financial costs of REDD+ projects included opportunity costs, management costs and transaction costs. Opportunity costs are defined as costs of foregone opportunities from the next best use of a resource if not for the current use (Naidoo *et al.* 2006). Management costs are ongoing and include operating and maintenance expenses (Naidoo *et al.* 2006). Transaction costs include one-off costs of identifying and negotiating REDD+ projects and the ongoing costs of monitoring, reporting and verifying on carbon emissions (Pearson *et al.* 2014). The total economic costs of REDD+ also include downstream costs, such as taxes paid to the government, however the majority of the cost literature I examined was focused on financial costs (such as lost revenue from timber extraction). Opportunity costs account for the largest share of total REDD+ costs (Pagiola and Bosquet 2009), however transaction costs can be significant additional costs depending on the project scale (Fisher *et al.* 2011c). Strategy-specific estimates of transaction costs are not available in the literature, therefore I applied a generic estimate of transaction costs for a REDD+ project (US $2.21 per tCO_2 or $89 per ha; Pearson *et al.* 2014). Insurance (buffering the risk associated with non-permanence) accounts for the largest share of transaction costs, followed by monitoring and regulatory approval costs, whereas search, feasibility and negotiation costs account for a low portion of transaction costs (Pearson *et al.* 2014). I relied on the available data to estimate and compare the costs of different strategies, recognising there are differences in the costs accounted for between strategies. Table 2.1 explains the cost components that were estimated for each strategy.

Net Present Value (NPV) is the most commonly used measure of REDD+ project costs, which is the discounted value of the sum of projected future cash flows expected under the business-as-usual scenario (Stone 1988). To maintain consistency between estimates, I prioritised NPVs extrapolated over 30 years, which is consistent with the average timeframe for timber and oil palm concessions (Irawan *et al.* 2011). Most studies applied a discount rate of 10% per annum, which is not unusually high in the developing country context (Dang Phan *et al.* 2014). I standardised all financial estimates into a single currency and year (US 2010) using the national inflation rate for the respective country (The World Bank 2016) and the 2010 exchange rate (XE 2016).

If the financial analysis paper used estimates of carbon benefits to calculate the cost of reducing emissions, I used the individual $\$\cdot tC^{-1}$ figures from the paper, otherwise I calculated the price of reducing emissions using an average carbon benefit from the literature.

Carbon benefits

In the analysis, the carbon benefit is the net emissions reduced by each strategy or the carbon sequestered by regenerating forests (see Appendix 1 for details). The carbon estimates used here are from the loss of above- and below-ground carbon (AGC; BGC). I used a root:shoot ratio of 21:100 to convert AGC to total carbon in natural forests and timber plantations (Kotowska *et al.* 2015; Saatchi *et al.* 2011) and 32:100 in oil palm concessions and mixed-crops (Kotowska *et al.* 2015; see below). I opted to omit carbon-rich peat soils because the impacts of different strategies on peat soils was not consistently available. For the oil palm strategy, the carbon benefit was measured as the difference in carbon stored between oil palm plantations and natural forest in Southeast Asia. A similar comparison was made between natural forest and timber plantations. I ascertained from the literature the carbon emissions reduced by engaging RIL compared to CL techniques. Cacao, oil palm, rubber and coffee (hereafter 'mixed-crops') are commonly planted crops in Indonesian protected areas following deforestation (Swallow *et al.* 2007). I estimated the carbon lost from the conversion of forests to mixed-crops and multiplied it by the deforestation rate to project the carbon emissions from illegal deforestation. Finally, for the reforestation strategy, I estimated the 30-year sequestration rate of regenerating forests. The carbon sequestration estimates for reforestation included tropical regions other than Southeast Asia, as there was insufficient regional data available. All carbon values are in tonnes (1 tonne = 1 Mg) of carbon (C). Carbon dioxide (CO_2) was converted to carbon by dividing by 3.67 (van Kooten *et al.* 2004). Biomass was converted to carbon by multiplying by 0.492 (Pinard and Putz 1996).

Cost of reducing emissions

I calculated the cost of reducing emissions using the formula below, to directly compare the cost-effectiveness of each strategy and for ease of comparison against carbon prices.

$$\text{Cost of reducing carbon } (\$\cdot\text{tC}^{-1}) = \frac{\text{Cost } (\$\text{ ha}^{-1})}{\text{Carbon benefit } (\text{tC ha}^{-1})}$$

where

$\$\cdot tC^{-1}$ = the cost of reducing one tonne of carbon, $\$ ha^{-1}$ = the cost per hectare and $tC ha^{-1}$ = tonnes of carbon reduced per hectare

2.4 Results

I found that Indonesia is the regional leader in REDD+ projects, hosting 39 out of the 57 projects surveyed in Southeast Asia (Figure 2.2; see Appendix 1 for details). Vietnam hosted five projects, Cambodia and Laos hosted four projects each, Malaysia and the Philippines hosted two projects each and Brunei hosted one project. In Indonesia, projects are concentrated on the islands of Borneo and Sumatra; which are the two islands that experienced the highest forest loss for 2000–2010 (Miettinen *et al.* 2011).

REDD+ projects primarily deployed seven main strategies: (1) reducing deforestation from oil palm, (2) reducing deforestation from timber plantations, (3) reducing deforestation from community threats (such as subsistence agriculture), (4) improving the management of protected areas to reduce fires and illegal logging, (5) employing RIL techniques to reduce wastage and collateral damage during log harvesting operations,(6) moving oil palm permits to degraded land with suitable growing conditions ('permit swaps'), and (7) reforestation (including afforestation and peat restoration). Of these, reforestation was the most common strategy, used at 42 of the 57 project sites (Figure 2.3). Improving the management of protected areas was the second-most commonly used strategy (adopted at 35 sites). Agroforestry was grouped into the 'other' category and was commonly implemented adjacent to protected areas to buffer the conservation zone from broader landscape threats. Reduced-impact logging was adopted at 17 sites and more commonly adopted by research institutions and private companies than NGOs or governments. Avoiding deforestation from oil palm was less commonly adopted (at 12 sites), followed by oil palm permit swaps (adopted at 9 sites). Projects targeting oil palm were implemented more by NGOs than other proponents. On average, 3 strategies were adopted at each of the 57 project sites. Projects developed by private companies made up the largest share of total projects (39%), followed by NGOs (32%), governments (24%) and research institutions (5%).

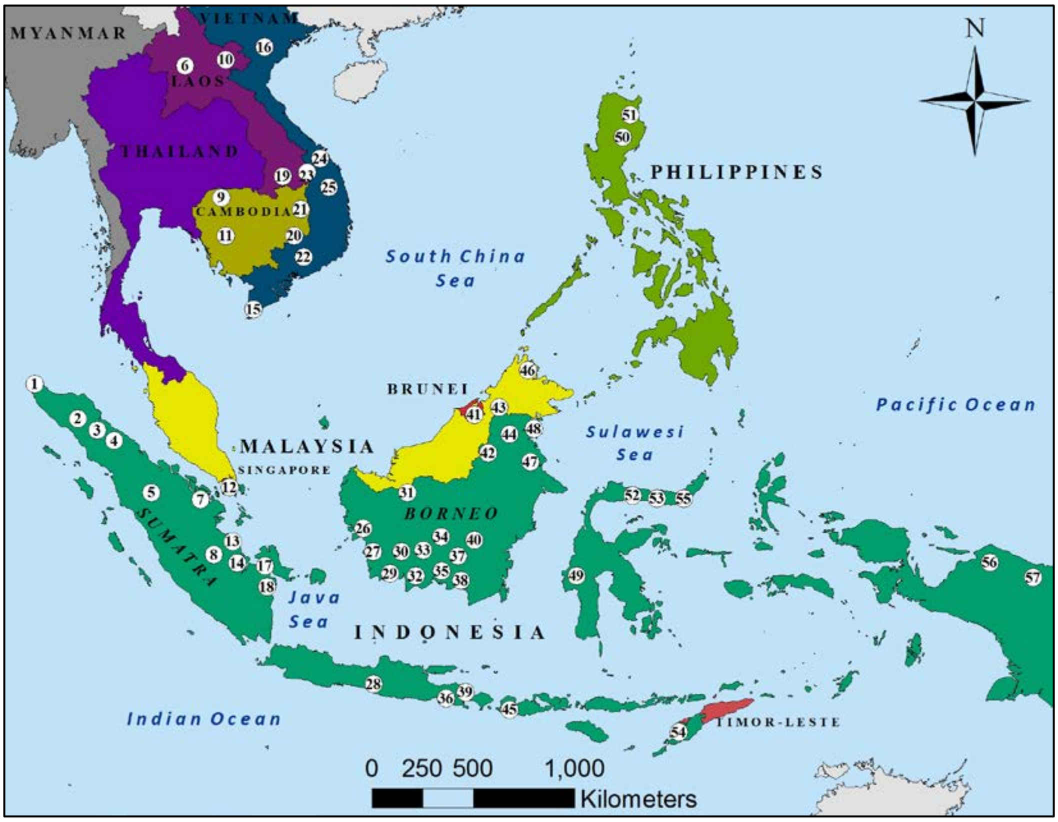

Figure 2.2 Southeast Asia showing the location of 57 REDD+ projects that were included in the project review. Refer to Table A1.2 for project name, country and strategy (or strategies) employed at each site.

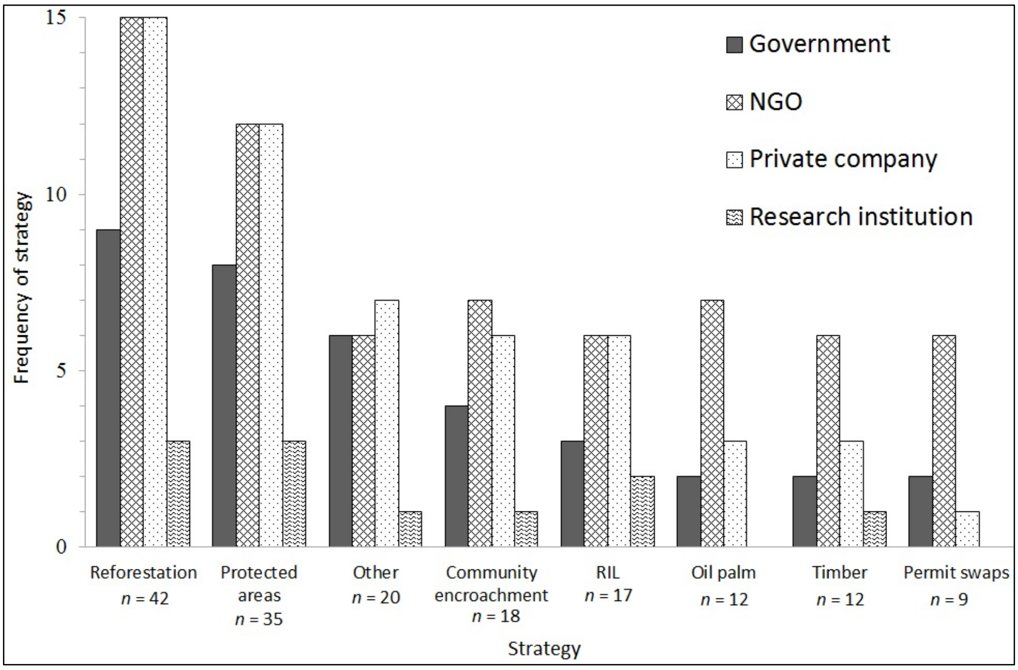

Figure 2.3 The frequency of REDD+ projects in Southeast Asia that adopt each of the strategies assessed. On average, three strategies were adopted at each project site. RIL: reduced-impact logging. Other strategies include: agroforestry, agricultural intensification and improving land tenure.

The average cost of reducing one tonne of carbon by employing the REDD+ strategies that were reviewed ranged from \$9 to \$75$\cdot$tC^{-1} (Table 2.2). There is a high level of variation in estimates of both costs and carbon benefits between strategies. I found that reforestation was the most cost-effective strategy (\$9$\cdot$tC^{-1}), followed by investing in protected areas to reduce illegal forest loss (\$13$\cdot$tC^{-1}), employing RIL techniques instead of CL (\$25$\cdot$tC^{-1}), reducing the expansion of timber plantations into forested areas (\$35$\cdot$tC^{-1}), and limiting the expansion of oil palm concessions into forests (\$75$\cdot$tC^{-1}). Employing RIL techniques had the lowest per hectare carbon benefit (42tC ha^{-1}), but was the third-most cost-effective strategy for reducing emissions due to low per hectare opportunity costs. Although stopping the expansion of oil palm into forests had the second-largest carbon benefit (144tC ha^{-1}), the high yields and value of oil palm as a commodity result in high opportunity costs of employing this strategy. As a result, limiting oil palm was the most expensive REDD+ strategy both per hectare and for reducing one tonne of carbon emissions.

In the financial cost literature, there was more research focused on estimating the opportunity cost of oil palm than on any other strategy. In contrast, there was no single paper that estimated the projected carbon benefits of investing in improved protected area management in Southeast Asia, despite the well-documented poor performance of Indonesian protected areas (Bruner *et al.* 2004; Gaveau *et al.* 2007; 2009; James *et al.* 1999). Reducing the expansion of timber plantations was the second most expensive strategy due to the high prices attracted by timber from parts of the region (Ruslandi *et al.* 2011). While reforestation was costly to implement ($1,743 ha^{-1}), it had the largest carbon benefit of all strategies (193tC ha^{-1}), making it the cheapest strategy per tonne of carbon reduced. Additional costs for reforestation on degraded peatlands amount to $240 ha^{-1} for building mounds to improve seedling survival rates in flood-prone and maintaining dams where peat canals have been drained (Budiharta *et al.* 2014; Silber 2011), which when combined with the cost of reforestation inflates the cost to $1,983 ha^{-1} or $10·tC^{-1}. The data sources interrogated for the financial and carbon estimates are detailed in Appendix 1 (Table A1.1).

Table 2.2 Mean cost and carbon benefit estimates per hectare and the cost per tonne of carbon reduced for REDD+ strategies. Values in parentheses represent the range of estimates. The cost and benefit (measured by C) per hectare were estimated over 30 years. The mean cost per hectare of oil palm and timber plantations includes the profits from timber extraction prior to planting.

REDD+ Strategy	Cost per ha (US$ ha^{-1})	Carbon benefit per ha (tC ha^{-1})	Cost per tC ($\$\cdot tC^{-1}$)
(1) Oil palm	9,942 (2,112 – 28,352)	144.20 (80.72 – 235.39)	74.90 (20.74 – 202.71)
(2) Timber	4,383 (1,506 – 11,735)	133.02 (46.82 – 199.85)	35.34 (17.95 – 64.96)
(3) Protected areas	689 (319 – 1,411)	90.96 (22.39 – 159.33)	13.38 (9.31 – 21.31)
(4) RIL*	833 (159 – 2,150)	41.77 (33.00 – 51.38)	25.49 (8.66 – 58.40)
(5) Reforestation	1,743 (606 – 4,193)	192.96 (136.90 – 251.40)	9.02 (3.14 – 21.73)

* Reduced-impact logging

2.5 Discussion

This chapter assessed the economic cost and carbon benefit of a range of strategies oriented at mitigating climate change by improving the amount of carbon stored in Southeast Asian forests. I estimate that reducing emissions through REDD+ would cost between \$9 and \$75$\cdot tC^{-1}$, depending on the strategy employed. For comparison against market prices, the 2010 end-of-year carbon price was \$89$\cdot tC^{-1}$ (www.investing.com). Reforestation and investing more funds into protected area management were the most cost-effective and widely adopted strategies used in over 60% of projects. In contrast to its high profile in the literature, reducing deforestation from oil palm was the most expensive and one of the least commonly used strategies in Southeast Asia. It is my contention that the prevalence of a particular strategy is at least partly a reflection of its cost-effectiveness alongside other considerations deriving from local political economies.

Although high costs have been a documented limitation to the widespread practice of reforestation in some regions (Erskine 2002), reforestation was the least costly strategy for reducing one tonne of carbon that was assessed in this review and the most prolific strategy adopted by REDD+ projects. I expect this result is influenced by low labour costs in Southeast Asia and the high rate of carbon sequestration in regenerating tropical forests (Silver *et al.* 2000). Alongside carbon and financial considerations, the social and ecological outcomes of REDD+ strategies are also important to consider when comparing strategies. In the case of reforestation, a large risk to biodiversity lies in the incorrect classification of grasslands as degraded lands that are deemed suitable for reforestation (Veldman et al 2015). Also, targeting threatened species conservation in addition to carbon storage can reduce the carbon incentive of reforestation by up to 24% compared to efforts that purely target low-cost carbon storage due to trade-offs between carbon and biodiversity (Budiharta *et al.* 2014). There are 6.1 Mha of low carbon, degraded land in East Kalimantan (Indonesian Borneo) that are considered suitable for forest regrowth (Budiharta *et al.* 2014), therefore the scope for this strategy is vast.

