Title

REDD and BLUE Carbon: Carbon Payments for Mangrove Conservation

Author

Yee, Shannon

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REDD and BLUE Carbon: Carbon Payments for Mangrove Conservation

Shannon M. Yee

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Capstone Advisory Committee

Signature __________________________ Print Name _Dr. Theodore Groves____ Date _______________

Affiliation __UCSD--Economics______ Email __tgroves@ucsd.edu _________ Phone 858-534-2818____

Signature __________________________ Print Name _Dr. James Leichter______ Date _______________

Affiliation ___SIO__________________Email _ jleichter@ucsd.edu _________ Phone 858-822-5330____

Signature __________________________ Print Name _Dr. Junjie Zhang_______ Date _______________

Affiliation __UCSD—IRPS__________ Email _junjiezhang@ucsd.edu_______ Phone 858-822-5733___

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Abstract

Mangroves are highly efficient blue carbon sinks that sequester and store large quantities of carbon in standing stock biomass and sediments for long time periods. The conversion of one hectare of mangrove to shrimp farming in Thailand can release 330 mt CO^2e/ha/yr. Reducing Emissions from Deforestation and Forest Degradation-Plus (REDD+) provides international payments and assistance for avoiding anthropogenic emissions from deforestation. REDD+ must compensate land users for lost income. In Thailand, shrimp farming resulted in rapid mangrove deforestation with profits ranging from $725/ha (low) upwards of $36,000/ha (high), with an average income of $6,235.58/ha. Given that one hectare of mangroves grants 231 carbon credits per year, for a low-profit shrimp farmer, the price per ton of CO^2e would have to equal $3.14/mt CO^2e. For the average shrimp farmer, a price of $27.00/mt CO^2e makes conservation as profitable as shrimp farming. For a high-profit farmer, the price per ton of carbon must equal $156.00/ mt CO^2e. Prices in existing carbon markets can cover the opportunity costs of *marginal* shrimp farmers in Thailand despite the high profits of shrimp aquaculture. REDD+ carbon credits and incorporation into existing markets present an opportunity to provide a substantial funding and tangible incentives for mangrove conservation.

Deforestation and Climate Change

Current climate change discussions focus on greenhouse gas emissions from burning fossil fuels, which releases “black carbon.” Less well known is “green carbon,” the carbon removed from the atmosphere and stored in terrestrial ecosystems such as forests, grasslands, and croplands. Forests are highly efficient carbon sinks that have the potential to reduce atmospheric carbon concentrations over long time periods by capturing and holding carbon in standing biomass stocks and sediments.

Deforestation is a land use change that results in the immediate release of carbon stored in biomass and soils back into the atmosphere, as well as a reduction in the future carbon sink potential. These emissions are referred to by the Intergovernmental Panel on Climate Change (IPCC) as “land-use emissions.” In 2000, the IPCC concluded that land-use emissions account for up to 23% of total global CO^2 emissions and that global net deforestation “[accounts] for nearly all the land-use emissions of CO^2” (IPCC 2000). More recent studies estimate that deforestation and land use changes account for 15%-20% of global carbon emissions (Figure 1) (Niles et al 2002; Nellemann et al. 2009; Dutschke and Wolf 2007).

Efforts to reduce deforestation traditionally focused on terrestrial environments, such as temperate and tropical forests. However, recent studies investigating the contribution of coastal and marine ecosystems to mitigate climate change through carbon sequestration and storage concluded that these ecosystems can rival their terrestrial counterparts. Management of these "blue carbon" sinks are currently not accounted for in climate change policies and are excluded from national carbon inventories and international carbon payment schemes (Lasco 2004). Blue carbon sinks include the open ocean, kelp forests, salt marshes, sea grass beds, coral reefs, and mangroves. All of these coastal ecosystems encounter the same problems of land use conversion and degradation as terrestrial habitats.

The Global Status of Mangroves

At the 2006 Australian mangrove meetings (MMM), a group of the world's mangrove experts unanimously agreed that "[humanity faces] the prospect of a world deprived of the services offered by mangrove ecosystem" within the next century (Duke et al. 2007). "Mangrove" can describe either a plant or ecosystem with specialized adaptations to brackish water environments (Figure 2). Mangrove establishment is highly affected by temperature and hydrology, which dictates tidal patterns and salinity levels (Krauss et al. 2008). Low temperatures tend to control the latitudinal distribution of mangroves which generally grow between 25°N and 25°S (Figure 3) (Saenger et al. 1977). These latitudes coincide with the 20°C inter isotherm of seawater (Duke et al. 1998). Mangroves occur in 124 countries in the tropics and sub-tropics, with 48% of the global mangrove area in only five countries—Indonesia, Australia, Brazil, Nigeria, and Mexico (FAO 2007).

Chapman (1976) estimated that mangrove forests accounted for 75% of tropical coastlines worldwide. The current total global area of mangroves is estimated at 157,000 to 160,000 km^2 (15-16 million hectares), representing 1% of global land cover (Komiyama et al. 2002; Duarte et al. 2005). Because of increased human pressures on these ecosystems, this area is less than 50% of the original total cover (Spalding et al. 1997, Valiela et al. 2001). Mangrove deforestation has continued with 20% (3.6 million hectares) of mangroves lost since 1980 (FAO 2007). This rate of loss is greater than or equal to losses in coral reefs or tropical rainforests (Duke et al. 2007). In June 2010, the first global assessment of mangroves will list 11 of the 70 mangrove species on the IUCN Red List of Threatened Species (Table 1) (Chadwick Personal Communication 2010). An additional six species of mangroves are "vulnerable" and could become threatened with continuing trends in deforestation. Southeast Asia contains the most extensive area (6,048,000 ha) and diverse assemblage of mangrove species (over 50 species, with some endemic to the region) (FAO 2007). It is also the region exhibiting the greatest mangrove deforestation rates with approximately 1% (~61,000 ha) annually (FAO 2007).