The second most popular strategy was to invest funds into improved protected area management. This involves better policing and surveillance as well as infrastructure, education and training programs to prevent illegal logging and agricultural encroachment – both of which are common in many parts of Southeast Asia (Curran *et al.* 2004; Gaveau *et al.* 2007). The incentives of improved protected area management include the carbon benefits alongside biodiversity, tourism and, if well managed, local livelihoods through non-timber forest economies. The biodiversity and community benefits have proved useful for appealing to investors coming from a corporate social responsibility angle, who are seeking 'good news' stories that go beyond profit motives (Dixon and Challies 2015). As for all projects, the risk of failure is high if the local drivers of forest loss are not addressed, however inadequate funding of protected areas plays a large role in illegal forest exploitation due to weak law enforcement (Bruner *et al.* 2004; James *et al.* 1999), which can potentially be addressed with REDD+ finance.

The third most cost-effective strategy was RIL, which was employed at approximately one third of the project sites. This shows that carbon interests are becoming better understood and influential in the forestry sector, with REDD+ proponents seeking to influence how timber is harvested. The benefits to the forestry industry of employing sustainable forestry practices are two-fold; RIL is a certified-REDD+ strategy that can generate income for the sector, and it can also increase future timber harvests by adopting more sustainable and less damaging logging techniques (Pinard and Putz 1997). Selectively logged forests also have important biodiversity value. For example, once-logged forests retain 76% of carbon and 85–100% of species of mammals, birds, invertebrates and plants as pre-logged forests (Edwards *et al.* 2010; Putz *et al.* 2012). However, less than one percent of total tropical forest area in Asia is under certified forest management (Siry *et al.* 2005). Given these environmental benefits, there is potential to considerably expand RIL operations at the expense of conventional logging projects, and off-set the financial costs with REDD+ revenue. A perverse risk could be if REDD+ is used to generate the required capital to commence logging operations that were previously underfinanced. Other risks are if lower intensity logging is off-set by expanding logging area, or increasing logging intensity at another site, known as 'leakage' (Newton *et al.* 2015).

These results show that buying oil palm and timber permits, where operations cause severe degradation or deforestation and conserving these forests, are expensive options for REDD+. The destruction of forests for oil palm has been a rapidly increasing trend over the past 40 years in Indonesia and Malaysia (Koh and Wilcove 2008) and is a key source of deforestation in Southeast Asia, alongside other agricultural commodities such as rubber and coffee (Stibig *et al.* 2014). Limiting the expansion of new oil palm and timber plantations in forests is vitally important for biodiversity conservation, however it is an expensive practice to pursue for climate mitigation. Further, there is limited scope for REDD+ to target oil palm and timber concessions when compared to other industries. In Indonesia, ~2.7 Mha of remnant forest is contained in timber concessions and ~1.7 Mha in oil palm concessions, compared to ~17.1 Mha in logging concessions (Abood *et al.* 2015) and a protected area network covering ~22.6 Mha (IUCN and UNEP-WCMC 2016). The relatively low uptake of oil palm projects indicates a reluctance from REDD+ proponents to engage in these activities, for financial and/or political reasons, and a challenge in convincing concession holders to cooperate.

In terms of oil palm, I found some interesting initiatives oriented at redirecting plantations to low carbon degraded land. Oil palm permit swapping provides a pathway for furthering agricultural expansion without the loss of additional tropical forests (Venter *et al.* 2012). It involves retiring existing permits on carbon dense land and taking-out new permits on highly degraded land that has suitable climatic and edaphic conditions for cultivating oil palm, by undertaking spatial-targeting and community surveys of candidate sites (Gingold *et al.* 2012). The benefits of permit swapping are manifold; reducing emissions from the oil palm sector whilst also finding productive uses for abandoned land. The costs incurred from this process include purchasing new permits, negotiating with affected permit holders, communities and governments (Venter *et al.* 2012) and can include substantial legal costs. Financial compensation would need to be provided to concessionaires to harness support, such as through a compensation fund or by offering discounted credit to those willing to participate, as timber revenues from clearing forests are used to defray plantation set-up costs (Irawan *et al.* 2013). Ideally, the restrictions would be integrated into a spatial-planning reform, whereby high taxes are imposed for plantations planned on carbon-rich forests (Van Paddenburg *et al.* 2012). Of critical importance is ensuring that the interests of those using abandoned or degraded land are actively involved in any decision-making regarding land planning (McGregor 2015).

The following caveats should be considered when interpreting these results. The cost and benefit estimates presented here are averages, however spatial variation has a large influence on the costs and benefits of REDD+ projects (Pagiola and Bosquet, 2009). This can be interpreted from the high level of variation in both the cost and carbon benefit estimates within strategies. For example, opportunity costs will vary based on terrain and distance to markets, and carbon benefits will vary based on soil type. Reducing emissions undertaken on peat soils would result in larger carbon benefits (Page *et al.* 2002) and hence lower costs than mineral soils. Despite the portrayal in this chapter, land use trajectories are not mutually exclusive and most projects employ numerous strategies at a site to combat the range of land-use pressures affecting any given location. In addition, strategy-specific transaction costs of REDD+ were not available in the literature, therefore I applied a generic cost across all strategies, however these could vary significantly between strategies. It should be noted that the literature reviewed used different methods to calculate the costs and benefits of REDD+ strategies, with not all papers including the same cost components or carbon pools. The purpose of this chapter was not to address the finer-scale variation, an important area for future research, but to explore the broad cost-effectiveness of a range of REDD+ strategies.

In terms of strategies, I did not collect quantitative estimates of the categories termed 'community encroachment' or 'other' because I felt the costs and benefits would be too variable to capture with a single estimate. I also found that the reforestation literature was incomplete and contained no estimates of the costs of natural forest regeneration in Southeast Asia. Rather than omit this strategy from the analysis, I used cost estimates of monocultures as a proxy and included carbon sequestration estimates from other tropical regions. Understanding the costs of assisted natural reforestation is an important area for future research, given the high number of projects undertaking this strategy, and its likely focus within Indonesia's recently announced Peatland Restoration Agency.

2.6 Conclusions

When REDD+ was first conceived, it sought to Reduce Emissions from Deforestation (RED; see den Besten *et al.* 2014). As it expanded to reducing degradation (REDD) as well as conserving and sustainably managing forests, and enhancing forest carbon stocks (REDD+), a range of new opportunities opened up for targeting forest carbon loss, including RIL, reforestation and investing in improved protected area management. This analysis shows that these recently included strategies are more common and cheaper in the Southeast Asian region than the former that target high profit and politically-sensitive industries, such as oil palm and timber. The debate about REDD+, however, often remains focused on whether or not it can compete economically with these lucrative industries. Based on the relatively modest profits from forest carbon financing compared to the profits from oil palm and timber plantations, REDD+ will remain ill-suited to slowing these intensive industries across the region. However, this does not mean that REDD+ is failing but that it is shifting from its original focus towards more economical and less politically contentious activities. The discussion about REDD+ needs to be reoriented towards what REDD+

can and cannot do within its current budget. These findings have broad policy implications for Southeast Asia. Until carbon finance escalates, emissions reductions could be maximised from reforestation, RIL and increased investment in protected area management. This does not mean that all projects focused on slowing the expansion of oil palm are unviable, but that regional plans for mitigating climate change will achieve maximum carbon outcomes within the current budget by pursuing alternative strategies. Targeting cost-effective opportunities for REDD+ is important to improve the efficiency of national REDD+ policy, which in-turn fosters greater financial and political support for the mechanism. As REDD+ projects are designed to address site-specific environmental threats and consider the unique socio-political context in which they exist, these broad patterns of cost-effectiveness need to be supported by finer-scale research into the spatial variation in costs, carbon benefits, biodiversity and social implications. These issues should continue being explored and the research outcomes used to guide spatially targeted REDD+ projects that support national forest management plans.

Chapter 3

Spatially explicit estimates of forest carbon emissions, mitigation costs and REDD+ opportunities in Indonesia[2]

3.1 Abstract

In this chapter, I used spatial analysis to measure the total scope for REDD+ strategies in Indonesia and estimated the spatially-explicit carbon emissions and mitigation costs. The average per hectare costs collated in Chapter 2 were modified based on spatially-explicit site characteristics, such as carbon stocks, remaining forest cover, oil palm suitability and peat forests. I analysed the cost-effectiveness of the following REDD+ strategies in Indonesia, one of the world's largest sources of carbon emissions from deforestation: halting additional deforestation in oil palm and timber concessions and protected areas, reforesting degraded land and employing reduced-impact logging techniques in logging concessions. I discover that when spatial variation in costs and benefits is considered, low-cost options emerged even for the two most expensive strategies: protecting forests from conversion to oil palm and timber plantations. To achieve a low emissions reduction target of 25%, I suggest funding should target deforestation in protected areas, and oil palm and timber concessions to maximise emissions reductions at the lowest cumulative cost. Low-cost opportunities for reducing emissions from oil palm are where concessions have been granted on deep peat deposits or unproductive land. To achieve a high emissions reduction target of 75%, funding is allocated across all strategies, emphasising that no single strategy can reduce emissions cost-effectively across all of Indonesia.

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[2] Graham V, Laurance S G, Grech A and Venter O 2017 Spatially explicit estimates of forest carbon emissions, mitigation costs and REDD+ opportunities in Indonesia *Environmental Research Letters* **12** 044017

3.2 Introduction

Tropical forests are important reservoirs of carbon, containing around half (55%) of the carbon stored in forests worldwide (Pan *et al.* 2011). Globally, tropical forests declined at a rate of ~0.5% per annum for the period 1990-2010, which equated to ~120 million ha (Achard *et al.* 2014) and contributed to ~15% of anthropogenic carbon emissions (Houghton 2013). Indonesia is one of the largest contributors of carbon emissions from tropical deforestation and degradation (Baccini *et al.* 2012). The Indonesian government have pledged to curb the conversion of tropical lowland forests and one of the initiatives they are supporting to achieve this goal is REDD+ (for Reducing Emissions from Deforestation and forest Degradation plus conserving, sustainably managing forests and enhancing forest carbon stocks). REDD+ payments are intended to provide the economic incentives needed to conserve forests by linking financial rewards to emissions reduced or carbon sequestered (Agrawal *et al.* 2011). When REDD+ was first conceived in 2005 it sought to Reduce Emissions from Deforestation (RED; see den Besten *et al.* 2014) at which point it was chiefly concerned with limiting tropical deforestation. During early-stage discussions, the scope of REDD+ was broadened to include reducing degradation (REDD) as well as conserving and sustainably managing forests and enhancing forest carbon stocks (REDD+). This development opened up a range of new opportunities for addressing forest carbon loss, including activities that sequester carbon, such as reforestation, and that reduce degradation, such as reduced-impact logging (RIL; Alexander *et al.* 2011; Putz *et al.* 2008b).

Through its range of strategies, REDD+ has the potential to reduce carbon dioxide (CO_2) concentrations in the atmosphere, which will aid in the transition to a low fossil fuel global economy (Houghton *et al.* 2015). Since its inception, REDD+ has attracted over US$7.3 billion in funding, including pledges of over US$2 billion to Indonesia alone (Forest Trends Association 2016). A key issue hindering the implementation of REDD+ is how well cost-effective climate mitigation activities align with the rights of local forest users, with concerns raised that the priorities of international investors will be privileged over those of local communities (Howson and Kindon 2015). Additionally, economic concerns have been centred on the unlikelihood that REDD+ will generate sufficient finance to off-set lost revenues from alternative land-use activities, drawing comparisons against the moderate level of funding directed towards REDD+ relative to the high profits generated from deforestation-dependent activities such as timber and oil palm production (Venter and Koh 2011). The literature shows that projects aimed at limiting deforestation from large-scale oil palm production are expensive due to the high forgone revenues (i.e. opportunity cost) from converting forest into oil palm (e.g. Butler *et al.* 2009; Fisher *et al.* 2011a; Irawan *et al.* 2011; Ruslandi *et al.* 2011; Venter *et al.* 2009).

An alternative and potentially cheaper pathway for REDD+ to contribute towards carbon mitigation is via reforestation, reducing illegal deforestation in protected areas and reducing forest degradation. The optimal approach to allocating REDD+ resources will be influenced by the spatial context in which each project is applied, as costs and carbon benefits can vary spatially (Pagiola and Bosquet 2009). Site-specific factors that influence costs and benefits include terrain, distance to markets and soil type (Gibbs *et al.* 2007; Pagiola and Bosquet 2009). Recent studies undertaken in Indonesia highlight how applying a spatially-targeted approach to regional development can reduce the trade-offs of agricultural or timber expansion and forest protection (Koh and Ghazoul 2010; Venter *et al.* 2012). A key question therefore is how does spatial variation influence the effectiveness of REDD+ strategies to mitigate forest-based carbon emissions at low-cost across Indonesia.

To address this question, I used spatial analyses to assess the variation in costs and carbon benefits of various REDD+ strategies in Indonesia and identified the factors that drive cost-effectiveness. I used maps of carbon stocks, forest cover, peatlands and crop suitability to estimate the potential for REDD+ to slow or reverse carbon emissions from oil palm, timber and logging permits, protected areas and on degraded land. I explored the cost-effectiveness of REDD+ strategies for reducing one tonne of carbon and for achieving a range of emissions targets. I compared the results from this spatial analysis to the estimates from Chapter 2 that used average costs and benefits. This chapter is designed to deliver fine-scale information to policy-makers on spatially-targeted opportunities for mitigating carbon emissions from deforestation and forest degradation in Indonesia.

3.3 Materials and Methods

In this chapter, I estimated the 30-year carbon emissions and financial costs from anticipated land conversion and determined the carbon sequestered from restoring land that is not slated for urban development or agriculture across Indonesia. The term 'permits' refers to land use rights issued to companies for logging, oil palm or timber concessions. I ranked all permits, protected areas and reforestation sites by the cost of reducing one tonne of carbon (from low to high), to determine the combination of strategies that achieve emissions targets (25%, 50%, 75%, 100%) most cost-effectively. All carbon values are in tonnes (1 tonne = 1 Mg) of carbon (C). Carbon dioxide (CO_2) was converted to carbon by dividing by 3.67 (van Kooten *et al.* 2004). Biomass was converted to carbon by multiplying by 0.492 (Pinard and Putz 1996). All financial figures are in 2010 US dollars. Here I present a summarised version of the steps involved in calculating the spatially explicit emissions and costs individually for each permit, protected area or reforestation site. See Appendix 2 for details on the input data and detailed methods.

Estimating carbon benefits of REDD+ strategies

Spatial analysis was performed in ArcGIS v10.3 (ESRI 2014). I used 250m spatial resolution land cover maps for 2000 and 2010 that were produced using Moderate Resolution Imaging Spectroradiometer (MODIS) images and Daichi-Advanced Land Observing Satellite data (Miettinen *et al.* 2012b). I created binary maps of 2000 and 2010 natural forest cover (Figure 3.1a) by classifying: mangrove forest, peat swamp forest, lowland forest, lower montane forest and upper montane forest as natural forest (hereafter referred to as '*forest*'). To create a layer of deforestation, I used the erase function to estimate net forest loss for the decade 2000 to 2010 (Figure 3.1b). I resampled all layers to a ~250m resolution to match the Miettinen *et al.* (2012b) land cover dataset and projected all spatial data into Asia South Albers Equal Area Conic. I measured carbon emissions from loss of above- and below-ground carbon (AGC; BGC; Figure 3.1c-d). Baccini *et al.* (2012) used field data and remote sensing to estimate and map AGC for all of Indonesia. I used a root:shoot ratio of 21:100 to convert the AGC estimates from the Baccini map to total carbon in natural forests and timber plantations (Kotowska *et al.* 2015; Saatchi *et al.* 2011) and 32:100 in oil palm concessions and mixed-crops (Kotowska *et al.* 2015). I tested the sensitivity of the results to changes in the forest cover and carbon input data by analysing all of the scenarios using high spatial resolution (30m) land cover maps for 2000 and 2010 (Hansen *et al.* 2013) and a map of above- and below-ground biomass produced circa 2000 (Saatchi *et al.* 2011) - refer to Appendix 2 for details. Carbon benefits refer to emissions reduced from avoided deforestation and degradation, as well as carbon accrued from reforestation.

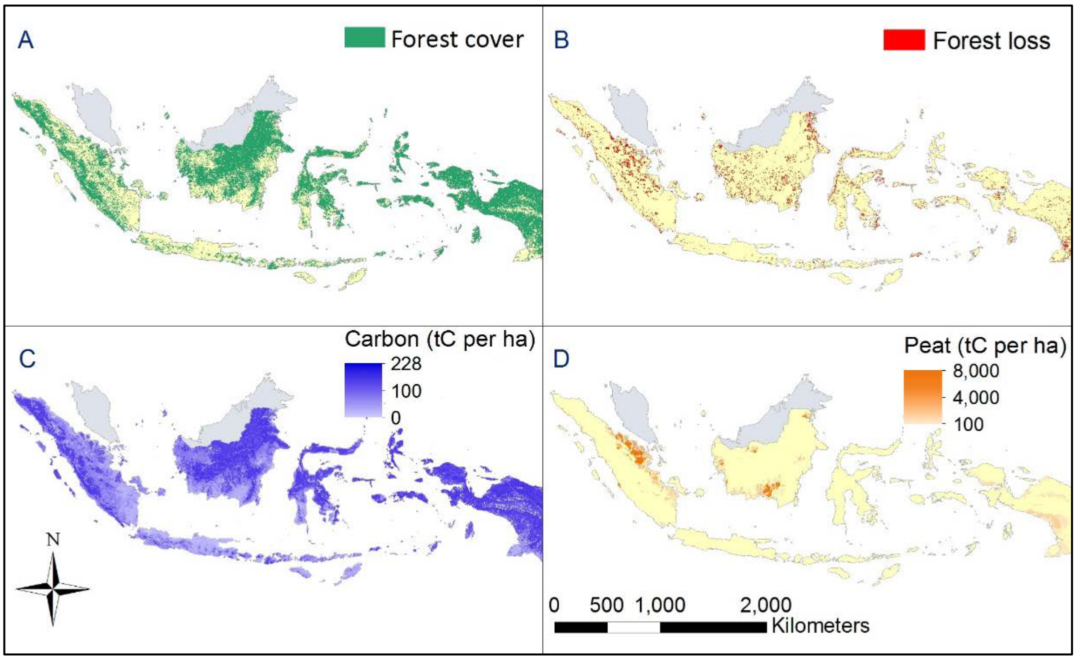

Figure 3.1 Forest and carbon data used in the spatial analysis: (A) 2010 forest cover (Miettinen *et al.* 2012b); (B) forest loss between 2000 and 2010; (C) terrestrial above-ground carbon for the period 2007-2008 (Baccini *et al.* 2012); and (D) carbon stored in peat swamps for 2002 (Minnemeyer *et al.* 2009).

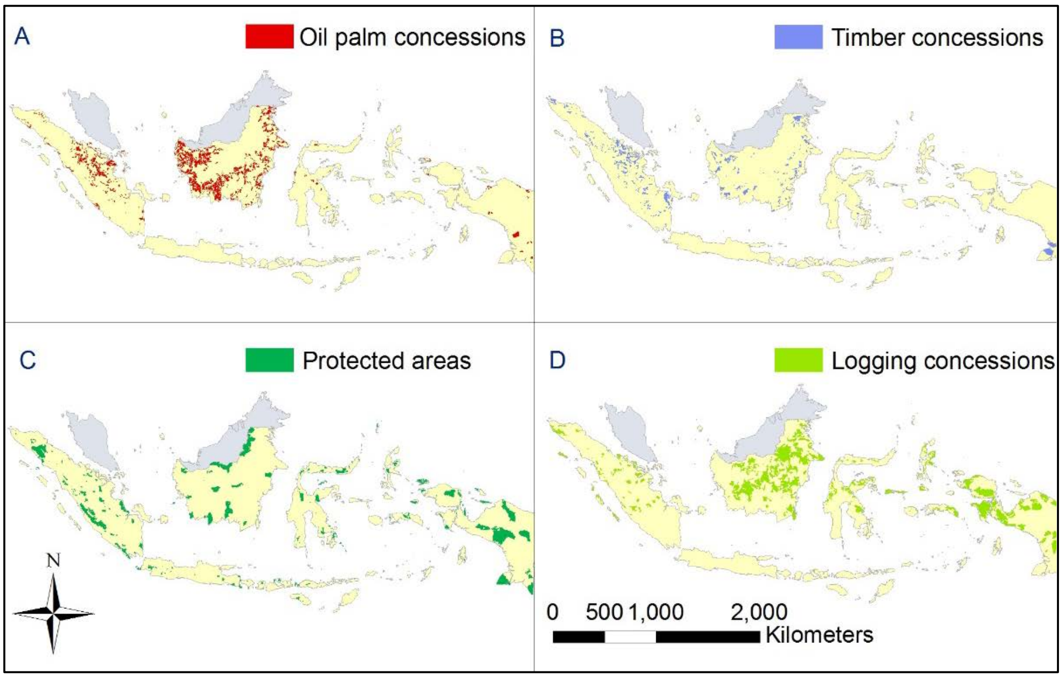

Figure 3.2 Cadastral data layers used in the spatial analysis: (A) oil palm concessions (Greenpeace 2011); (B) timber concessions (Minnemeyer *et al.* 2009); (C) protected areas (IUCN and UNEP-WCMC 2016); and (D) logging concessions (Minnemeyer *et al.* 2009).

Oil palm and timber concessions

I overlayed maps of oil palm (Greenpeace 2011; Figure 3.2a) and timber concessions (Minnemeyer *et al.* 2009; Figure 3.2b) with the 2010 forest cover and AGC maps to estimate the total carbon contained within the forested part of each permit and estimated the emissions that would result from clearing the forest and replacing it with plantations (see Appendix 2). If a permit was highly suitable for growing oil palm, I accounted for carbon stocks in the replacement vegetation (a carbon benefit), whereas if a permit was unsuitable for oil palm, I accounted for no carbon benefit following deforestation. Prior to the establishment of oil palm and timber plantations, peat swamps are firstly drained (FAO 2014b), leading to additional carbon emissions from the oxidation and increased probability of fires after draining. I calculated the extent of peat emissions by intersecting the map of forest threatened by oil palm and timber with a map of carbon stored in peat swamps (Minnemeyer *et al.* 2009; Figure 3.1d).

Illegal deforestation within protected areas

For each terrestrial protected area (IUCN and UNEP-WCMC 2016; Figure 3.2c), I projected 30 years of future emissions from illegal activities using a linear extrapolation of deforestation observed over the period 2000-2010 (Miettinen *et al.* 2012b). It is common in Indonesia to plant cacao, oil palm, rubber and coffee (hereafter 'mixed-crops') in protected areas following deforestation (Swallow *et al.* 2007). I estimated the carbon lost by converting natural forests to mixed-crops (accounting for carbon stocks in replacement vegetation) and multiplied it by the deforestation rate to project the carbon emissions from illegal deforestation. I assumed that half of the deforestation activities that occur on peat soils in protected areas require drainage while the other half do not (FAO 2014b). I calculated the extent of peat emissions by intersecting the map of forest threatened by agriculture in protected areas with a map of peat soil and multiplied this by 0.5 and by the deforestation rate.

Reduced-impact logging

Employing reduced-impact logging (RIL) techniques to logging operations saves an additional 19% of the pre-harvest biomass compared to conventional logging (CL; Healey *et al.* 2000; Pinard and Cropper 2000; Putz *et al.* 2008b). I estimated the emissions that could be reduced from minimising forest degradation during log-harvesting under RIL practices, by multiplying the 30-year carbon benefit of RIL (19%) by the carbon stored in each existing logging concession (Minnemeyer *et al.* 2009; Figure 3.2d). Selective logging of forests can be conducted without major disturbances to peat hydrology (FAO 2014b) and therefore I did not account for emissions from peat drainage in logging permits.

Reforesting abandoned land

I overlayed a map of biomes (Olson *et al.* 2001) with the 2010 forest cover map to find sites where forests previously existed but had been cleared. I disregarded 'afforestation' activities (planting forests in historically non-forest locations). I classified the World Wildlife Fund for Nature (WWF) biomes 'tropical and subtropical moist broadleaf forests', 'tropical and subtropical dry broadleaf forests' and 'mangroves' as '*forest'*. I then refined the area to 'highly degraded land' that I identified as areas with less than 35 $tC{\cdot}ha^{-1}$ (Baccini *et al.* 2012), which is a recommended practice for identifying degraded forest lands in Indonesia (Gingold *et al.* 2012). I excluded areas that overlapped with oil palm, timber or logging concessions and all areas classified as 'APL', which is outside of the national forest estate (Minnemeyer *et al.* 2009). I created 2,214 'hypothetical management units' for reforestation in areas of 900 ha in size to compare against permits and protected areas. I estimated the potential carbon benefit of reforestation projects in Indonesia based on the 30-year sequestration rate (Appendix 2) of regenerating tropical forests.

Cost of reducing emissions

The financial costs of employing each REDD+ strategy as calculated in Chapter 2 (see Appendix 2 for details) included opportunity, management and transaction costs. Most costs were presented as net present values, which are the discounted value of the sum of projected future cash flows expected under the business-as-usual scenario (Stone 1988), that were extrapolated over 30 years at a discount rate of 10% per annum. In this chapter, I modified the average (per hectare costs) based on spatially-explicit site characteristics. Spatially-explicit opportunity costs of oil palm were estimated by overlaying a suitability map for oil palm (FAO 2012) to determine where oil palm is profitable. Opportunity costs of land that is unsuitable for oil palm are restricted to the profits from timber extraction. Conversely, sites that have high suitability for oil palm will generate larger revenues from its production and sale, as well as from timber extraction, than sites that have low or no suitability. Depending on a plantation's suitability, I applied different costs to permits (see Appendix 2). Costs for oil palm, timber, protected areas and logging permits were calculated based on the forested part of the permit. I calculated the cost of reducing emissions ($\${\cdot}tC^{-1}$) by dividing the total cost by the total carbon benefit for each permit, protected area and reforestation site, using the formula below.

$$\text{Cost of reducing carbon } (\$\cdot\text{tC}^{-1}) = \frac{\text{Total cost } (\$)}{\text{Total carbon benefit (tC)}}$$

3.4 Results

Across Indonesia, ~85.3 Mha of forest cover remained as of 2010, of which logging concessions represented the largest area (~17.8 Mha; 21%; Table 3.1), followed by: protected areas (~13.8 Mha; 16%), oil palm concessions (~3.00 Mha; 4%) and timber concessions (~2.05 Mha; 2%). Sites suitable for reforestation covered ~5.00 Mha of degraded land. I estimated the maximum potential 30-year carbon benefit of employing five REDD+ strategies: (1) reforesting degraded land could sequester 965 MtC; (2) limiting the expansion of oil palm into forests could reduce 836 MtC; (3) limiting the expansion of timber plantations into forests could reduce 831 MtC;(4) employing RIL techniques in logging concessions could reduce 638 MtC; and (5) halting illegal forest loss in protected areas could reduce 414 MtC. On an annual basis, the combined carbon benefit of applying these strategies across Indonesia is 123 MtC at a cost of \$1.9 billion, or \$15.7 tC^{-1}.

Table 3.1 Summary information on the total area (ha), cost (US$) and carbon benefit (C) of the following REDD+ strategies: targeting deforestation within timber and oil palm concessions, halting illegal forest clearing in protected areas, reforesting degraded land and employing reduced-impact logging techniques at logging concessions. Total figures are for all of Indonesia and means are the average across all permits, protected areas or reforestation sites. The cost of reducing emissions ($\$ \cdot tC^{-1}$) at each site is displayed in Figure 3.3. Reforestation has no forest area because the target area for forest restoration is where forest has been cleared and no variance because of the flat rate of carbon accrual used.

REDD+ strategy	Palm oil	Timber	Protected areas	RIL*	Reforestation
Number of sites	1845	429	289	557	2,214
Total area (ha)	15,200,084	8,586,711	18,425,301	29,575,904	5,002,200
Total forested area (ha)	3,003,896	2,053,338	13,831,004	17,775,332	-
Average forest area (ha)	3,530	8,181	62,584	33,922	-
Total cost (US$ millions)	18,028	8,978	7,306	14,791	8,717
Total carbon emissions (tC millions)	836	831	414	638	965
Mean carbon benefit ($tC \cdot ha^{-1}$) including peat	234	308	54	35	193
Mean cost (and range) of reducing emissions ($\$ \cdot tC^{-1}$)	73.14 (6 – 8,272)	56.36 (5 - 972)	39.27 (2 – 1,725)	23.77 (21 - 30)	9.03 9.03 - 9.03

* Reduced-impact logging

On average, reforestation is cheaper than the other strategies assessed in terms of cost-effectiveness for reducing emissions ($\$9 \cdot tC^{-1}$), but has no variance in costs due to the flat carbon sequestration rate applied here (Table 3.1). Oil palm and timber concessions and protected areas had some of the cheapest ($<\$7 \cdot tC^{-1}$) and the most expensive sites ($>\$200 \cdot tC^{-1}$) for reducing emissions and the most variation (Table 3.1), indicating site-specific factors strongly influence the cost of reducing emissions at each permit or protected area.

To reduce emissions from oil palm, cost-effective locations are mainly in Borneo (Figure 3.3a), where remaining forests occur on peat deposits (31% of permits with forest), or where land has climatic and edaphic conditions that is not highly suitable for cultivating oil palm (85% of permits with forest). The cost of reducing emissions in oil palm permits with low or no suitability (~$\$39 \cdot tC^{-1}$) is seven times cheaper than permits with high suitability (~$\$265 \cdot tC^{-1}$). Cost-effective locations for reducing emissions from timber plantations (Figure 3.3b) are where carbon-rich forests (e.g. peat forests) remain, while expensive locations have remaining forests of low quality. Approximately 40% of forested timber plantations in Indonesia overlapped with peat soils, predominantly in eastern Sumatra, storing on average twenty times more carbon, and making these permits four times cheaper for reducing emissions than forests on mineral soils. Cost-effective opportunities to reduce illegal forest carbon loss in protected areas occur on all islands (Figure 3.3c) and are characterised by high deforestation rates (>3% per annum between 2000 and 2010) and dense carbon stores (>500tC ha^{-1}). Across Indonesia, logging concessions consistently provide low-cost options for reducing emissions from forest degradation through opportunities for employing RIL practices (Figure 3.3d).

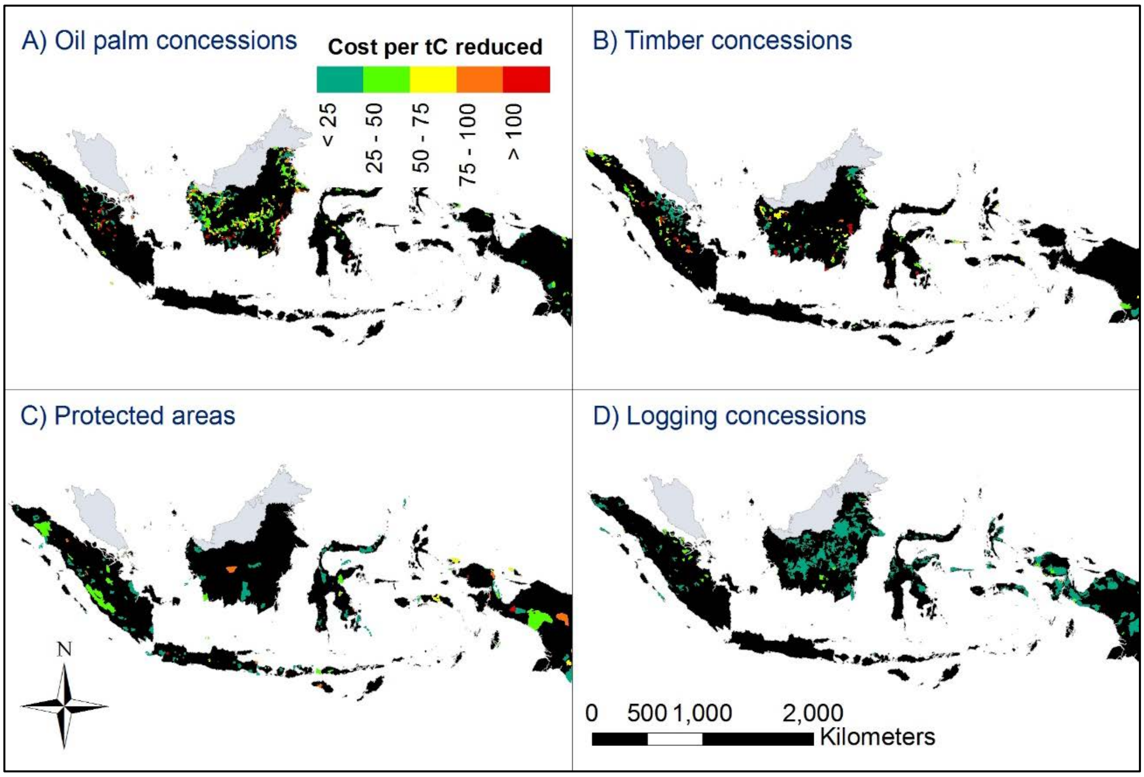

Figure 3.3 The cost of reducing carbon emissions within: (A) oil palm concessions; (B) timber concessions; (C) protected areas; and (D) logging concessions in Indonesia. Costs are per tonne of carbon reduced (US$·tC^{-1}) for the forested part of the permit or protected area. Only permits and protected areas with forest cover are included in these figures. To improve visibility, the whole permit or protected area has been displayed on the map, regardless of where the remaining forest exists. Reforestation sites are not shown here as they have a fixed cost for all areas.

I found that different REDD+ strategies are effective at varying budgets and emissions reduction targets (Figure 3.4a-b) and that a combination of strategies should be employed to reduce emissions cost-effectively across Indonesia. For example, to achieve a low emissions reduction target of 25% (920 MtC) through REDD+, funding should be allocated between protected areas, and timber and oil palm concessions, which incur a total cost of $5.1 billion (Table 3.2). The least costly approach to reduce 50% of forest carbon emissions (1,842MtC) includes these three strategies, as well as reforesting degraded, which incurs a combined cost of $12.9 billion. A reduction of 75% of emissions (2,746 MtC) can be achieved at a total cost of $25.7 billion by employing a combination of all strategies: targeting deforestation within oil palm and timber concessions, investing in better managed protected areas, employing RIL techniques in logging concessions and by promoting reforestation. Reducing 100% of emissions from these strategies (3,684 MtC) costs $57.8 billion. The findings of the spatial-targeting approach show that even the strategies that were most expensive on average (limiting oil palm and timber expansion into forests), provided some of the cheapest locations for reducing emissions, while the cheapest strategies on average (reforestation and RIL) were not as competitive for meeting low emissions targets (i.e. had few very low-cost opportunities).