More recently, particularly in Southeast Asia, the expansion of aquaculture resulted in 52% of global mangrove deforestation (Valiela et al. 2001). The major form of aquaculture production is shrimp farming, contributing to 38% of mangrove loss alone (Figure 4) (Valiela et al. 2001). Other key drivers of deforestation of mangroves includes logging and harvest of wood product (26%), freshwater diversion from upland and coastal development (11%), and land reclamation for other uses (5%).

The Value of Mangroves

Mangrove ecosystems have been acknowledged for decades for their many ecosystem goods and services—including forestry value, fisheries value, storm protection, and carbon cycling—that benefit the local, national, and international community (Table 2). Studies of total economic value (TEV) for mangrove ecosystems have estimated values as high as $200,000-900,000/ha (Wells et al. 2006). Increased awareness on the value of intact mangrove forests encouraged some countries to slow their rates of deforestation and begin improving degraded mangroves. However, continued deforestation could have potentially serious impacts considering many ecosystem goods and services provided by mangroves weaken with decreasing area and environmental quality.

These ecosystems continue to be destroyed even though they are attributed such a high economic value. Many of the economic benefits of mangrove ecosystem goods and services are qualitative values and have not been, or are only beginning to be monetized. Forestry, fisheries, and ecotourism values provide quantitative economic incentives to promote sustainable development of mangroves. Some goods and services—such as storm protection, water quality or pollutant uptake, sediment retention—provide cost savings, but do not directly generate revenue for the management of these areas. Because not all of the values of these ecosystems are accounted for, mangroves are undervalued. Undervaluing of mangrove conservation compared to other land uses results in unwise decisions and policies.

While the management of mangrove conservation relies on national and local implementation, the international community benefits from the existence of mangroves. The conservation of mangroves relies of local, national, and international support. International free riding on global public goods, such as carbon sequestration and storage, will continue unless international payments are provided to encourage the conservation of these ecosystem goods and services.

Objectives

The emergence of carbon markets provides a valuable tool to account for the true carbon value of these blue carbon sinks and create tangible economic incentives for mangrove conservation. Reducing Emissions from Deforestation and Forest Degradation-Plus (REDD+) would fund carbon projects that prevent the release of greenhouse gases stored in plant biomass. In order to assess the potential for carbon payments to conserve mangrove forests, understanding the dynamics of carbon cycling and the amount of carbon storage in these sinks compared to other areas is critical.

This paper will review the literature on the magnitude and fluctuations of carbon in mangrove ecosystems. Using the carbon storage capacity supported by the literature, the potential sellable carbon credits per hectare of mangrove will be calculated and compared to the opportunity costs of alternative land uses, such as shrimp farming in Thailand, to find the price per ton CO^2e could forest conservation payments equal income from alternative land uses that result in deforestation. These prices represent the tipping price of carbon needed to create incentives for mangrove conservation by providing alternative incomes to deforestation.

Blue Carbon in Mangroves

Mangrove forests are highly productive carbon sinks that absorb and store more carbon than they release. Mangroves absorb carbon dioxide from the atmosphere to convert to sugars and other organic compounds via the process of photosynthesis. Also known as carbon fixation, carbon sequestration binds carbon in different forms of primary production where it accumulates over decades and centuries. Above ground pools includes the primary production of leaves, stems and wood. The below ground primary production includes coarse and fine roots. This carbon accumulates and increases the biomass standing stock. Over time, dead leaf litter and woody debris fall to the forest floor where they are consumed by local fauna, remineralized into the atmosphere, exported to adjacent coastal environments, or buried in mangrove sediment (Figure 5).

On a per area basis, mangroves have comparable plant standing stock biomass (7990 g C/m^2 or 293 mt CO^2e/ha using the standard conversion of 1 t C = 3.67 mt CO^2e) to terrestrial ecosystems, with the exception of tropical forests (Table 3) (Laffoley and Grimsditch 2009). Other estimates of aboveground standing biomass are double or triple this value. Lecocq and Chomitz (2001) estimated that tropical mangrove forests release 152 to 224 t C/ha, with an average of 184 t C/ha (674.67 mt CO^2e). A study by Ong (1993) measured 200 t C/ha (733.33 mt CO^2e/ha) in the Matang Mangrove Forest Reserve. And Twilley et al. (1992) estimated that the global storage of carbon in mangrove biomass at 4.03 Pg C (923.54 mt CO^2e/ha).

Primary Productivity

Leaf Production

Most estimations of mangrove primary productivity are based on leaf litter traps. However, measuring only leaf litter production will underestimate mangrove stock biomass since leaf litter accounts for only 31% of total productivity (Alongi et al. 2005; Bouillon et al. 2008). Leaf litter biomass tends to decrease with increasing latitudes, due to changes in temperature and precipitation (Saenger and Snedaker 1993). Leaf fall rates in lower latitudes average 5.2 ± 2.3 t C/ha/yr (19.07 ± 8.6 mt CO^2e/ha/yr) and 2.35 ± 1.05 t C/ha/yr (8.62 ± 3.85 mt CO^2e/ha/yr) in higher latitudes (Bouillon et al. 2008). Higher estimates suggested that the global rate of leaf litter fall could contribute 92 Tg C/yr (33.73 mt CO^2e/ha/yr) (Jennerjahn and Ittekkot 2002).