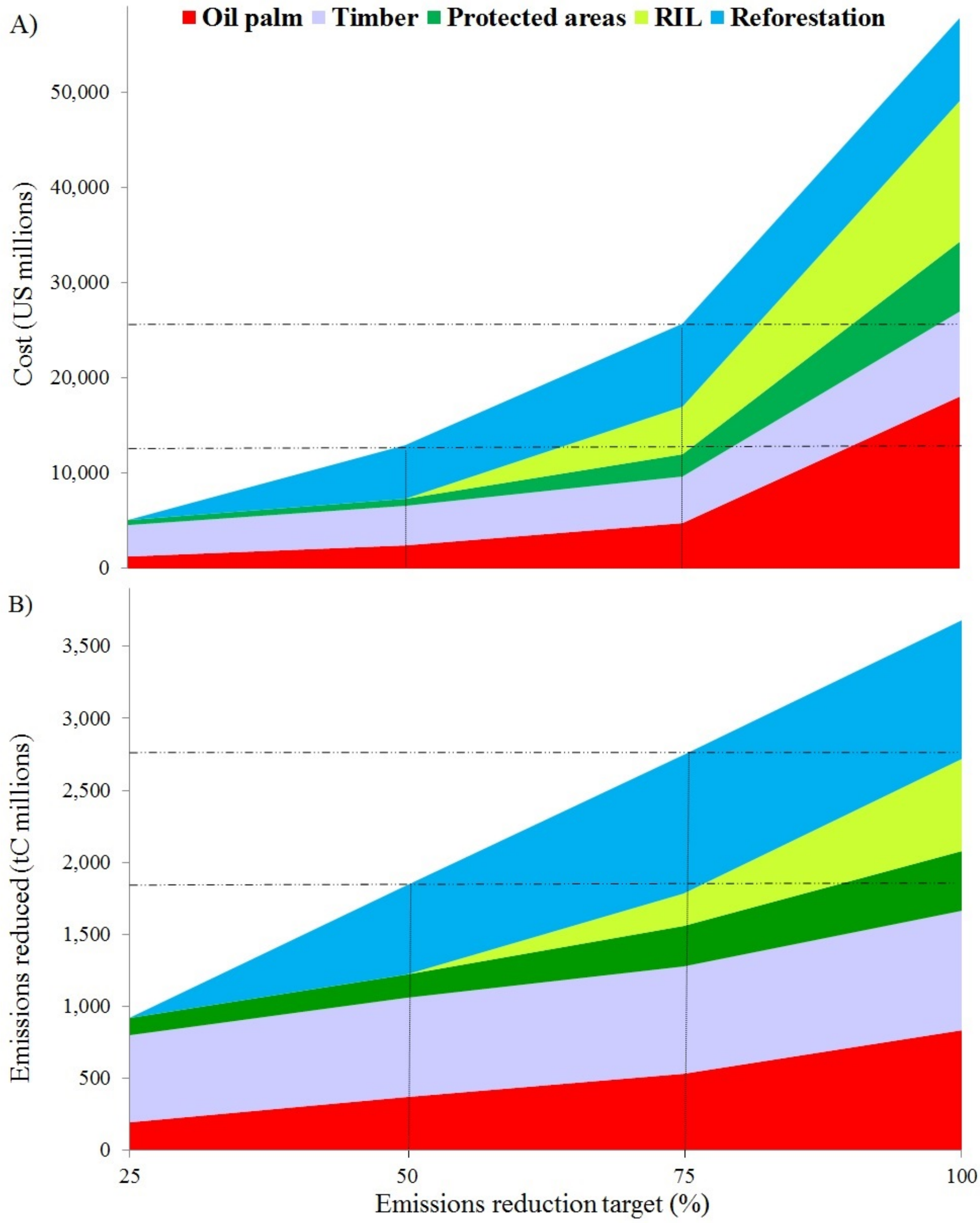

Figure 3.4 Accumulation curves showing the proportion of each REDD+ strategy employed to reduce emissions at the lowest cost. The x-axis represents: the emissions reduction target and the y-axis represents: (A) the cumulative cost (in US$ millions); and (B) the cumulative emissions reduced (tC millions). Strategies are prioritised by the cost of reducing one tonne of carbon, from lowest to highest. Dashed lines display: (A) the costs of achieving two emissions reduction targets; and (B) the carbon emissions reduced. For example, spending $12,942 million will reduce 1,842 MtC (50% of emissions) and spending $25,678 million will reduce 2,746 MtC (75% of emissions). RIL = reduced-impact logging.

Table 3.2 The cost of reducing 25%, 50%, 75% and 100% of carbon emissions from five REDD+ strategies. The mix of strategies that contributes to achieving the emissions target is prioritised by the cost of reducing one tonne of carbon at each site (concession, protected area or reforestation site), from low to high.

	Emissions reduction target			
	25%	50%	75%	100%
Cost (US$ millions) of achieving emissions reduction targets:				
1) Oil palm	1,219	2,462	4,757	18,028
2) Timber	3,377	4,137	4,913	8,978
3) Protected areas	467	763	2,374	7,306
4) RIL*	-	-	4,917	14,791
5) Reforestation	-	5,579	8,717	8,717
All strategies	5,063	12,942	25,678	57,820
Average cost per tonne of avoided emissions ($\$\cdot tC^{-1}$)	5.50	7.03	9.35	15.70

* Reduced-impact logging

The results from the sensitivity analysis showed that using surrogate maps of forest cover and carbon, or both combined, caused quantitative variances in the proportion of strategies employed to meet emissions reduction targets, but did not change the combination of strategies employed (Appendix 2, Table A2.3). Using a surrogate forest cover map resulted in the average cost of reducing emissions to increase for protected areas, and oil palm and timber concessions (Appendix 2, Table A2.4). However, using a surrogate carbon map caused the cost of reducing emissions to decrease for all strategies, except for reforestation, which did not change, or RIL, which did not change by more than $\$1\cdot tC^{-1}$.

3.4 Discussion

This chapter reports on the cost-effective allocation of REDD+ resources in Indonesia using a spatially-targeted approach. The maximum potential carbon benefit of applying the REDD+ strategies at all potential locations is 123 $MtC\cdot yr^{-1}$. This is 17% more than the 105 $MtC\cdot yr^{-1}$ estimated from deforestation for 2000-2005 reported by Harris *et al.* (2012), however my approach differed by accounting for carbon losses from degradation (logging) and carbon gains from reforestation and replacement vegetation (where cleared forests were expected to be replaced by other crops). The prevention of emissions of this scale would involve: employing RIL techniques at all logging concessions; stopping further deforestation within all protected areas, and oil palm and timber permits; and reforesting all degraded land that has been cleared of forest but were not part of the 'non-forest estate'. Clearly, this is a highly ambitious scenario and unlikely to be implemented in the near term. A more realistic emissions reduction target for Indonesia, in the range of 25% - 50%, would reduce 920 MtC - 1,842 MtC respectively over 30 years (31 MtC·yr^{-1} – 61 MtC·yr^{-1}). When compared to the average cost estimates from Chapter 2 that did not consider spatial heterogeneity, the inclusion of spatially-discrete cost-benefit estimates caused large changes in the average cost of reducing emissions for the timber, oil palm and protected area strategies. This is because for these three strategies, carbon stored in natural forests is lost when cleared and converted to agriculture, whereas the RIL strategy assesses the proportional carbon benefit from reduced degradation and the reforestation strategy uses a flat rate of carbon accrual. These results highlight that at lower emissions targets, it is crucial to choose the most cost-effective strategies in the most cost-effective locations, as costs and benefits of REDD+ vary spatially in Indonesia.

This spatial analysis revealed that because of the variability in cost-effectiveness, low-cost opportunities exist for all of the strategies, depending on emissions target and budget. To reduce the first 25% of emissions through REDD+, only three strategies offered very low-cost opportunities – reducing deforestation from oil palm, timber and protected areas. A factor driving this result is that ~82% of oil palm permits have been granted on land with partial suitability and 3% on land that has no agricultural potential for oil palm, mostly in Borneo, resulting in costs that are seven times cheaper than sites with high potential. For protected areas, priority areas for REDD+ projects are spread across all major Indonesian islands and are driven by high deforestation rates coupled with dense carbon stores. A significant opportunity for climate mitigation and biodiversity conservation lies in abating the high level of illegal forest loss (Spracklen *et al.* 2015) and the carbon emissions predicted to occur in the future (414 MtC) if the current pace (~2% pa) of illegal deforestation in Indonesia continues. Within individual protected areas, the allocation of resources should be prioritised by accessibility factors, as some areas within parks are protected 'de facto' due to inaccessibility, while lowland forests that are close to roads or urban areas are exposed to greater risk of forest conversion and should be prioritised (Gaveau *et al.* 2009; Laurance *et al.* 2012).

At a 50% emissions target, reforesting degraded land becomes the most important strategy, alongside lowering forest carbon loss in protected areas and oil palm and timber concessions. Employing RIL in logging concessions is not cost-effective until targeting a 75% emissions reduction. Although some strategies are more expensive on average (e.g. limiting timber and oil palm expansion), these strategies are still very important for achieving even the lowest of emissions reduction targets (25%–50%) through REDD+, when spatially-explicit costs and benefits are considered. Conversely, some strategies with low average costs (e.g. reforestation and RIL) are less important for meeting low emissions targets, highlighting the importance of spatial-targeting when prioritising the allocation of REDD+ resources.

The most widespread spatial pattern observed in this analysis was the importance of protecting forests on lowland peat swamps, which cover peat deposits of up to 20 metres in depth (Page *et al.* 1999). Peatlands in Borneo have been declining by 2.9% per annum and by 4.6% per annum in Sumatra over the last two decades (Miettinen *et al.* 2012a), presenting an increased challenge for Indonesia to meet their climate mitigation targets, as once cleared, peatlands are highly fire-prone (IPCC 2007) and their emissions have contributed substantially to the high level of national emissions (Baccini *et al.* 2012). Approximately 21% of protected areas, 40% of timber permits and 31% of oil palm permits with remnant forest cover in Sumatra, Borneo and Papua occur on peatlands (mainly in eastern Sumatra and southern Borneo); representing high priority areas for forest protection through REDD+. In terms of size, peat forests account for 9% of forested area in protected areas, 26% of forested area in oil palm concessions and 62% of forested area in timber plantations.

This chapter has focused on carbon and financial elements of REDD+, however other social and ecological dimensions of these strategies are also important determinants of which strategies should be employed and where. While scholars are debating the non-carbon benefits and risks, little attention has been directed to how the outcomes vary between project type. For example, projects that focus on avoided deforestation have the greatest opportunity for delivering biodiversity co-benefits (Stickler *et al.* 2009). Conversely, projects tacking illegal deforestation in protected areas have high social risks to forest-dependent communities whereby communities can be displaced or deprived of access to livelihood resources (Brockington *et al.* 2006), yet they can also create employment opportunities for communities associated with implementation (Mustalahti *et al.* 2012) and can lead to enhancements in ecosystem service function (Mullan 2014). Biodiversity benefits from reforestation can be large where regrowth is promoted on degraded forest, but one of the most serious risks to biodiversity is afforestation, which could lead to carbon-rich plantation forests being valued over biodiverse, low-carbon grasslands (Veldman *et al.* 2015). Logging concessions provide a significant opportunity to achieve biodiversity benefits in tropical Asia (Abood *et al.* 2014; Fisher *et al.* 2011b; Gaveau *et al.* 2013) because in Indonesia they contain more forests (~17.8 Mha; 21%) than protected areas (~13.8 Mha;16%) and are advocated for their role in biodiversity conservation (Fisher *et al.* 2011b; Gaveau *et al.* 2013). For example, concessionaires that operate well-managed RIL policies and protect forests from agricultural encroachment can maintain a comparable amount of forest cover as protected areas (Gaveau *et al.* 2013; Putz *et al.* 2012). Also, approximately 76% of carbon and 85–100% of species of mammals, birds, invertebrates and plants are retained in once-logged forests (Edwards *et al.* 2010; Fisher *et al.* 2011b; Putz *et al.* 2012). Directing REDD+ finance towards logging operations could assist the industry to expand RIL practices and achieve these environmental benefits, if managed well.

While reducing greenhouse gas emissions cost-effectively was the original motivation for REDD+, it is widely agreed that projects need to achieve broader environmental and social objectives, such as enhancing the livelihoods of local people and conserving biodiversity (Vijge *et al.* 2016). These are referred to as ‘non-carbon outcomes’ (Agrawal *et al.* 2011). The majority of projects in Indonesia are implemented in highly biodiverse areas and show no consistent spatial correlation with carbon stocks (Murray *et al.* 2015), demonstrating that factors other than carbon are driving REDD+ project implementation. Although they are clearly important outcomes, most nations are yet to develop capacities for monitoring non-carbon outcomes (Vijge *et al.* 2016), though they should be considered nonetheless.

This analysis could be enhanced with the addition of spatial information on the potential rate of carbon accrual during forest regeneration. Remote sensing forest cover data can confound natural forest with forest plantations resulting in overestimating forested areas (Sexton *et al.* 2016). To address this issue, I imposed a minimum carbon requirement on forest cover, which is an accepted approach to reduce ambiguity in global forest classification (Sexton *et al.* 2016). In Appendix 2 I discuss these issues and disclose the carbon threshold applied for each strategy. In this chapter, I did not assess emissions from the 57% of remaining forest cover that occurs outside of protected areas or logging, timber and oil palm concession areas. Roughly 55% of deforestation in Indonesia is estimated to occur outside concession areas driven by logging, oil palm, smallholder agriculture, rubber, coffee, mining, urban development and fire (Abood *et al.* 2014; Stibig *et al.* 2014). This analysis did not incorporate fluctuations in opportunity costs in response to supply and demand conditions – an effect picked up in dynamic models (Lu and Liu 2015; Wertz-Kanounnikoff 2008). For example, limiting production at an oil palm concession that could have been profitable, can increase the opportunity costs at another location as decreased land supply causes costs to rise. These measurements do not include the recovery state of forest carbon stocks following deforestation and degradation for rotational farming in protected areas because spatial data on the proportional area of rotational farming, as well as the state of recovery, is not available for all of Indonesia. Future research should investigate spatial patterns of deforestation in Indonesian protected areas and rates of carbon accrual in forest regrowth, as this information will more accurately inform spatial-targeting of REDD+ finance.

By substituting the primary forest layer with surrogate data, I found the average cost of reducing emissions was much higher for timber and oil palm concessions and protected areas, because the secondary forest map confounds plantation forests with natural forests causing the projected carbon emissions to decrease and the cost of reducing emissions to increase. There are two reasons for this. First, natural forests that are cleared and replaced with plantation forests may be still classified as forests in this map and therefore the carbon emissions resulting from this type of deforestation may not be included. Second, plantation forests with higher than average carbon levels could be mistaken for natural forests, which would drag down the average carbon stored in natural forests at that site.

3.5 Conclusions

The optimal allocation of REDD+ resources should consider the spatial heterogeneity of landscapes and use this information to apply spatially-targeted strategies. This analysis demonstrates that when fine-scale variation in costs and carbon benefits is considered, there is no single-strategy for curbing future forest carbon loss cost-effectively at all potential REDD+ locations. Rather, adopting a spatially-targeted approach to resource allocation reduces carbon emissions most effectively. This approach involves identifying the cheapest locations for reducing carbon emissions for each REDD+ strategy and targeting these as priority areas for investment. Across Indonesia, avoiding additional deforestation on peat soils and minimising forest degradation caused during log-harvesting (by employing RIL) are highly cost-effective opportunities for reducing emissions. This type of spatial analysis marks a crucial step forward in multi-disciplinary land-use planning in Indonesia. The outcomes of this analysis can guide the implementation of national and regional plans towards priority areas for combatting forest carbon loss cost-effectively through REDD+.

Chapter 4

Discussion

Without the land, the rivers, the oceans, the forests, the sunshine, the minerals and thousands of natural resources we would have no economy whatsoever

Satish Kumar (2008)

4.1 Summary

In this chapter, I synthesise the outputs of previous chapters and highlight key opportunities for individual REDD+ strategies and locations to provide cost-effective emissions reductions in Southeast Asia. I recommend that future research should focus on identifying optimal sites for REDD+ to achieve both carbon and non-carbon objectives in Southeast Asia and investigate the cost premium associated with delivering both outcomes. I conclude that there are multiple opportunities for protecting carbon-rich forests cost-effectively in Southeast Asia and discuss the management implications of these findings for policy-makers.

4.2 Minimising carbon emissions from land use in Southeast Asia

Accelerating anthropogenic greenhouse gas (GHG) emissions are contributing to global climate change (IPCC 2014) and 15% of global carbon emissions are stemming from the deforestation and degradation of tropical forests (Houghton 2013). It is widely understood that global agreements to limit climate change must include policies to reduce emissions from land use and land use change in the tropics (Watson 2000). Southeast Asian forests and the biodiversity they support are amongst the most threatened globally, owing to plantation agriculture, international demand for tropical timber, oil palm and overexploitation of wildlife (*see* Chapter 1). Southeast Asian forests are also the most diverse of all tropical forests and are among the most carbon-dense in the world, highlighting their importance in conservation and carbon-mitigation (Baccini *et al.* 2012; Sullivan *et al.* 2016). Implementing policies to lower deforestation and forest degradation incur opportunity costs from foregone income from extractive activities. Providing economic incentives for retaining or improving forest carbon stocks is one of the climate policies supported by the United Nations to protect tropical forests (UNFCCC 2015).

REDD+ was proposed in 2005 by a group of 15 developing nations in a bid to address the accelerating level of tropical forest loss in the tropics and provide support for developing nations to overcome economic barriers to achieving conservation objectives, such as high poverty rates. To overcome these barriers, REDD+ facilitates monetary incentives to nations that preserve or enhance the carbon storage function of natural forests and in this way, supports developing countries in meeting their own emissions reduction targets. REDD+ has rapidly grown to become the most prominent international financial mechanism for conserving tropical forests, in recognition of the importance of protecting tropical forests and the difficulties that developing economies face in protecting them (Agrawal *et al.* 2011). Indonesia is the global leader in REDD+ readiness and demonstration activities (Cerbu *et al.* 2011), largely due to it being one of the largest global sources of emissions from tropical deforestation and degradation, alongside Brazil (Baccini *et al.* 2012).

4.3 Contributions of this thesis

The goal of this thesis was to inform policies regarding financially viable opportunities for REDD+ in Southeast Asia by assessing the mitigation costs and opportunities for reducing emissions for a broad range of strategies. I achieved this goal by: (1) identifying the types of REDD+ strategies employed in Southeast Asia and comparatively assessing their average costs and carbon benefits; and (2) identifying low-cost opportunities and locations for reducing emissions in Indonesia. I expanded on previous studies that focused predominantly on the costs and benefits of reducing deforestation by incorporating a broader range of strategies including those that address illegal deforestation, lower forest degradation and enhance forest-carbon stocks, such as: (1) conserving forest carbon stores by improving the management of protected areas; (2) implementing reduced-impact logging (RIL) to lower forest degradation during log-harvesting; and (3) enhancing terrestrial carbon stores through reforestation and peat restoration (Chapter 2). Where previous work has focused on estimating average unit costs, I estimated spatially-explicit emissions and costs using maps of land tenure, forest cover, carbon stocks and agricultural suitability (Chapter 3). The outcomes of my thesis present a more accurate portrayal of the financial competitiveness of REDD+ in Southeast Asia.

4.3.1 The uptake and average cost-effectiveness of REDD+ strategies

My literature review (Chapter 1) revealed a key gap in the literature of REDD+; strategies for reducing illegal deforestation, lowering forest degradation or enhancing carbon stocks are not widely included in the financial analyses of the mechanism. While numerous papers have compared the financial viability of avoiding additional deforestation for large-scale oil palm plantations (*see* Butler *et al.* 2009; Fisher *et al.* 2011a; Venter *et al.* 2009), not a single paper had estimated the carbon benefits of reducing illegal deforestation in Southeast Asian protected areas, despite the well-documented poor performance of some protected areas in the region (Bruner *et al.* 2004; Gaveau *et al.* 2007; 2009; James *et al.* 1999). Chapter 2 was the first study to analyse and assess the financial competitiveness of a broad range of REDD+ strategies in the region by collating data from multiple sources.

In Chapter 2, I found that REDD+ projects in Southeast Asia primarily pursue strategies that focus on promoting regrowth of degraded forests (74% of projects) and reducing illegal deforestation in protected areas (61% of projects). I also found that different project proponents favoured different strategies. For example, research institutions and private companies more commonly employed RIL at project sites than projects led by NGOs or governments. Not surprisingly, projects targeting oil palm were implemented more by NGOs (e.g. WWF). As discussed in Chapter 2, cost-effectiveness may or may not be a key driving factor of strategy selection for different proponents. For example, strategies that target deforestation have the greatest opportunity for delivering biodiversity co-benefits (Stickler *et al.* 2009) and therefore appeal to stakeholders with a biodiversity conservation focus (e.g. WWF), though these projects were found to be the most expensive. An important contribution of this thesis was to demonstrate the cost-effectiveness of five prominent REDD+ strategies in Southeast Asia and highlight where carbon emissions reductions can be maximised per dollar spent. Of the five strategies assessed, we found that reforestation, RIL and improving the management of protected areas were the most cost-effective ways of reducing emissions. A key factor that affects the ability of each strategy to reduce emissions across scale, alongside cost-effectiveness, is scope for implementation. In Indonesia alone, logging concessions and protected areas cover ~17 Mha and ~23 Mha respectively (Abood *et al.* 2015; IUCN and UNEP-WCMC 2016), while oil palm and timber concessions cover a mere ~2 Mha and ~3 Mha (Abood *et al.* 2015).

The findings from Chapter 2 indicate that more economical opportunities exist for reducing emissions in Southeast Asia than indicated by the literature, which has focused narrowly on projects targeting oil palm production –one of the most economically profitable crops produced in Southeast Asia (Koh and Wilcove 2007). As these results are based on averages from the literature, it is worth commenting on some of the variation between data sources for the same strategy type. While I found that RIL is a cost-effective option for reducing emissions, some of the recent literature is conflicting. For example, Griscom *et al.* (2014) reported that common RIL metrics (felling, skidding and hauling) were not reliable indicators of reducing emissions, however, this study was over a shorter time frame (1 and 10-year periods) than my analysis, which focused on a 30-year period. Also, a meta-analysis by Martin *et al.* (2015) into logging practices reported no carbon gain from RIL when controlling for logging intensity (timber harvested per hectare), but suggested that lower-intensity harvesting using RIL techniques could reduce the most carbon emissions from logging. Given the high global demand for timber (Putz *et al.* 2008b), lowering logging-intensity at one site may suffer impermanence, or cause leakage - if logging concessions are pushed into new areas to meet demand (Newton *et al.* 2015), resulting in adverse outcomes.

4.3.2 Spatially-explicit emissions, mitigation costs and scope for REDD+

As REDD+ projects are designed to address site-specific environmental threats, the broad patterns of cost-effectiveness identified in Chapter 2 needed to be supported by finer-scale research into the spatial variation in costs and carbon benefits to inform spatial-targeting of REDD+. Southeast Asian forests were cleared at an average rate of 0.59% per annum for the period 2000 to 2010, yet vast forest areas still remain (236 Mha in 2010), with 44% (104.4 Mha in 2010) of the remaining forests found in Indonesia (Stibig *et al.* 2014). However, deforestation in Indonesia was the highest in Southeast Asia, accounting for approximately 60% of regional decadal forest loss (Stibig *et al.* 2014). Quantifying the carbon emissions resulting from planned developments can identify priority areas to curb future emissions and guide policies for stimulating economic growth with minimal impact to the environment (Bateman *et al.* 2015).

In Chapter 3, I quantified the carbon emissions that would incur from planned oil palm, timber and logging operations and illegal deforestation within protected areas in Indonesia (assuming current rates of deforestation will persist) and calculated the costs of mitigating these emissions. I found that the scope for the cheapest strategies identified in Chapter 2 is vast and that reforestation had the largest potential net carbon benefit over 30-years (sequestering up to 965 MtC). Reforestation, sustainable forest management (employing RIL techniques in logging concessions) and limiting additional deforestation in protected areas and oil palm or timber plantations could reduce a combined 123 MtC annually in Indonesia.

Reforestation provides a significant opportunity to lower carbon emissions through REDD+, however, it is important to draw attention to some of the barriers in scaling-up the restoration of degraded land in Indonesia. Not all land that appears to be suitable for reforestation is suitable. First, insecure land tenure makes the task of identifying abandoned land a considerable challenge. There are millions of hectares of degraded forest in Indonesia that are considered idle (Budiharta *et al.* 2014), however some of these areas may still be under ownership. Second, it is important to consider the agricultural potential of degraded land, as highly productive land for agriculture may be less appropriate for reforestation than land with poor agricultural potential (Edwards and Laurance 2012).

When compared to the average cost estimates from Chapter 2, the inclusion of spatially-discrete cost-benefit estimates caused the average cost of reducing emissions to increase in protected areas and timber concessions (Table A2.3), while the other strategies showed a slight decrease or no change at all. Halting forest loss in protected areas, or timber and oil palm permits, offered opportunities for reducing emissions for under $US7 per tonne of carbon. This result demonstrates that low-cost opportunities exist even for strategies with high average costs (e.g. the oil palm and timber strategies) that can only be detected from spatial analysis. Priority opportunities for REDD+ identified in Chapter 3 cover not only cost-effective strategies, but also cost-effective locations within each strategy.

Some of the spatial patterns that emerged that influenced cost-effectiveness included agricultural productivity and land use trends. For example, 85% of oil palm permits with remaining forests were on land that is not highly suitable for cultivating oil palm, resulting in avoided deforestation that costs seven times less than sites with high agricultural potential. Protected areas with high deforestation rates coupled with carbon-rich forests represent another priority area for REDD+ investment. As discussed in Chapter 3, I recommend that the allocation of resources within protected areas be prioritised by accessibility factors, as some areas within parks are protected 'de facto' due to inaccessibility, while forests close to roads are exposed to increased threats and should be prioritised (Gaveau *et al.* 2009; Laurance *et al.* 2012).

The most significant finding of Chapter 3 was the importance of protecting forests on lowland peat swamps. Tackling emissions from peat forests stood out as a prime opportunity for REDD+ as the magnitude of emissions from peat can be huge (Page *et al.* 2002), causing the cost of reducing emissions to plummet. The scope for reducing emissions across all strategies that overlie peat is also vast. For example, 21% of protected areas, 40% of timber permits and 31% of oil palm permits with remnant forest cover in Sumatra, Borneo and Papua overlie peat. For timber plantations, this amounts to 62% of total forested area. These areas should be considered high priority locations for forest protection through REDD+. A significant contribution of this thesis was to prepare maps and synthesise spatial patterns of cost-effective locations for reducing emissions.

4.4 Financially attractive opportunities for REDD+ in Southeast Asia

A major criticism of REDD+ is that the mechanism is economically unviable in Southeast Asia because the revenues from converting forest into oil palm, a primary driver of deforestation in the region, far outweigh the revenues from trading the carbon credits on voluntary markets (Butler *et al.* 2009; Fisher *et al.* 2011a). However, the mitigation costs of reducing emissions from forests are highest when targeting oil palm concessions, therefore these costs are not representative of the wide range of strategies that REDD+ supports. In fact, all of the other strategies reviewed in this thesis offered lower cost avenues for reducing emissions by: (1) reducing deforestation in protected areas; (2) implementing RIL; and (3) enhancing terrestrial carbon stores through reforestation and peat restoration. I also found that the scope for implementing these low-cost strategies is vast. Across Indonesia, up to 36 million hectares of land were identified as candidate sites to employ reforestation, RIL techniques and to lower deforestation in protected areas (*see* Chapter 3). As identified in this thesis, reforesting degraded land offers the largest carbon benefit per hectare over 30 years, both on average (*see* Chapter 2) and when scope for implementation is considered across Indonesia (*see* Chapter 3), followed by reducing deforestation within oil palm and timber concessions. When costs are considered, reforestation is the most cost-effective strategy for reducing a tonne of carbon, followed by improved management of protected areas and RIL. Conversely reducing deforestation from oil palm and timber concessions become the most expensive strategies. However, this does not mean that all projects focused on slowing the expansion of oil palm or timber plantations are unviable.

In fact, when spatial information was considered, low-cost opportunities emerged even for projects targeting emissions from oil palm, owing to spatial variability in costs and benefits (*see* Chapter 3). Halting forest loss in protected areas, timber concessions and oil palm permits offered some of the cheapest and most expensive options for reducing emissions (*see* Chapter 3). Deep peat deposits and high carbon stocks were two variables that led to locations being highly cost-effective for all strategies. Also, for projects tackling the expansion of oil palm, permits that are granted on land with poor or no suitability for cultivating the crop offered cheap avenues for reducing emissions. These findings reiterate the importance of spatial-targeting in guiding the optimal allocation of REDD+ resources, as demonstrated in other studies (Koh and Ghazoul 2010; Venter *et al.* 2012). The outcomes of my analysis can guide the implementation of national and regional plans towards priority areas for combatting forest carbon loss cost-effectively through REDD+.

Policy recommendations: reducing emissions cost-effectively in Southeast Asia

The outcomes of my thesis have broad policy implications for Southeast Asia. First, emissions reductions can be maximised per dollar spent by targeting reforestation, RIL and protected area management (*see* Chapter 2), highlighting that REDD+ offers more economical strategies than competing with the oil palm and timber industries, which have been focused on heavily in the economic literature. Also, the scope for these low-cost strategies is vast (*see* Chapter 3). When REDD+ was first conceived, it sought to Reduce Emissions from Deforestation (RED; see den Besten *et al.* 2014). As it expanded to reducing degradation (REDD) as well as conserving and sustainably managing forests, and enhancing forest carbon stocks (REDD+), a range of new opportunities opened up for targeting forest carbon loss, including RIL, reforestation and investing in improved protected area management. My analysis shows that these recently included strategies are more common in Southeast Asia and on average, are cheaper, than those strategies that target high profit and politically-sensitive industries, such as oil palm and timber. However, this does not mean that slowing the expansion of oil palm or timber is not beneficial for mitigating carbon and conserving biodiversity, or that it is prohibitively expensive in all cases. By considering the spatial heterogeneity of the landscape, finer-scale cost-efficiencies emerged even for oil palm projects.

4.5 Research approach and limitations

In this section, I evaluate the approach adopted in this thesis and identify the most significant limitations of the work, which in turn are proposed as important areas for future research.

The focus of this thesis was to evaluate the financial costs and carbon benefits of a broad range of strategies for protecting, sustainably managing and enhancing forest carbon stocks that are the core focus of the REDD+ mechanism. In this work, I did not consider non-carbon constraints and outcomes, such as social, governance and biodiversity factors, which may be as important as carbon-outcomes for determining project success (Newton *et al.* 2016). Assessing the non-carbon outcomes of different REDD+ strategies would be the next logical step forward with this research. Some of the main non-carbon considerations are synthesised here.

While the principal interests of private investors may be carbon storage, local communities and NGOs are likely to place higher emphasis on livelihoods, land rights and biodiversity conservation (McGregor *et al.* 2015). Concerns were raised regarding biodiversity-climate trade-offs at the United Nations Framework Convention on Climate Change and (UNFCCC) Conference of the Parties in Cancun 2010 and measures to negate adverse biodiversity and social outcomes have been implemented (UNFCCC 2011). Studies investigating how well carbon and biodiversity benefits align through REDD+ are conflicting. For example, analyses of planned oil palm plantations in Kalimantan found the sites that are most cost-effective for REDD+ contain almost twice the mammal species density as more expensive areas (Venter *et al.* 2009). Whereas, Murray *et al.* (2015) found that highly biodiverse areas showed no consistent spatial correlation with carbon stocks. Investing in more effective management of protected areas has large incentives for biodiversity conservation and can provide employment opportunities for local people associated with project implementation. Projects that can offer indirect environmental benefits to forest-dependent communities may generate greater support from locals and therefore have more chance of success. For example, a well-managed protected forest can have indirect benefits to adjacent communities in terms of improving water quality, lowering rates of disease and increasing rainfall

(Mullan 2014) that would appeal to agricultural settlements in the vicinity if REDD+ projects lead to increased productivity of nearby agricultural land.

Social concerns of REDD+ include the risk of 'fortress conservation' in which the priorities of international investors are privileged over those of local forest users and that new forms of intimate exclusions will be experienced at the local-scale (Howson and Kindon 2015). Community opposition (Eilenberg 2015; Lounela 2015) and poor knowledge and communication (Howell 2015) have been seen to stall project development. In the forest frontier district of Kapuas Hulu, Indonesian Borneo, communities resisted to engage with proponents due to uncertainty about the terms of inclusion and future rights to resources under proposed governance models, which triggered increased local discourse over access to land (Eilenberg 2015). Such resistance could significantly delay projects and incur large additional costs. Therefore, understanding the likely impacts on communities and ensuring transparent communication from early stage project discussions is of paramount importance to avoiding additional costs, delays and other adverse outcomes. Both social and biodiversity factors could influence local and financial support, more so when these factors are closely aligned with the vision of donors. The ability of REDD+ to achieve multiple benefits simultaneously at no additional cost, remains questionable.