Above-ground Wood Production

Few estimates calculate aboveground wood production (stems and branches) even though it accounts for 31% of mangrove productivity (Bouillon et al. 2008). Similar to leaf litter trends, above-ground biomass decreases with increasing latitudes (Komiyama, Ong, and Poungparn 2008). Near the equator, carbon stocks of above-ground wood production were 141.8 Mg C/ha (520 mt CO^2e/ha) and 52.1 Mg C/ha (191 mt CO^2e/ha) in temperate zones (Twilley et al. 1992). However, Khan, Suwa, and Hagihara (2007) found a more conservative average above-ground wood production of 31.53 Mg/ha (115.61 mt CO^2e/ha). Twilley et al. (1992) estimated an average rate of wood production of 67 mol C/m^2/yr (29.75 mt CO^2e/ha/yr). Bouillon et al. (2008) calculated a global above-ground wood production rate of 66.4 ± 37.3 Tg C/yr (36.67mt CO^2e/ha/yr).

Below-ground Wood Production (Roots)

True mangroves are characterized by unique physiological and structural adaptations to tidal environments, such as complex aerial root systems (Tomlinson 1986). The extensive system of prop and aerial roots give mangroves stability in the soft tidal sediment, facilitate gas exchange, and gather nutrients from deep in the soil layer (Komiyama et al. 2000; Ong, Gong, and Wong 2004). A larger allocation of resources to root production is necessary to cope with the harsh conditions of mangrove environments (Khan, Suwa, and Hagihara 2007). The characteristic root system of mangrove species accounts for 38% of primary productivity (Figure 6). In terrestrial forests, root biomass can represent up to 20% of total biomass (Nilsson and Schopfhauser 1995).

Not accounting for the belowground biomass in mangrove will dramatically underestimate the carbon stored in these ecosystems. Allometric equations estimating the whole or partial weight (biomass) using measureable tree dimensions show that the below-ground (BG) biomass can be greater than or equal to above-ground (AB) biomass so that up to 50% of the total biomass in mangroves can be held in the roots (Twilley et al. 1992; Alongi and Dixon 2000; Komiyama, Ong, and Poungparn 2008). Generally, the ratio of aboveground to belowground biomass is between 2.0 and 3.0 compared to a value of 4.0 to 5.0 in upland vegetation (Komiyama, Ong, and Poungparn 2008).

Alongi et al. (2003) estimated carbon accumulation in below-ground biomass for *Rhizophora stylosa* and *Avicennia marina* ranging from 1,400 to 3,300 g/m^2 (51 mt CO^{2}e/ha to 121 mt CO^{2}e/ha) and 1,200 to 3,600 g/m^2 (44 mt CO^{2}e/ha to 132 mt CO^{2}e/ha). Khan, Suwa, and Hagihara (2007) found similar root production of 26.8 Mg/ha (98.3 mt CO^{2}e/ha). Kristensen et al. (2008) and Bouillon et al. (2008) found similar rates of belowground root productivity equal to19.36 mt CO^{2}e/ha/yr and 18.98 mt CO^{2}e/ha/yr).

Consumption by Fauna

Direct herbivory is not a major carbon pathway because of the high C: N ratios of leaf litter and tannins (Komiyama et al. 2008). The majority of mangrove-derived detritus is of low nutritional value and a minor food source for secondary production (Jennerjahn and Ittekkot 2002). More frequently, foliage falls and decomposes on site or is exported to adjacent systems.

Re-mineralization

Re-mineralization is the process where organic carbon compounds are transformed into inorganic carbon, such as carbon dioxide. The degree of carbon re-mineralization in mangroves is largely unknown. Measurements of net CO^2 efflux from sediments are used as a proxy for re-mineralization rates. Re-mineralization rates range from 7.0 mol C/m^2/yr (3.08 mt CO^{2}e/ha/yr) to 21.54 mol C/m^2/yr (9.48 mt CO^{2}e/ha/yr) (Suratman 2008; Bouillon et al. 2008).

Export

Estimates of the degree of export of organic carbon vary widely depending on local hydrodynamics (Dittmar and Lara 2001; Bouillon et al. 2003). In riverine mangroves, tidal flushing exports mangrove-derived and riverine-imported organic matter to coastal and open ocean environments where it contributes to other food webs, supporting Odum and Heald's "outwelling" hypothesis (1968). However, lagoon mangroves with less tidal forcing can actually exhibit a net import of detritus from outside of the mangrove ecosystem.

Twilley et al. (1992) estimates 10-50% of leaf litter production is exported in mangrove forests with the rate of annual export ranging from 200 g C/m^2/yr (7.333 mt CO^{2}e/ha/yr) to 287.52 g C/m^2/yr (10.54 mt CO^{2}e/ha/yr) (Twilley et al. 1992; Bouillon et al. 2008). Jennerjahn and Ittekkot (2002) estimate 15% of the carbon content in marine sediments is mangrove-derived carbon. However, Rodelli et al. (1984) found that the role of organic matter on mangrove sedimentation and connectivity with adjacent ecosystems in Malaysia is restricted to the local vicinity of 2 km^2 and does not significantly contribute to carbon accumulation in the open ocean sediments. Jennerjahn and Ittekkot (2002) found similar results in Brazil where mangrove-derived carbon was restricted to localized areas.