In this analysis, I did not estimate the uncertainty of the cost estimates used in Chapters 2 and 3. The purpose of this thesis was not to address the finer-scale variation and uncertainty but to explore the broad cost-efficiencies of a range of REDD+ strategies and locations for implementing them. However, some limitations should be noted. In Chapter 2, I used average cost and benefit estimates, recognising that the variation between source estimates was high within strategies. The literature on costs and benefits was patchy, with some strategies having better quality data (e.g. oil palm) than other strategies (e.g. reforestation). Also, a generic transaction cost of a REDD+ project was applied across all strategies because strategy-specific estimates were not available in the literature. The reforestation literature was incomplete and contained no estimates of the costs of natural forest regeneration in Southeast Asia. Because I used cost estimates of monocultures as a proxy and included carbon sequestration estimates from other tropical regions, the actual rate of carbon accrual in regenerating natural forests in

Southeast Asia could be much higher, and the costs of reforestation projects could be much lower, than what I estimated. This would not change the outcomes of this thesis, because reforestation still appeared as offering the largest scope for reducing carbon emissions in Indonesia and had the lowest average cost. However, the inclusion of variable rates of carbon accrual could open up some very low-cost opportunities for this strategy that were not detected in my analysis. For the RIL strategy, I assumed that REDD+ finance could incentivise logging operators to adopt sustainably managed practices. Finally, land use trajectories are not mutually exclusive and most projects employ numerous strategies at a site to combat the range of land-use pressures affecting any given location. This is a limitation of my approach but one that I accepted in order to incorporate a large amount of literature from multiple disciplines (forestry, conservation science and economics) and achieve some tangible results within my project time frame and budget. Opportunity costs respond to supply and demand market conditions, therefore reducing emissions in a productive oil palm area could push up the costs of reducing emissions at another concession as demand for this land increases in response to decreased supply. Models exist that reflect the complex relationships between opportunity costs and land use scenarios, called dynamic models (Wertz-Kanounnikoff 2008). Applying such a modelling approach on this large geographic scale was beyond the scope of this thesis, however, it is likely that REDD+ project costs may increase over time as land for agriculture becomes scarcer (Lu and Liu 2015).

4.6 Future research opportunities

In this section, I discuss how this research could be expanded to address some of the remaining literature gaps. The reciprocal benefits of protecting carbon-rich forests and biodiversity have been widely studied for the purpose of supporting conservation planning for multiple objectives (Pressey *et al.* 2007; Sullivan *et al.* 2016). While some studies have identified positive relationships between carbon and biodiversity across the pan-tropics (Cavanaugh *et al.* 2014; Chisholm *et al.* 2013), recent analysis based on more extensive sampling shows these patterns do not translate across broad-scales, rather, that the relationship is highly site-dependent and not spatially consistent (Sullivan *et al.* 2016). It is also clear that biodiversity and carbon trade-offs will differ not only geographically, but also between the types of REDD+ strategies employed. I recommend that investigating how trade-offs differ between strategies is an important area for future research and an issue I propose to address in a PhD. For example, the greatest opportunity for REDD+ to deliver biodiversity co-benefits is by lowering rates of deforestation (Stickler *et al.* 2009). Alternatively, one of the greatest risks to biodiversity through REDD+ is incentivising large-scale timber plantations (e.g. *Acacia mangium*) to replace low-carbon, highly biodiverse landscapes such as natural grasslands (Putz and Redford 2009; Stickler *et al.* 2009) or misconceiving natural grasslands for degraded forests with grassy-regrowth and planting new forests in place of grasslands (Veldman *et al.* 2015).

Targeting non-carbon benefits may increase costs, if not funded by REDD+ payments directly, and reduce carbon benefits in some locations. There is a risk that attempting to capture too large a range of diverse objectives may cause the mechanism to fail if it struggles to maintain its cost-effectiveness for mitigating carbon (the core focus). For example, targeting threatened species conservation in addition to carbon storage reduced carbon incentives of reforestation by up to 24% compared to efforts that purely target low-cost carbon storage (Budiharta *et al.* 2014). The question of how additional costs will be funded has been raised and financial models proposed for attracting additional biodiversity funds include charging additional biodiversity premiums (Dinerstein *et al.* 2013; Murray 2015). It is evident that non-carbon outcomes are important and should be considered (Murray *et al.* 2015), though they are more difficult to measure than carbon outcomes and most nations are yet to develop capacities for monitoring them (Vijge *et al.* 2016). Still, this represents an important area for knowledge expansion.

Finally, the development of spatial models to inform this analysis would lead to improved accuracy in the results and make the outcomes more useful for policy-makers and practitioners. For example, applying a dynamic modelling approach to estimate opportunity costs, that incorporates fluctuations in supply/demand conditions, would mark significant expansion in this area of research. Also, projections of deforestation trends in protected areas made using models that consider timber supply and accessibility, would be useful to improve spatially-targeted pathways for REDD+. Developing maps of carbon accrual across Indonesia is another important area that future work should address.

4.8 Conclusions

Informing policy-makers regarding financially appropriate ways forward for REDD+ in Southeast Asia is reliant on comprehensive information on the financial costs and carbon benefits of the range of opportunities supported under the mechanism. The literature to date has focused almost exclusively on the mitigation costs of reducing deforestation from oil palm, which is an expensive strategy. The broader approach I adopted in this thesis allowed me to identify a range of cost-effective strategies and locations for reducing emissions in Southeast Asia, which can guide REDD+ policies.

As with all policy instruments, the financial and political support for REDD+ depends on its cost-effectiveness, therefore, gaining knowledge on the financial competitiveness of different options for reducing emissions can increase support for the mechanism, if more efficient opportunities are found. I found that there are multiple opportunities for protecting forest carbon cost-effectively in Southeast Asia, from halting forest loss in protected areas, timber or oil palm permits, all presenting locations for reducing emissions for under $US7 per tonne of carbon. Across the whole region, reforestation was the cheapest strategy for reducing emissions. Future research should assess how well non-carbon outcomes align with carbon outcomes and estimate the cost premium associated with achieving both.

Looking forward, although REDD+ was designed to utilise market-based finance from carbon markets, the first decade of its implementation has seen the majority of funds pledged by bilateral and multilateral donors, including the World Bank and the Norwegian government, with as little as 10% of funds generated through the voluntary carbon market (Fletcher *et al.* 2016). A pertinent question therefore to ask is can REDD+ survive if it is not market-funded? In comparison to its failed predecessors, a distinction of REDD+ is that its model of finance offers greater flexibility. Although carbon markets are not showing positive signs of providing a long-term cash pool for clean development as hoped, REDD+ offers other opportunities to source finance, which may be its saviour.

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Appendix 1

Chapter 2 Supplementary Methods and Tables

Oil Palm and Timber strategies

Most of the financial estimates (Table A1.1) for limiting oil palm expansion in forests include the profits from the sale of timber cleared prior to planting. I amalgamated the revenues for oil palm and the sale of timber to reflect the total value of that land use activity. When calculating the opportunity costs, I included lost employment, lost tax revenue and lost profits to the permit holder if this level of detail was available in the study. Some studies provided only an average yield from oil palm as opposed to an NPV (Koh and Wilcove 2007; Venter *et al.* 2009) and in this instance, I extrapolated the yield data over 30 years. I disregarded any studies with negative NPVs because I deemed activities that are not profitable are not a prominent threat to forests. I collected an estimate of the difference in carbon stored between natural forests and oil palm or timber plantations (Table A1.1). The carbon benefit for oil palm was calculated as the difference between the amount of carbon stored in standing forests versus oil palm plantations. The same approach was adopted to estimate the carbon benefit of reducing the expansion of timber plantations into forests.

Protected area strategy

To compile estimates of the costs and benefits of protected areas as a strategy for reducing forest carbon loss in Southeast Asia I synthesised the results of three different bodies of literature. First, I estimated the financial cost of optimally managing a protected area based on documented budget shortfalls from protected areas in the region. The estimates of required funds to optimally manage parks found in the literature (Table A1.1) were based on information from park staff and included large infrastructure items as well as staffing requirements. Second, I measured the rate of forest loss in protected areas and extrapolated this over 30 years. The average deforestation rate in protected areas was 1.93% per annum (Kinnaird *et al.* 2003; Curran *et al.* 2004; Linkie *et al.* 2004; Phong 2004; Gaveau *et al.* 2007, 2009). Cacao, oil palm, rubber and coffee (hereafter 'mixed-crops') are commonly planted crops in Indonesian protected areas following deforestation and store on average 59 tC ha^{-1} (Swallow *et al.* 2007; Wulan 2012). Third, I calculated the carbon emissions that could be reduced from improved management of protected areas by multiplying the deforestation rate by the carbon lost from the conversion of forests to mixed-crops (Table A1.1). An underlying assumption of this strategy is that better management of protected areas can halt ongoing forest loss.

Reduced-impact logging strategy

Reduced-impact logging (RIL) substantially reduces tree damage compared to conventional logging (CL) by directional felling and planned extraction of timber on properly constructed skid trails (Putz and Pinard 1993). Reduced-impact logging can result in half as many trees being damaged and half as much forest crushed by extraction equipment, equating to an estimated saving of 36 tC after two years and a cost of $135 per ha (Putz and Pinard 1993). Due to the stringent guidelines adhered to under RIL, there are frequently large differences between the actual area logged and the area designated for logging, resulting in RIL impacting a smaller area than CL (Dykstra 2012). As a result, profits from RIL are generally lower if compared across a full logging concession due to more area being excluded from logging, but are not consistently lower if compared by harvested area (Dang Phan *et al.* 2014). If both figures were supplied, I took an average of both estimates. Some of the RIL literature presented both economic and financial analyses. The economic analyses evaluated logging from society's perspective and included non-traded costs and benefits that could be valued, such as differences in carbon storage, non-timber forest products, soil value, recreational value and biodiversity value (Dagang *et al.* 2005; Samad and Rahim 2009). Although the economic analysis provided a thorough representation of macroeconomic value, I refrained from using it to avoid double counting of carbon offsets (I accounted for carbon emissions when converting cost per hectare into cost per tonne of carbon reduced) and to maintain greater consistency in the financial costs across different REDD+ strategies. The short-term net costs of engaging RIL (over one year) were higher ($1,492 ha^{-1}; Dagang *et al.* 2005; Healey *et al.* 2000; Samad and Rahim, 2009) than over the long-term ($833 ha^{-1} over at least 30 years and two harvests; Table A1.1) when compared to CL. Reduced-impact logging becomes more cost-effective over the long-term due to higher revenues generated from the second timber harvest, as forests recover faster and carbon increases at a greater rate than those logged without stringent forestry management guidelines. Many of the studies used a simulation model RILSIM to estimate the net cost and revenue associated with logging operations to compare short-term financial costs and returns expected from RIL with those expected from CL under identical local site conditions (Dykstra 2003). Much of the RIL literature was conducted at the Innoprise Project site in Sabah. This site was used to test the costs and outputs of RIL against CL. The RIL standards from the original Innoprise project were certified under the Forest Stewardship Council (FSC), based on guidelines developed for tropical forests in Queensland, Australia (Marsh *et al.* 1996). I collected an estimate of the difference in carbon emissions (or carbon storage) between CL and RIL from each paper (Table A1.1). Most of the carbon measurements used DIPSIM, a model developed by the Sabah Forestry Department to simulate stand growth of dipterocarp forests in Sabah, Malaysia for up to 60 years (Ong and Kleine 1996).

Reforestation strategy

The costs of reforestation under REDD+ include establishment costs, and the ongoing costs of protecting and maintaining the reforestation site (Chokkalingam *et al.* 2006), as well as the transaction costs associated with identifying and negotiating REDD+ projects and the ongoing costs of monitoring, reporting and verifying on carbon benefits (Pearson *et al.* 2014). However, there were minimal data available on the costs of reforestation as a strategy for REDD+ in Southeast Asia. I did not account for opportunity costs of reforestation as the aim of this strategy is to utilise degraded land that was designated for plantations but is not being actively used for this purpose and restoring forests (main text, Table A1.1). The reforestation papers included costs of germplasm collection, nursery costs, planting, and maintenance (Korpelainen *et al.* 1995). The aim of most of the papers was to compare the profitability of different plantation models (e.g. large-scale industrial tree plantation versus small-scale agroforestry model), planting styles (e.g. line versus and gap planting) and different species for planting (e.g. *Acacia mangium* versus *Canarium album* versus mixed species). I took an average cost of all of the estimates from each paper (Table A1.1).

Threequarters of the estimates sourced for carbon sequestration of regenerating forests were for mixed-species plantations (or succession) and one-quarter for monocultures (Table A1.1).

Table A1.1 Summary data collected and used in the meta-analysis on the net costs and carbon emission benefits of REDD+ strategies. The profits from oil palm and timber plantations include the profits from timber extraction prior to planting.

REDD+ strategy	1) Timber	2) Oil palm	3) RIL*	4) Protected areas†	5) Reforestation
Parameter	Net cost	Net cost	Net cost	Net cost	Net cost
Unit	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}
Mean	4,383	9,942	833	689	1,743
Estimates	11735, 2,707, 1506, 1582	3298, 2112, 3104, 28352, 7707, 9506, 7965, 7741, 24212, 6520, 9541, 9251	2150, 190, 159	319, 1411, 338	713, 4193, 606, 3502, 610, 832
Sources	Canesio (2003); MoFor (2008); Irawan *et al.* (2011); Sofiyuddin *et al.* (2012)	Tomich *et al.* (2002); Belcher *et al.* (2004); Zen *et al.* (2005); Koh and Wilcove (2007); MoFor (2008); Butler *et al.* (2009); Swarna Nantha and Tisdell (2009); Venter *et al.* (2009); Fisher *et al.* (2011a); Irawan *et al.* (2011); Ruslandi *et al.* (2011); Wulan (2012)	Healey *et al.* (2000); Dagang *et al.* (2005); Samad and Rahim (2009)	James *et al.* (1999); Emerton *et al.* (2003); McQuistan *et al.* (2006)	Korpelainen *et al.* (1995); Kosonen *et al.* (1997); Maswar *et al.* (2001); Nakama *et al.* (2005); Chokkalingam *et al.* (2006); Nguyen *et al.* (2014)
Parameter	Net emissions benefit	Net emissions benefit	Net emissions benefit	Net emissions benefit	Sequestration rate
Unit	tC ha^{-1}	tC ha^{-1}	tC ha^{-1}	tC ha^{-1}	tC ha^{-1}
Mean	133.02	144.20	41.77	90.96	192.96
Estimates	199.85, 165.57, 141.21, 180.11, 183.59, 46.82, 64.04, 83.00	163.36, 208.16, 141.00, 180.11, 105.99, 161.29, 235.39, 80.72, 103.98	40.10, 51.38, 33.00	94.17, 159.33, 96.52, 27.91, 84.75, 22.39	190.06, 193.48, 136.90, 251.40
Sources	Canesio (2003); Swallow *et al.* (2007); Gibbs *et al.* (2008); MoFor (2008); Adachi *et al.* (2011); Irawan *et al.* (2011); Saatchi *et al.* (2011); Khun and Sasaki (2014)	Syahrinudin (2005); Swallow *et al.* (2007); Gibbs *et al.* (2008); MoFor (2008); Venter *et al.* (2009); Adachi *et al.* (2011); Irawan *et al.* (2011); Saatchi *et al.* (2011); Khun and Sasaki (2014)	Healey *et al.* (2000); Pinard and Cropper (2000); Putz *et al.* (2008b)	Kinnaird *et al.* (2003); Curran *et al.* (2004); Linkie *et al.* (2004); Phong (2004); Gaveau *et al.* (2007, 2009)	Silver *et al.* (2000); Nakama *et al.* (2005); Olschewski and Benítez (2005); Budiharta *et al.* (2014)

* Reduced-impact logging

† The sources listed for the carbon emissions benefit for the protected area strategy are papers that estimated the rate of forest loss in protected areas. Estimates of the carbon stored in natural forests were sourced from: Swallow *et al.* (2007); Gibbs *et al.* (2008); Adachi *et al.* (2011); Saatchi *et al.* (2011); Khun and Sasaki (2014). Estimates of the carbon stored in mixed-crops were sourced from: Swallow *et al.* (2007); Wulan (2012).

Table A1.2 List of the 57 REDD+ projects in Southeast Asia that were included in the Chapter 2 project review with details on the strategies employed at each site. The project number corresponds to the number on the map in Figure 2.2.

				REDD+ Strategy								
Project no.	Project name	Proponent	Country	Longitude/ Latitude	Oil palm	Timber	Community threats	Permit swaps	Protected areas	RIL	Reforestation	Other
1	Reducing Carbon Emission from Deforestation in the Ulu Masen Ecosystem	Private company	Indonesia	5.68158333° 95.32287500°					✓	✓	✓	
2	Leuser Ecosystem REDD Project	Private company	Indonesia	4.13824167° 97.25097778°	✓	✓	✓		✓	✓		✓
3	Tree Flights - Sumatra	NGO	Indonesia	3.62307222° 98.11065833°							✓	
4	Yagasu	NGO	Indonesia	3.589836° 98.668101°							✓	
5	Lebong Carbon Conservation Project	Private company	Indonesia	0.84660278° 100.52078333°			✓				✓	
6	Participatory Land and Forest Management Project for Reducing Deforestation	NGO	Laos	19.85234722° 102.01585278°		✓						✓
7	Kampar Carbon Reserve REDD+ Project	Government	Indonesia	0.526039° 102.704752°		✓				✓	✓	
8	Adaptive and Carbon-Financed Forest Management in Tropical Rainforest Heritage of Sumatra - Kerinci Seblat, Gunung Leuser and Bukit Barisan Selatan	NGO	Indonesia	-2.254611° 102.968548°			✓		✓		✓	✓
9	Reduced Emissions from Degradation and Deforestation in Community Forests – Oddar Meanchey	NGO	Cambodia	14.171720° 103.636272°			✓		✓		✓	✓
10	Lao-German Climate Protection through Avoided Deforestation for (CliPAD) Program	Government	Laos	20.455810° 103.636477°					✓			✓
11	Helping Address Rural Vulnerabilities and Ecosystem Stability (HARVEST) programme	Private company	Cambodia	12.573224° 103.819765°					✓		✓	✓
12	Small-scale and low-income community-based mangrove afforestation project on tidal flats around Batam City, Riau Islands Province	Research Institution	Indonesia	1.085012° 104.008521°							✓	

13	Berbak Deforestation Rate Analysis for piloting REDD	Government	Indonesia	-1.286799° 104.239509°					✓	✓	✓	✓
14	Merang REDD Pilot Project	NGO	Indonesia	-1.71773056° 104.29183889°	✓	✓			✓		✓	
15	Mangroves and Markets: supporting mangrove protection in Ca Mau Province	Government	Vietnam	8.664939° 105.005643°							✓	✓
16	Cao Phong Reforestation Project	Private company	Vietnam	20.686314° 105.313185°							✓	
17	REDD+ project in mangrove forests in South Sumatra	NGO	Indonesia	-2.41619722° 105.56176667°			✓		✓		✓	
18	Promoting the partnership efforts to reduce emission from deforestation and forest degradation of tropical peatland in south Sumatra through the enhancement of conservation and restoration activities	Government	Indonesia	-3.024759° 105.656780°				✓			✓	✓
19	XePian	NGO	Laos	14.549339° 106.074743°					✓		✓	
20	Deforestation and Degradation in Seima Protection Forest	NGO	Cambodia	12.136975° 106.921028°				✓	✓			✓
21	Lomphat National Wildlife Sanctuary REDD+	NGO	Cambodia	13.369791° 107.057834°					✓			
22	Cat Tien Landscape Pro-Poor REDD Project/ Harnessing Carbon Finance to Arrest Deforestation and Forest Degradation to Conserve Biological Diversity	Government	Vietnam	11.450776° 107.402590°			✓		✓			
23	CarBi REDD+ - Laos	Private company	Laos	15.475645° 107.496650°			✓		✓			
24	CarBi REDD+ - Vietnam	NGO	Vietnam	15.475645° 107.496650°					✓		✓	
25	CO2OL Biodiversity	Government	Vietnam	14.623376° 107.834031°							✓	
26	Investigating the potential of Carbon Credit Financing to protect the Gunung Palung – Sungai Putri Ecological Corridor from Deforestation and Fragmentation.	Private company	Indonesia	-1.186304° 110.121952°	✓			✓	✓			
27	Reducing Emission from Deforestation caused by the Oil Palm Sector in Ketapang and Kapuas Hulu, West Kalimantan	Private company	Indonesia	-1.548193° 110.291066°	✓			✓	✓	✓	✓	

28	Borobudur Reforestation Program	Private company	Indonesia	-7.68895833° 110.39896944°							✓	✓
29	Community carbon project for Lamandau	Government	Indonesia	-2.758528° 111.366798°					✓		✓	
30	Marubeni Proposed REDD+ Project, Central Kalimantan	Private company	Indonesia	-2.41000278° 111.74026944°					✓		✓	
31	Forest and Climate Change Program in Indonesia (FORCLIME) in Kapuas Hulu, Malinau and Berau	Government	Indonesia	0.843914° 111.895161°						✓		
32	Rimba Baya Reserve	NGO	Indonesia	-3.112356° 111.902678°	✓		✓		✓			
33	Agroforestry pro poor emission reduction	Private company	Indonesia	-1.23874167° 112.61070000°							✓	
34	Katingan Peatland Restoration and Conservation Project	Private company	Indonesia	-0.982184° 112.817534°							✓	
35	NEWTrees Reforestation Initiative	NGO	Indonesia	-2.41366111° 113.56504722°							✓	
36	Tropical Forest Conservation for Reducing Emissions from Deforestation and Forest Degradation and Enhancing Carbon Stocks in Meru Betiri National Park	Government	Indonesia	-8.458991667° 113.8243361°					✓		✓	✓
37	Rewetting of Tropical Peat Swamp Forest in Sebangan National Park	NGO	Indonesia	-2.45880833° 114.01611389°							✓	
38	Kalimantan Forests and Climate Partnership (KFCP)	Government	Indonesia	-2.787982° 114.099425°			✓		✓		✓	✓
39	Reforestation of degraded areas surrounding the West Bali National Park (WBNP) and the adjacent conservation forest areas	Research Institution	Indonesia	-8.144324° 114.474864°			✓		✓	✓	✓	✓
40	Mawas Peatlands Conservation Area Project	NGO	Indonesia	-1.81244167° 114.59838889°	✓	✓			✓		✓	
41	Heart of Borneo (HoB) Initiative - Brunei	Government	Brunei	4.627527778° 115.9752389°	✓	✓	✓	✓	✓	✓	✓	
42	Heart of Borneo (HoB) Initiative - Indonesia	Private company	Indonesia	4.360497222° 114.5522472°	✓	✓	✓	✓	✓	✓	✓	
43	Heart of Borneo (HoB) Initiative - Malaysia	Private company	Malaysia	1.367927778°	✓	✓	✓	✓	✓	✓	✓	

				114.5417833°								
44	Avoided deforestation project in Malinau, East Kalimantan	Private company	Indonesia	3.869925° 116.122598°			✓		✓	✓		
45	Community-Based Reforestation on Degraded Lands in East Lombok	Private company	Indonesia	-8.819239° 116.460084°							✓	
46	INFAPRO Rehabilitation of logged-over dipterocarp forest in Sabah, Malaysia	Private company	Malaysia	6.290101° 116.935763°					✓		✓	
47	Berau Forest Carbon Program	Private company	Indonesia	2.20219444° 117.36694167°	✓	✓	✓	✓	✓	✓	✓	✓
48	Forest Resources Management for Carbon Sequestration (FORMACS), Nunukan Island in East Kalimantan	Private company	Indonesia	4.027267° 117.670840°						✓		✓
49	Mamuji Habitat - Keep the Habitat	Government	Indonesia	-2.619945° 119.092231°					✓	✓	✓	
50	Forest Carbon Project in Quirino Province Sierra Madre Biodiversity Corridor, Luzon	Research Institution	Philippines	16.66776944° 121.4813222°					✓		✓	✓
51	Philippine Peñablanca Sustainable Reforestation Project	NGO	Philippines	17.662665° 121.947280°							✓	
52	REDD+ and Bio-Fuel Production and Utilisation in Gorontalo Province, Feasibility Study	Private company	Indonesia	0.719586111° 122.2682194°			✓		✓			✓
53	Nantu Forest Conservation in Gorontalo, North Sulawesi	Private company	Indonesia	0.827189° 122.290528°		✓			✓	✓	✓	
54	Mitigation of Climate Change Through Promotion of Community-Based Economic Growth	NGO	Indonesia	-9.622766° 123.731332°							✓	✓
55	Forest Land Use and Climate Change in North Sulawesi (FLUCC) in the Poigar Forest	Government	Indonesia	0.569293° 124.192521°			✓			✓	✓	
56	Perpetual Finance for Carbon Benefits - The Papua REDD project	NGO	Indonesia	-2.261995° 137.811670°	✓	✓			✓			
57	Community REDD+ Readiness in Jayapura District	Private company	Indonesia	-2.549819° 139.925832°	✓	✓	✓	✓		✓		✓

Appendix 2

Chapter 3 Supplementary Methods, Figures and Tables

We selected datasets to include in the spatial analyses that we deemed to have the most influence on the carbon emissions from REDD+ strategies. All calculations are spatially explicit, with carbon stores and emissions calculated independently for each concession or protected area that contain residual forest cover.

1. Spatial datasets

Peat. Land clearing on peat results in additional emissions of 711 $tC \cdot ha^{-1}$ over 30 years (23.7 $tC \cdot ha^{-1} \cdot year^{-1}$; Table A2.1) due to the increased probability of peat oxidation following drainage (15 $tC \cdot ha^{-1} \cdot year^{-1}$) and increased probability of burning (8.7 $tC \cdot ha^{-1} \cdot year^{-1}$). We obtained a 2002 map of carbon stored in peat from the World Resource Institute's (WRI) Interactive Atlas of Indonesia's Forests (Minnemeyer *et al.* 2009), which originated from Wetlands International. The carbon emissions resulting from peat (increased oxidation and burning) were constrained by the total carbon stored in peat in the permit or protected area, so that the emissions could not exceed the total carbon stored in peat, an approach adopted in Venter *et al.* (2009).

Oil palm. We used a 2008 map of oil palm concessions (Greenpeace 2011) compiled by Greenpeace with data from The Ministry of Forestry and other government agencies. The oil palm data for Central Kalimantan is the unpublished 2006-2008 maps of palm oil concessions obtained from the National Land Agency; the Badan Pertanahan Nasional. The dataset is partial, best-available information, given the lack of sector transparency. Carbon emissions were calculated independently for each of the 801 oil palm plantations with residual forest cover. We predicted that some oil palm concessions are granted in areas with poor cultivation potential, as seen in Papua New Guinea (Nelson *et al.* 2014) and used to access and clear-fell tropical forests under the guise of oil palm development. Land that is not suitable for oil palm cultivation is a prime opportunity for a REDD+ project because of the lower opportunity costs compared to oil palm sites with high cultivation potential. We used a map of oil palm suitability (FAO 2012; Figure A2.1) to categorise concessions based on their agricultural potential and identify permits on unsuitable land. The map was modelled based on climatic and edaphic conditions required for cultivation and was projected for the period 2011-2040. We classified categories 'very high', 'high' and 'good' as '*high suitability*', categories 'medium', 'moderate' and 'marginal' as '*partial suitability*' and categories 'very marginal' and 'not suitable' as '*unsuitable*'.

Timber. We used a 2005 map of timber concessions (HTI - Hutan Tanaman Industri) that was supplied by WRI (Minnemeyer *et al.* 2009) and originated from the Indonesian Ministry of Forestry. Carbon emissions were calculated independently for each of the 248 timber plantations with residual forest cover.

Protected areas. We used a 2016 map of protected areas that was extracted from the World Database on Protected Areas (IUCN and UNEP-WCMC 2016). Carbon emissions were calculated independently for each of the181 protected areas with residual forest cover.

Reduced-impact logging. We used a 2005 map of logging concessions (legal classification: Hak Penebangan Hutan - HPH) that was prepared by WRI (Minnemeyer *et al.* 2009) and originated from the Indonesian Ministry of Forestry. Carbon emissions were calculated independently for each of the 524 logging concessions with residual forest cover.

Terrestrial Ecoregions of the World. We used the 'Terrestrial Ecoregions of the World (TEOW)' map from the World Wildlife Fund (WWF) to assess the original distribution of forest cover prior to clearing (Figure A2.2). The map classifies the world into 867 terrestrial ecoregions and 14 biomes such as forests, grasslands, or deserts (Olson *et al.* 2001). We categorised biomes 'tropical and subtropical moist broadleaf forests', 'tropical and subtropical dry broadleaf forests', 'tropical and subtropical coniferous forests' and 'mangrove' as '*forest*' and 'tropical and subtropical grasslands, savannas and shrublands' and 'montane grasslands and shrublands' as '*non-forest*'.

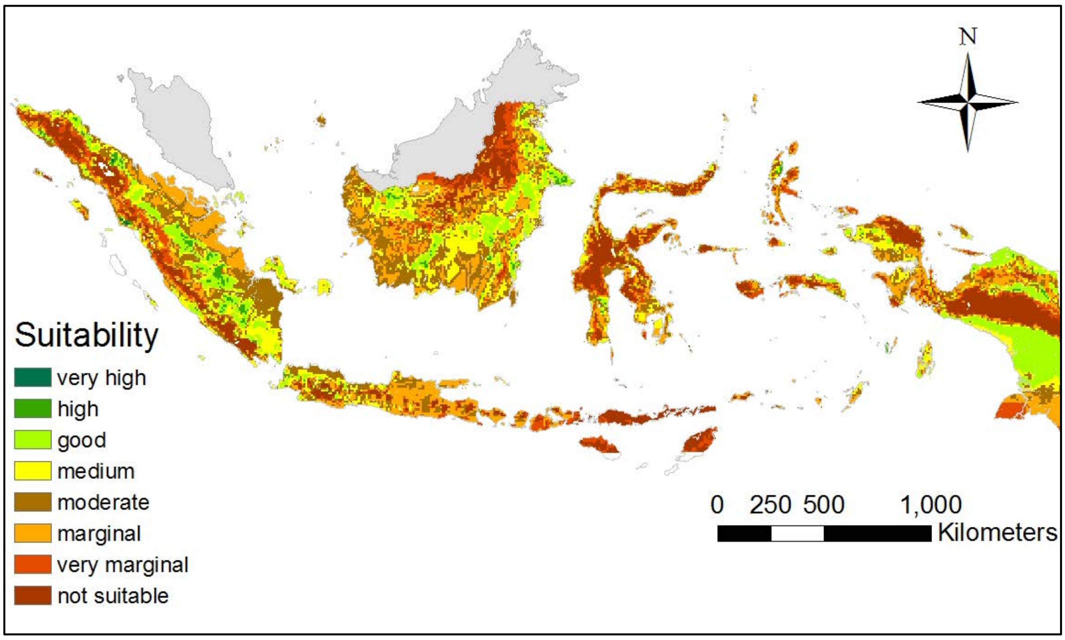

Figure A2.1 Crop suitability index (class) estimated for intermediate input level rain-fed oil palm applied for the period 2011-2040 (FAO 2012).

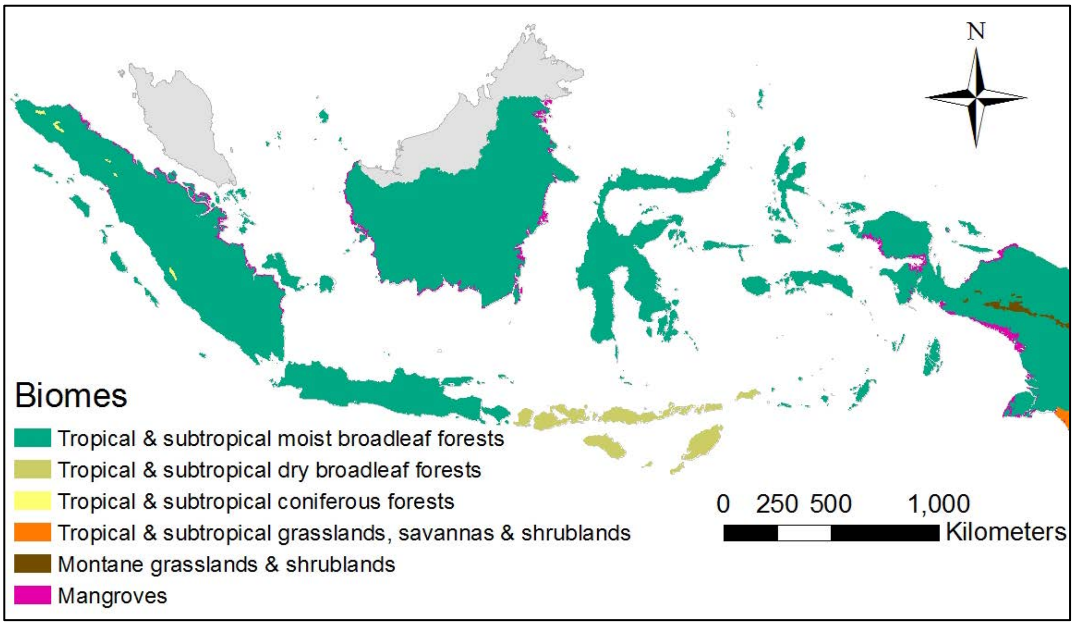

Figure A2.2 Six World Wildlife Fund biomes classified for Indonesia (Olson *et al.* 2001).

2. Sensitivity analysis to changes in forest cover and carbon input data

The 250m spatial resolution land cover maps for 2000 and 2010 (Miettinen *et al.* 2012b) were selected as the primary layers to inform our analyses, because they were developed specifically for Southeast Asia and classified forest into twelve categories, distinguishing between natural forest and commercial forest plantations. One of the objectives of our analysis was to quantify the conversion of natural forests to pulp and oil palm plantations, which is widespread in Indonesia (Margono *et al.* 2014), therefore we selected this dataset because it distinguished between these types of land cover. We created binary maps of 2000 and 2010 natural forest cover by classifying: a) 'plantation regrowth', 'lowland mosaic', 'montane mosaic', 'lowland open', 'montane open' and 'urban' as '*non-forest*'; and b) 'mangrove forest', 'peat swamp forest', 'lowland forest', 'lower montane forest' and 'upper montane forest' as '*natural forest'*, hereafter referred to as '*forest*'. The 2010 forest cover map has an additional category for 'large-scale palm plantation' that we classified as '*non-forest*'.