Burial

While consumption, export, and remineralization are significant carbon pathways, they do not contribute to the carbon stored within a mangrove ecosystem. The fraction of carbon that is not assimilated into living tissues, decomposed by detritivores, or exported to adjacent ecosystems is locked away in the sediments and stored over long periods of time. Primary production represents a major fraction of the total carbon stock in mangrove ecosystems, holding carbon for decades to centuries. However, the true carbon sink is in the sediment. Unlike terrestrial forests, coastal ecosystems can store large stocks of organic matter for millennia. Organic carbon in the top 1.5 m in Brazil's Furo de Meio mangrove forest dated back 400 to 770 years old (Dittmar and Lara 2001).

Burial rates in coastal ecosystems, such as mangroves, are orders of magnitude greater than terrestrial environments. Carbon accumulation rates in mangroves were 10 times the rate for temperate forests and up to 50 times the rate for tropical forests (Table 3) (Laffoley and Grimsditch 2009). In other words, 1 km^2 of mangrove area results in the equivalent long term sequestration in 50 km^2 of tropical forests. Coastal ecosystems represent a better investment for long term greenhouse gas emission reductions because they accumulate and bury more carbon than terrestrial ecosystems.

The hydrologic conditions and dense root system in mangrove environments trap organic sediments. The root system's ability to attenuate and dissipate wave energy allows sediments to settle out. Mangroves occur along sedimentary coastlines where large quantities of these suspended organic matter and sediment imported by tides from adjacent coastal environments and rivers (allochtonous: phytoplankton, seagrass-derived, terrestrial non-mangrove forests) are accumulated in the sediment with mangrove-derived detritus (autochthonous: mangrove-derived) (Cebrian 2002; Kristensen 2007; Lafolley and Grimsditch 2009). Carbon burial is highly dependent upon the sediment accumulation rate (Eq. 1).

Carbon burial = (bulk density)*(%C of sediment)*(accumulation rate) (Eq. 1)

The high sediment accumulation rates reduce the residence time of detritus in surface sediments where microbes and other detritivores have less opportunity to metabolize and further degrade the organic matter (Reay and Hewitt and Grace 2007). Marine invertebrates, such as mud crabs, enhance the burial of organic carbon by transporting leaf litter in their burrows which stores organic matter belowground and reduces litter export (Dittmar 1999; Skov and Hartnoll 2002; Kristensen et al. 2008). High carbon organic matter (as high as 75% carbon concentration) can be found as deep as 8m belowground (Bouillon et al. 2003; Chmura et al. 2003).

Burial rates will also be affected by abiotic and biotic factors. Climatic conditions related to decomposition explain variability in organic matter concentrations. Higher temperatures and wet environments result in increased decomposition rates in wetlands soils (Chmura et al. 2003; Reay and Hewitt and Grace 2007). Efficiency of carbon sequestration in sediments improves with the age of the mangrove forest, from 16% for a 5-year old stand to 27% for an 85 year old stand (Alongi et al. 2004; Lafolley and Grimsditch 2009). Kristensen et al. (1995) found that litter decomposition rates also differed between mangrove species. Leaves from *Avicennia spp*. decompose faster than *Sonneratia spp*. and *Rhizophora spp*. because they are thinner and contain less tannin and sink faster.

Chmura et al. (2003) found that the average carbon density of mangroves equals 55,000 g/m^3 (2016.67 mt CO^2e/ha per meter depth). Ong et al. (2002) estimated that sediments in mangrove forests held 700 tons of carbon per meter depth per hectare. While not all of the carbon would oxidize, excavating the top 2 meters, given a 50% oxidation ratio, would release 70 tons of carbon per hectare per year (256.6 mt CO^2e/ha/yr) over ten years. This rate of loss is 50 times the annual burial of carbon in mangrove sediments of 1.5 t C/ha/yr (5.5 mt CO^2e/ha/yr) (Ong 1993). Global estimates of annual burial have ranged from 18.4 to 23.6 Tg C/yr (4.22 to 5.4 mt CO^2e/ha/yr) (Lafolley and Grimsditch 2009; Bouillon et al. 2008; Jennerjahn and Ittekkot 2002). Alongi et al. (2001) estimated a higher rate of carbon burial in a Thailand mangrove forest, ranging from 183.6 to 280.8 g C/m^2/yr (6.73 to 10.30 mt CO^2e/ha/yr).

Mangroves as Carbon Sinks

Mangroves are highly efficient carbon sinks, holding large quantities of carbon in standing biomass and in sediments. When a forest is cleared, the amount of carbon released to the atmosphere from standing stock alone rivals terrestrial ecosystems. And when also considering the high concentrations of carbon in sediments that have accumulated over millennia, the turnover of mangrove soils from clearing and development releases equal, if not greater, quantities of carbon. Because of the potential for coastal and marine ecosystems to act as long term carbon sinks, it is both logical and necessary to account for these offsets into existing international and national emissions inventories, and incorporate these ecosystems into carbon revenue schemes. Any changes in land use that would result in the losses of these carbon sinks will have profound effects on global climate change.

Carbon Markets and International Payments

A carbon market is a forum for the exchange of payments for a good or service rendered, in this case for carbon sequestered and stored. Carbon payments monetize reductions in the greenhouse gas emissions and provide compensation for a unit of carbon, where one carbon credit equals one metric ton of carbon dioxide equivalent (mt CO^2e). The price per ton of carbon represents the price investors were willing to pay in order to sequester and store one ton of carbon. Several carbon markets exist worldwide. They are grouped into regulatory and voluntary markets depending upon whether or not the credits bought count towards regulatory obligations to monitor and reduce their greenhouse gas emissions.

Regulatory Markets

Regulatory, or compliance, markets supply carbon credits to parties that must fulfill responsibilities to emissions reduction commitments. The European Union's Emissions Trading

Scheme (EU ETS) and UNFCCC's Clean Development Mechanism (CDM) are examples of compliance carbon markets. Since parties are required to meet the emissions reduction commitments, there is a significantly greater demand for credits in compliance markets than in voluntary markets. Credits are held to stricter standards for verification in order to ensure the validity of emissions reductions. The higher demand and verified "quality" of credits in regulatory markets result in a higher price per metric ton (mt) of CO^2e. One metric ton of CO^2e is traded for \$18-23 in the EU ETS and \$9-16 per mt CO^2e in the CDM.

However, the forestry offsets have not been a significant proportion of carbon credits brought and sold. Under the CDM, one afforestation project is registered with six more at the validation stage. There are 12 registered reforestation projects and 31 more at validation. However, these afforestation and reforestation projects represent only 1% of all CDM projects, which have focused on renewable energy (60% of projects) and "CH^4 Reductions and Cement/Coal" (20% of projects).

Voluntary Markets

Voluntary markets sell credits to parties who want to offset their emissions but are not held to the commitments of parties in the regulatory markets. The Chicago Climate Exchange (CCX) is an example of a voluntary market in the US. The demand for forestry offsets is low, but growing in voluntary markets. The standards for verified credits are less strict. Prices per metric ton of CO^2e range from \$5-10.

Including Deforestation

In 1997, policies related to deforestation and forest degradation were excluded from the Kyoto Protocol. And currently, only reforestation and afforestation efforts are credited. Reforestation is the human-induced reestablishment of a forest after its removal and afforestation involves growing a forest where a forest had not previously existed within the last 50 years (Brown et al. 1986, Angelsen 2008). The current carbon market accounting for afforestation and reforestation attempt to increase the amount of carbon absorbed by creating natural sinks. Reforestation and afforestation projects reduce emissions by increasing sequestration potential to result in a real reduction of atmospheric CO^2.

However, there is no current mechanism to decrease the amount of carbon released by preserving existing sinks. It is important to both reduce deforestation and increase reforestation and afforestation globally to make significant steps in reducing overall carbon emissions. While reducing deforestation can stabilize greenhouse gas emissions, it is a necessary step to protect the existing carbon stored while increasing the carbon sink through reforestation and afforestation. Only by incorporating avoiding deforestation can mitigation efforts work towards true greenhouse gas reductions.

Reducing Emissions from Deforestation and Forest Degradation-Plus (REDD+)

In the 2005 UNFCCC Montreal Conference of Parties meeting, a proposal was submitted for the addition of a carbon credit system for avoided deforestation to commence after the first commitment period ending in 2012. The original Reducing Emissions from Deforestation and Forest Degradation (REDD) mechanism was later changed to Reducing Emissions from Deforestation and Forest Degradation-Plus (REDD+) to reflect the goals of also providing the co-benefits of biodiversity conservation and poverty alleviation into REDD efforts. While the framework and structure of how REDD+ will operate is still under negotiation, this international mechanism holds promise for providing international payment and assistance for avoiding anthropogenic deforestation. Existing carbon markets award credits to individual projects. The REDD mechanism has been proposed for inclusion in meeting national emission targets by crediting entire nations (Miles and Kapos 2008). This framework allows developing countries with high deforestation rates that are not covered under existing global emissions commitments, such as Brazil and Indonesia, to reduce greenhouse gas emissions.

REDD is currently funding five pilot projects to assess 1) the need for capacity building, 2) the development of monitoring and measurement, and 3) the viability of selling carbon credits on voluntary markets. Initial phase of REDD will focus on capacity building and assistance to set the stage for national implementation of REDD programs. Later phases will focus more on results and selling carbon credits to investors. Before carbon credits can be awarded, project proposals must provide evidence that their efforts and policies result in real carbon savings that are additional, permanent, and avoid leakage while providing co-benefits of REDD+ objectives.

Requirements for Carbon Projects

Additionality

Carbon credits can only be granted if they result in actual carbon savings. Hence, credits would not be issued for land use changes that would happen without the carbon projects. Therefore, deforestation projects, similar to reforestation and afforestation projects, are assessed in relation to a baseline scenario of business-as-usual or the most likely land use activity. Historical land use or projected land use with the highest opportunity cost are the most logical baselines. The additional carbon is equal to the net avoided emissions or the difference between the carbon stock of an intact forest and the carbon stock of the baseline land use. The carbon stock will vary depending on the carbon richness or density within any one type of land. In one sense, the additional avoided emissions are the change in carbon storage per hectare. Because mangroves forests and soils have higher carbon densities than other types of terrestrial ecosystems, their deforestation represents a significant release of stored carbon. The net avoided emissions (AE) are the sum of emissions released from above-ground stocks (E_{AB}) and below-ground stocks (E_{BG}) less the emissions sequestered (E_{SQ}) by the land use change (Eq. 2).

$$AE = E_{AB} + E_{BG} - E_{SQ} \qquad \text{(Eq. 2)}$$

The decision for the baseline scenario dictates the amount of credits that can be awarded for avoiding deforestation. There is a moral hazard of inflating baselines to maximize additional credits. Countries that have been implementing policies to curb deforestation would argue for the use of historical baselines rather than use projected baselines to capitalize on higher past emissions from deforestation. It is also difficult to project deforestation rates that would continue to occur with certainty. There is also the perverse incentive for parties to increase deforestation rates if they feel it will benefit their baselines once a REDD+ mechanism is implemented in the future.