We tested the sensitivity of our results to changes in the land cover and carbon datasets by analysing all of the scenarios with surrogate data. For land cover, we used high spatial resolution (30 m) land cover maps for 2000 and decadal forest loss for 2000-2010 (Hansen *et al.* 2013; Figure A2.3A and C). These maps were derived from Landsat images where forest was classified as all vegetation taller than 5 m high that was displayed by continuous measures of tree cover (0%-100%). To create a binary forest cover map, we categorised forest as having tree cover of greater than or equal to 89%. We identified this threshold by running comparisons of the total forest area resulting from a range of thresholds and comparing it against the total forest area in the Miettinen *et al.* (2012b) forest cover map. We estimated decadal forest loss by combining annual forest loss for each year between 2000 and 2010 (Hansen *et al.* 2013). To create a 2010 land cover map (Figure A2.3B), we subtracted gross forest loss for the period 2000-2010 from the 2000 land cover map. Hansen *et al.* (2013) reported on annual gross forest loss, whereas Miettinen *et al.* (2012b) reported on net forest loss. Reporting net forest loss can underestimate deforestation rates by confounding areas of forest regrowth with primary forest cover, as regrowth can occur quite rapidly in the tropics (Chazdon 2008).

For carbon, we analysed all of the scenarios for a second time using a map of above- and below-ground carbon (AGC) produced circa 2000 (Saatchi *et al.* 2011; Figure A2.3D). This map was developed from field samples and using satellite light detection and ranging (Lidar) samples of forest structure to estimate carbon storage (Saatchi *et al.* 2011). There were differences in the carbon pools assessed in the two layers of biomass; Baccini *et al.* (2012) assessed only AGC whereas Saatchi *et al.* (2011) assessed both AGC and BGC. To improve consistency across methods, we applied a root:shoot ratio to estimate total carbon from the AGC map. We selected the Baccini *et al.* (2012) map as our primary carbon map because it was more current than the surrogate dataset.

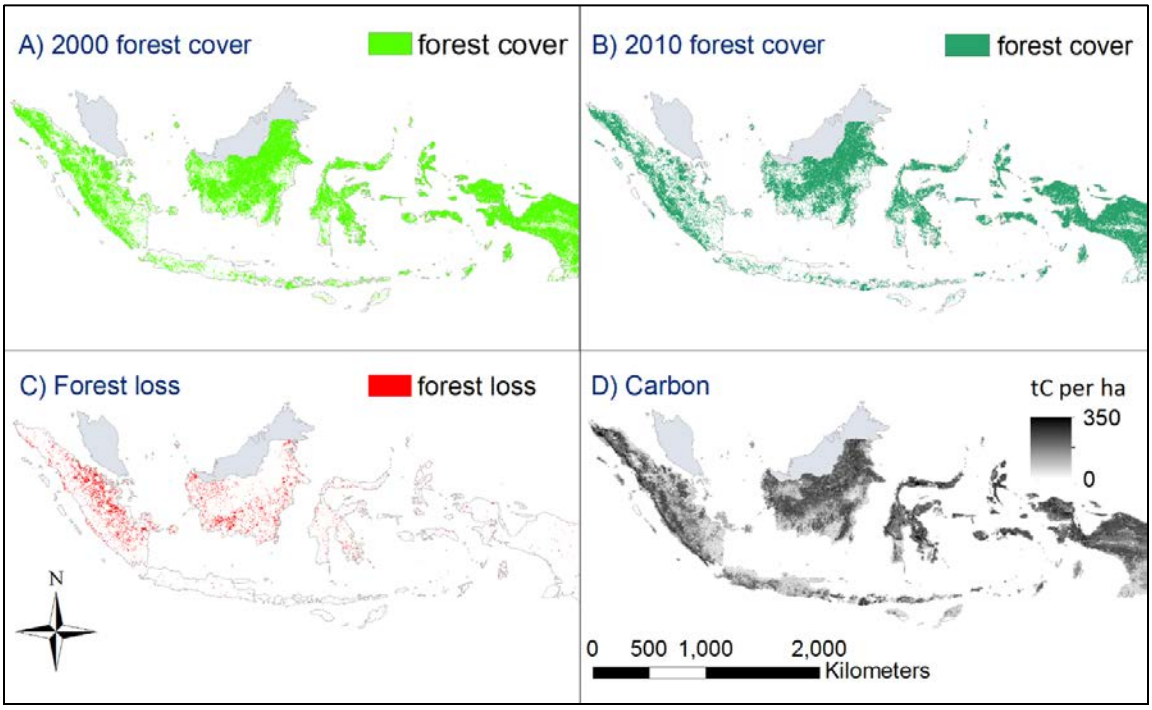

Figure A2.3 Surrogate maps used in the sensitivity analysis: (A) 2000 forest cover (Hansen *et al.* 2013); (B) 2010 forest cover; (C) gross forest loss between 2000 and 2010; and (D) above- and below-ground terrestrial carbon stores from the early 2000s (Saatchi *et al.* 2011).

3. Carbon benefit and financial cost input data

The carbon outcome of applying each REDD+ strategy was estimated using quantitative tools in ARC GIS and sourcing estimates of carbon benefits from the literature. Firstly, we estimated the carbon stored in the forested part of each permit and protected area and calculated the expected emissions benefit of each REDD+ strategy (see strategy-specific methods below). We used financial cost estimates of REDD+ strategies that were collated for a review of the average costs and benefits of REDD+ in Southeast Asia (Chapter 2; Table A2.2) and modified them based on spatially-explicit site characteristics. Financial costs can include opportunity costs, management costs and transaction costs. Opportunity costs are the foregone revenues from the next best use of land if not for the current use (Naidoo *et al.* 2006). Transaction costs are the costs of identifying and negotiating REDD+ projects and monitoring, reporting and verifying on carbon emissions (Pearson *et al.* 2014). Management costs include operating and maintenance expenses (Naidoo *et al.* 2006).

Reducing deforestation from oil palm and timber concessions

The emissions reduction from oil palm and timber concessions was estimated as the difference in carbon stored between natural forests and plantations. We estimated this for each permit by deducting the average amount of carbon stored in oil palm (71 $tC \cdot ha^{-1}$) or timber plantations (88 $tC \cdot ha^{-1}$) from the average carbon stored in the pre-cleared forested part of each permit (Table A2.1). Depending on oil palm suitability, we multiplied the amount of carbon stored in oil palm by a factor to represent the proportion of the permit that would be planted with oil palm following timber extraction. For the 'high suitability' scenario we assumed all of the land would be planted (factor = 1). For the 'partial suitability' scenario, we assumed half of the land would be planted (factor = 0.5), and for the 'unsuitable scenario', we assumed none of the site would be planted for oil palm (factor = 0). We imposed a minimum carbon threshold on forested permits of 71 $tC \cdot ha^{-1}$ for oil palm and 88 $tC \cdot ha^{-1}$ (Table A2.1) for timber to remove areas within the permits that were classified as forest but had carbon levels equal to or lower than carbon stored in plantation forests. We deleted any plantations that would result in total emissions of less than 10tC from clearing the forest and replacing with plantations, as we did not consider these priority areas for reducing emissions.

We applied different costs to permits based on whether the permit had '*high suitability*' for cultivating oil palm, '*partial suitability*' or was '*unsuitable*'. In areas where oil palm is not suitable, we included profits from the one-off timber harvest of \$3,661 per ha

(Butler *et al.* 2009; Fisher *et al.* 2011; Irawan *et al.* 2011; Ruslandi *et al.* 2011; Tomich *et al.* 2002; Venter *et al.* 2009; Zen *et al.* 2005). Alternatively, where land was deemed 'highly *suitable'* for oil palm and had remaining forest cover, we applied a cost of $9,942 per ha (100% profitable; Table A2.2) or for land that was deemed '*partially suitable*' and had remaining forest cover we applied a cost of $4,971 (50% of the total profits). Revenue from selling the initial timber that was cleared prior to planting were included in the oil palm profits.

Reducing illegal deforestation within protected areas

We measured decadal forest loss (2000-2010) for each of the 181 protected areas with residual forest cover and projected these deforestation rates over 30 years to estimate the forest carbon that would be lost if illegal deforestation continues unabated. We imposed a minimum carbon threshold on forest cover remaining within protected areas of 59 $tC{\cdot}ha^{-1}$ (Table A2.1), which was based on the average carbon stored in mixed-crops. This step is consistent with the approach adopted for the oil palm and timber strategies and served to remove areas within the permits that were classified as forest but had carbon levels equal to or lower than carbon stored in mixed agriculture (representing converted forests). We estimated the carbon lost from illegal deforestation by deducting the average amount of carbon stored in mixed-crops from the average carbon stored in the forested part of the park. We excluded protected areas with less than $10m^2$ of forest cover in 2010 and those projected to undergo less than 3% forest loss over 30 years. The cost of stopping illegal deforestation is estimated at $689 per ha (Table A2.2), based on the required budget to manage a park effectively to reduce forest loss (includes purchasing infrastructure items and staffing requirements), less the current budget allocated (i.e. the budget shortfall). We applied costs only to the forested part of the protected area. An underlying assumption of this strategy is that better management of protected areas can halt ongoing forest loss.

Reduced-impact logging

Reduced-impact logging (RIL) reduces tree damage compared to conventional logging (CL) by 19% (Table A2.1) by directional felling and planned extraction of timber on properly constructed skid trails (Putz and Pinard 1993). The net costs of engaging RIL are estimated at ($833 per ha; Table A2.2) over the long-term (over 30 years and two harvests) when compared to CL. Many of the data sources used a simulation model RILSIM to estimate the net cost and revenue of RIL compared with CL (Dykstra 2003), which was conducted at the Innoprise Project site in Sabah, with RIL standards certified under the Forest Stewardship Council (FSC). For consistency with the other strategies, we imposed a minimum carbon threshold on logged-forests of 148 $tC{\cdot}ha^{-1}$ (Table A2.1).

Reforesting abandoned land

Our approach for identifying degraded forest that is suitable for reforestation was guided by the methods detailed in Gingold *et al.* (2012), which utilises spatial information to identify candidate sites for reforestation. We started with all land in Indonesia that was classified as a forest biome. We then refined this by applying the following criteria; we removed areas 1) with forest cover remaining in 2010; 2) with greater than or equal to 35tc ha^{-1}; 3) that overlapped with oil palm, timber or logging permits; or 4) that were classified as 'APL: non-forest estate' (Minnemeyer *et al.* 2009). The costs of reforestation under REDD+ ($1,743 ha^{-1}; Table A2.2) included establishment costs and the ongoing costs of protecting and maintaining the reforestation site (Chokkalingam *et al.* 2006), as well as the transaction costs associated with identifying and negotiating REDD+ projects and the ongoing costs of monitoring, reporting and verifying on carbon benefits (Pearson *et al.* 2014). Specific costs included were germplasm collection, nursery costs, planting and maintenance (Korpelainen *et al.* 1995).

Table A2.1 Data sources used to estimate the carbon outcomes of REDD+ strategies.

Parameter	Mean	Unit	Sources
30-year above- and below-ground carbon sequestration benefit of regenerating tropical forests	193	$tC{\cdot}ha^{-1}$	Silver *et al.* (2000); Nakama *et al.* (2005); Olschewski and Benítez (2005); Budiharta *et al.* (2014)
Above- and below-ground carbon stored in oil palm plantations	71	$tC{\cdot}ha^{-1}$	Syahrinudin (2005); Swallow *et al.* (2007); Gibbs *et al.* (2008); Adachi *et al.* (2011)
Above- and below-ground carbon stored in timber plantations	88	$tC{\cdot}ha^{-1}$	Canesio (2003); Swallow *et al.* (2007); Irawan *et al.* (2011); Khun and Sasaki (2014)
Above- and below-ground carbon stored in mixed-crops	59	$tC{\cdot}ha^{-1}$	Swallow *et al.* (2007); Wulan (2012)
Above- and below-ground carbon stored in logged-forests	148	$tC{\cdot}ha^{-1}$	Putz and Pinard (1993); Healey *et al.* (2000); Pinard and Cropper (2000); Putz *et al.* (2008); Pinard and Putz (1996)
Percent of the pre-harvest biomass conserved by employing reduced-impact logging instead of conventional logging practices over 30 years	19	percent	Healey *et al.* (2000); Pinard and Cropper (2000); Putz *et al.* (2008)
Additional emissions from peat clearing due to peat oxidation and burning following drainage over 30 years	711	$tC{\cdot}ha^{-1}$	Murayama and Bakar (1996); Melling *et al.* (2005); Hooijer *et al.* (2006); Venter *et al.* (2009)

Table A2.2 Detailed description of each REDD+ strategy, the business-as-usual scenario against which it was compared and the financial cost estimates of applying five REDD+ strategies. This table is modified from Chapter 2.

REDD+ strategy	Description of strategy	Business-as-usual scenario	Net cost ($US ha^{-1})	Sources
Oil palm	Buying land that is planned for oil palm development before it is cleared and protecting it from forest carbon loss.	Establish oil palm plantation	9,942	Tomich *et al.* (2002); Belcher *et al.* (2004); Zen *et al.* (2005); Koh and Wilcove (2007); MoFor (2008); Butler *et al.* (2009); Swarna Nantha and Tisdell (2009); Venter *et al.* (2009); Fisher *et al.* (2011a); Irawan *et al.* (2011); Ruslandi *et al.* (2011); Wulan (2012)
Timber	Buying land that was planned for timber plantations and protecting it from forest carbon loss.	Establish timber plantation	4,383	Canesio (2003); MoFor (2008); Irawan *et al.* (2011); Sofiyuddin *et al.* (2012)
Protected areas	Investing in improved protected area management to prevent forest carbon loss through illegal clearing, logging and fire.	Continue current management plan	689	James *et al.* (1999); Emerton *et al.* (2003); McQuistan *et al.* (2006)
Reduced-impact logging	Promoting sustainable forest management practices, such as Reduced Impact Logging (RIL), in areas designated for logging, to reduce carbon lost during the logging process. Practices include reducing road and landing pad construction impacts, and reducing collateral damage to remaining trees during felling and extraction.	Conventional logging (CL)	833	Healey *et al.* (2000); Dagang *et al.* (2005); Samad and Rahim (2009)
Reforestation	Identifying degraded land that was cleared for plantations but is not being actively used for this purpose and restoring forests (and peat swamp forests) for carbon storage.	Land remains abandoned*	1,743	Korpelainen *et al.* (1995); Kosonen *et al.* (1997); Maswar *et al.* (2001); Nakama *et al.* (2005); Chokkalingam *et al.* (2006); Nguyen *et al.* (2014)

*I classify abandoned land as degraded forest that is not being actively managed for plantations or logging by a person or corporation. However, land that appears abandoned is not always abandoned. In many areas insecure land tenure makes the task of identifying potential land for reforestation a considerable challenge. There are millions of hectares of degraded forest in Indonesia that are considered idle, which present a vast opportunity for improving carbon storage by promoting forest regrowth (Boer 2012; Budiharta *et al.* 2014), but some of these areas that are close to villages are being actively worked by neighbouring communities. Methods for identifying degraded areas for plantations have been prescribed that utilise spatial information and community surveys (Gingold *et al.* 2012).

Table A2.3 The proportion (%) of each strategy employed to reduce 25%, 50%, 75% and 100% of carbon emissions from the five REDD+ strategies, using different spatial datasets: A) the primary spatial layers; B) a surrogate map of forest cover; C) a surrogate map of carbon; and D) both surrogate maps of forest cover and carbon. The mix of strategies that contributes to achieving the emissions target is prioritised by the cost of reducing one tonne of carbon at each concession, protected area or reforestation site, from lowest to highest.

REDD+ strategies	Optimal proportion of REDD+ strategies to meet each emissions reduction target			
	25%	50%	75%	100%
A) Primary spatial layers				
Oil palm	21	20	19	23
Timber	65	38	27	23
Protected areas	13	9	10	11
RIL	-	-	8	17
Reforestation	-	34	35	26
*B) Surrogate forest cover layer**				
Oil palm	35	20	20	28
Timber	50	26	24	25
Protected areas	16	9	7	6
RIL	-	-	17	17
Reforestation	-	45	31	23
C) Surrogate carbon layer†				
Oil palm	28	16	15	19
Timber	23	14	11	11
Protected areas	49	32	24	20
RIL	-	-	0.3	13
Reforestation	-	38	50	37
D) Surrogate forest cover and carbon† layers*				
Oil palm	33	27	23	32
Timber	59	35	27	27
Protected areas	8	6	5	5
RIL	-	-	4	5
Reforestation	-	32	42	32

*Hansen *et al.* 2013

† Saatchi *et al.* 2011

Table A2.4 The cost of reducing emissions from: A) Chapter 2: using average cost-benefit estimates (no spatial information); B) Chapter 3: using the primary spatial data; and C) Chapter 3: using surrogate maps of forest cover and carbon.

Outcome	A) Chapter 2	B) Primary spatial data	C) Surrogate spatial data		
Cost of reducing emissions (US$·tC^{-1})			Forest cover*	Carbon storage†	Forest cover and carbon storage
Timber	$35.34	$56.36	$156.57	$44.04	$76.71
Palm oil	$74.90	$73.17	$95.42	$55.21	$65.53
RIL*	$25.49	$23.77	$23.66	$22.66	$22.76
Protected areas	$13.38	$39.27	$84.03	$25.04	$65.27
Reforestation	$9.03	$9.03	$9.03	$9.03	$9.03

*Reduced-impact logging