Also, the baseline must consider the end product. Timber harvested for charcoal or fuel wood will result in the release of fixed carbon. But timber for furniture production will maintain that carbon storage. The exclusion of carbon stored in wood products or sequestered by crops will also inflate avoided emissions by estimating more credits than should be certified. However, it may be argued that eventually this form of carbon will find its way back to the atmosphere since there is little incentive to recycle discarded wood products (Reay and Hewitt and Grace 2007). The logistics of tracking and monitoring carbon maintained in wood products is complicated and resource-intensive.

Spatial Leakage

Another problem that must be assessed in carbon projects is ensuring that conserving forests by restricting use in one area does not lead to displacement of the activity to another area outside of the project, resulting in no net carbon savings. This spatial leakage of carbon is more likely if deforestation is handled at the individual project level, as with afforestation and reforestation projects, than if deforestation rates were assessed on national levels with national carbon budgets. If REDD+ is implemented on a national level, the "project" boundary would incorporate all areas of the nation. With increasing scope and scale of a project, the probability of leakage decreases since more activity must be accounted for within project boundaries (Olsen and Bishop 2009). However, the costs of monitoring and enforcement also increase with increasing project scope and scale. Regardless of REDD's design, REDD policies and monitoring will have to be put into place and enforced to ensure minimizing spatial leakage and loss of carbon credits. Potential solutions to reduce the chances of significant leakages include incorporating buffer areas at project boundaries, providing displaced activities with an alternative to current activities, or granting compensation for any lost use rights.

Permanence (Temporal Leakage)

The permanence of carbon credits can refer to the reversibility of some level of the carbon savings (Dutschke 2001). Projects must ensure that the carbon from the forest is conserved for the duration of credit payments and there is no temporal leakage. This is also a measure insuring that carbon credits have a long term impact on climate change reductions. Unlike afforestation and reforestation credits which grant credits for carbon sequestered, avoided deforestation credits parties for carbon stored. There is a real concern that once the project ends or the decision is made to convert the land, then these accumulated credits would be lost. There is also a risk of losses due to natural events, such as hurricanes, pests and infestations, fires, and flooding due to sea level rise. Political environments can also lead to uncertainty of future preservation of forests. The necessary timeframe for these types of projects often exceed a government's planning time horizon (~10 years) and it can be hard to confirm commitment into the future (Dutschke 2001).

Forest projects should be liable for their product, similar to crop commodities. Limiting the liability for credits creates disincentives for protecting the stock from natural losses. Managers should be actively reducing the vulnerability to natural disturbances that would result in lower carbon storage and an undersupply of verifiable carbon credits. One solution would be to require projects to hold a certain fraction of credits in a reserve pool, or buffer pool, as insurance in the case of unforeseen losses. In this sense, the total number of carbon offsets generated by a project should always be greater than the traded, or sellable, carbon offsets issued so that reserve offsets adequately cover the project risks. Sellable avoided emissions (AE_S) equals the total net avoided emissions (AE) reduced by a discount buffer factor (ɣ) (Eq. 3).

$$AE_S = (1-ɣ)*AE \qquad \text{(Eq. 3)}$$

Under different verifying and certifying bodies, the discount buffer factor generally ranges between 10-60% of the total carbon credits depending on the level of riskiness associated with the project (Forestry Carbon Standards 2008).

Alternatively, projects could be held liable for replacing and compensating for issued credits in the event of a release of stored carbon. Similar to a cap and trade system, projects must purchase additional credits if carbon is lost and the full credits are not covered even by a reserve pool. Also, the creation of an insurance market for carbon credits could help manage the risks of forestry offsets and spur investment in carbon projects.

Verification of Credits

All projects must be validated before credits are certified and sold on the market. Often, third party auditors, also known as verifiers, are consulted to confirm that the collection, quantification, and submission of GHG emissions reductions data are performed in accordance with independent international standards, such as the Voluntary Carbon Standard (VCS) and there are measures in place to establish additionality, minimize leakages, and ensure permanence.

REDD verification must work to avoid perverse incentives and un-equitable results. Priority should be given to conserving and restoring forests in natural states rather than tree plantations. Even though they may sequester similar or greater magnitudes of carbon, the additional co-benefits, such as biodiversity, of natural ecosystems make more natural habitats preferable to manicured tree rows. Carbon projects that set aside forested lands have been criticized for restricting the rights of local and indigenous communities that rely on the forests from subsistence uses. REDD+ attempts to honor the rights of these local peoples and encourage co-management between government or private NGOs and local communities. The Ban Sam Chong Tai village, supported by a government project, in Southern Thailand protects the mangroves as a community forest and has community rules on wood harvest and replanting in degraded areas (Barbier and Cox 2004).

Projects may fetch a price premium with certifications that reflect these increased benefits of other services provided by projects and/or the increased security of the investment apart from carbon benefits. The Community Climate Biodiversity Standard (CCBS) of the Community Climate Biodiversity Alliance (CCBA) ensures that community and biodiversity concerns are also incorporated into project considerations, in addition to separate carbon accounting standards such as CDM or VCS.

"REDD+ Readiness" and International Capacity Building

"REDD Readiness" refers to the capacity building and pilot projects currently being undertaken to prepare countries to undertake REDD projects that meet the requirements of additionality, permanence, and leakage minimization. REDD is assessing administrative, transaction, and implementation costs by investigating standardization of measurement and monitoring methodologies, implementation of REDD policies, and incorporation of REDD credits into existing carbon markets. These measures will help to reduce uncertainty about the feasibility of REDD on a global scale.

Similar to the case in Thailand, many governments and communities in the developing world with conservation laws in place have not successfully curbed deforestation because they lack the necessary resources to monitor and enforce laws. Guaranteeing adequate, long term sustainable funding sources and initial capital to invest in management is difficult. International payments and assistance can be used to overcome financial, technological, or institutional barriers to implementation. Payments can create incentives or increase access to resources that allow a project to be pursued or continue on such as supplying capital, reducing risk of research and development, or increasing capacity for new technology implementation.

And while some countries have the background survey information and data collection for natural resources that would reduce measuring and monitoring costs by making it easier to establish verifiable baselines, developing countries that may not have this information available will have higher initial measurement and monitoring costs due to the need to invest in preliminary capacity building. Monitoring, reporting, and verifying (MRV) of changing carbon stocks has proven to be a complex process. Standardizing methodologies will provide the most accurate, cost-effective, and transparent sampling, measuring, and monitoring of carbon stocks.

Governments and NGOs can assist by facilitating transfer of technologies and methodologies to improve information sharing. For example, the availability and use of Landsat and other remote sensing data will reduce these costs given technical expertise.

The administration, transaction, and implementation costs of REDD will vary country to country depending on its level of REDD readiness. These costs of REDD+ are highly uncertain since the design of REDD+ continues to be negotiated.   In past carbon crediting programs, these costs add roughly \$1/ t CO2e in addition to opportunity costs of alternative land use (Olsen and Bishop 2009). Implementation costs are predicted to exhibit significant economies of scale with lower costs per unit of emissions with increasing project size (Olsen and Bishop 2009). Winrock International, a non-profit economic development organization, has been a leader in carbon accounting methodology and found costs of measurement and monitoring as low as \$0.25 per ton of carbon to within ±6-8% (95 CI) ("Hearing on carbon sequestration measurements and benefits" 2001). Implementation costs can include patrolling forested lands to decrease illegal land use and shifting harvesting activities from natural forests to degraded lands. These costs favor larger forestry projects over small landowners on marginal lands. If REDD+ is adopted on a national scale, implementation costs are expected to be higher than in the past since implementation must account for all activities and land use changes within the national borders.

Transaction costs are considered fixed, not dependent on size of project but the number of projects (Olsen and Bishop 2009). In this sense, a large number of small projects have a higher transaction cost than the same area within one project. Therefore, REDD+ is inclined to favor large tracts of intact forestland for conservation. Cacho et al (2005) found that project costs per ton were negatively correlated with project size, supporting the fact that these transaction costs will be higher for small scale and more remote forest owners. Development of monitoring, reporting, and verifying (MRV) plans and distribution of payments and assistance to operators are examples of transaction costs for carbon projects. It is important to note that these administrative, transaction, and implementation costs do not decrease deforestation. Rather they allow carbon accounting and trading to occur smoothly and bring transparency and credibility to carbon crediting.

Opportunity Costs of Alternative Livelihoods

In addition to the administrative, transaction, and implementation costs of REDD+, the opportunity costs of forested lands must be included into the total costs of forest conservation projects. The opportunity costs of land use are considered the majority of program costs (Olsen and Bishop 2009). For a land owner deciding whether or not to preserve a forested area or convert it to an alternative land use, the decision lies in weighing the private benefits that this land owner would gain from each opportunity. The private benefit gained from any one land use equals the net profits, or income, per area.

Developing nations have the right to utilize their lands in such a way that maximizes these benefits. Carbon payments allow a beneficiary to compensate for the opportunity costs (i.e. lost profits and income) of competing land uses to ensure that carbon mitigation is equitable and fair. By generating an income of the same order of magnitude as other land uses, carbon payments could provide strong incentives to change people's behaviors and practices from an undesirable activity toward more sustainable uses, such as forest conservation. Carbon payments present an opportunity to provide a substantial funding mechanism and tangible incentives for mangrove conservation by offsetting the management costs through international investment in the conservation of these resources. The following section will investigate the potential for carbon payments to cover the opportunity costs of shrimp farming in Thailand, one of the major drivers of mangrove deforestation in Southeast Asia, by determining the price per ton of CO^2e needed for forest conservation payments to equal the income from shrimp farming.

Mangrove Conservation as an Alternative to Shrimp Farming

Background on Shrimp Farming

Currently, roughly 40% of global shrimp production is from aquaculture, 2.6 million tons per year (FAO 2008; FAO 2009). Thailand is one of the world's leading exporters of farmed shrimp with an export value of $1-2 billion annually and employs over 1 million people in direct and associated industry operations (Vandergeest, Flaherty, and Miller 1999; Leepaisomboon et al. 2009). Roughly 50-65% of original mangrove cover along the coastline was lost between 1975 (312,700 ha) to 1996 (168,683 ha) primarily due to conversion of mangroves to shrimp farming operations (Sathirathai 1998; Barbier and Cox 2004; Aksornkoae and Tokrisna 2004).

Extensive, or "traditional", shrimp farming has little inputs, with seeding and feeding occurring naturally in coastal waters. The sheltered environment of mangrove roots act as a nursery, providing protection from predation and valuable nutrients for development in their early life stages. Shrimp farming is essentially taking this mangrove ecosystem service—as a nursery and refuge—to produce commercial valuable shrimp. The average area of a farm is larger than intensive farming at 12.2 ha (Shang, Leung, and Ling 1998). Overhead costs are the major expenditures, including equipment and maintenance. Waste is minimal and does not adversely impact the environment. However, yields are low, ranging from 0.5 to 1.5 tons per hectare per year (Kautsky et al. 2000). These operations are typically held by local peoples and families.

Intensive shrimp farming in Thailand and commercialization of shrimp farming began in the 1980s with increasing demand for shrimp in Japan fetching prices up to $100 per kilogram

(Bantoon 1994). Shang, Leung, and Ling (1998) reported profits from intensive shrimp farming in Thailand of $28, 212 per hectare per year, compared to $744 per hectare per year for extensive farms. From 1981 to 1994, shrimp production in Thailand rose from 15 thousand metric tons to over 264 thousand metric tons (Kaosa-ard and Pednekar 1998). Land in shrimp farming rose from 3,779 farms on 31,906 ha in 1983 to 21,917 farms on 66,027 ha in 1996. Many intensive farms are owned by foreign investors rather than local peoples and contribute little to local economies. The changes in farm numbers and size characterize the shift from extensive shrimp aquaculture to intensive aquaculture practices.

Intensive farming relies on large inputs of seed, feed, fertilizers, and labor to accelerate growth and productivity. On average, feed costs account for 45.3% of variable costs, followed by seed and power at 13.6% and 7.7% respectively (Shang, Leung, and Ling 1998). Labor is often supplied by migrants and outsiders. Average farm size is 2 ha and average yields range from 7 to 15 ton of shrimp per ha per year, 14 to 100 times the yield of an extensive farm (Kautsky et al. 2000). These operations invest in facilities that oxygenate the ponds and regularly pump water through the system. The high density of shrimp per pond and intensive input of nutrients and other inputs result in intensive farming producing large quantities of polluted wastewater that are released into the local environment. These shrimp farming ponds last four to five years before water quality and disease outbreaks drastically reduce pond productivity (Vandergeest, Flaherty, and Miller 1999). Shrimp farmers abandon ponds and move their facilities to other coastal areas in Southern and Eastern Gulf of Thailand, and most recently across the Andaman Sea (Sathirathai 1998; Vandergeest, Flaherty, and Miller 1999). Because of the nature of these operations to clear large areas of forested lands and quickly move onto the next parcel, shrimp farming has gained the reputation of "slash and burn aquaculture."

Mangroves slowly regenerate, if at all, in shrimp ponds because the high acidity of soils from shrimp aquaculture. Table 4 illustrates the differences in size, expenditures, productivity and profits between intensive and extensive Thailand shrimp farming. Intensive shrimp farming accounts for 85% of farms in Thailand while 10% are semi-intensive (the intermediate of extensive and intensive systems) and 5% are extensive (Shang, Leung, and Ling 1998).

Profits from Shrimp Farming

During the initial expansion of shrimp farming in the 1980s, rice farmers making $500 per hectare per year converted to shrimp farmers making profits of $20,000 -40,000 per hectare per year (Quarto 1994). Today, with greater supply on the world market net incomes range from $744/ha (low) upwards of $36,000/ha (high) in Thailand (Shang, Leung, and Ling 1998; Wyban 2007). Anantanasuwong (2001) found private profit of $2,745.34/ha/yr and Hararika et al. (2000) calculated net income of $10,867.91/ha/yr. However, on average, a shrimp farmer will see profits on the order of $6,235.58/ha (Shang, Leung, and Ling 1998).

Because the social costs of certain environmental externalities are not internalized, intensive shrimp farming overestimates their economic value and is highly profitable. The value of carbon by avoiding deforestation of mangrove forest that could be traded on an international market must be greater than or equal to their current private profits, rather than economic profits, from shrimp aquaculture in order for landowners to change from their current livelihood.

Calculating the Sellable Emissions

The clearing of mangroves to construct shrimp ponds releases large amounts of carbon into the atmosphere including the carbon stored in the standing biomass and the soil carbon. The net avoided emissions (AE) equal the sum of above and belowground carbon stocks released by clearing and oxidizing the mangrove soils for pond and farm construction less the amount of carbon sequestered from shrimp farming. Mangrove standing biomass is cleared directly. In some cases, dykes constructed for the shrimp ponds flood mangroves, killing off remaining biomass.

Using Eq. 2, a conservative estimate of total aboveground biomass per hectare equal to 292.97 mt CO^2e/ha was used (Laffoley and Grimsditch 2009). Over the four year lifetime of a shrimp farming operation, 73.24 mt CO^2e/ha/yr (E_{AB}) would be released on average. Ong (2002) found that the belowground biomass per hectare (E_{BG}) could release 70 t C/ha/yr (256.67 mt CO^2e/ha/yr). The carbon losses from the sediment can be up to 50% over an eight year period (Granek and Ruttenberg 2008). While certain forms of agriculture and forestry may sequester carbon from the atmosphere, intensive shrimp farming requires the input of additional inputs and does not absorb atmospheric carbon dioxide. Therefore, the emissions reduced from sequestration (E_{SQ}) are assumed to be zero.

$$AE = E_{AB} + E_{BG} – E_{SQ}$$

$$AE = \frac{73.4\ \mathrm{mt\ CO^2e}}{\mathrm{ha} * \mathrm{yr}} + \frac{256.6\ \mathrm{mt\ CO^2}}{\mathrm{ha} * \mathrm{yr}} - \frac{0\ \mathrm{mtCO^2}}{\mathrm{ha} * \mathrm{yr}} = \frac{330\ \mathrm{mt\ CO^2e}}{\mathrm{ha} * \mathrm{yr}}$$

For Eq. 3, of the 330 mt CO2e in avoided emissions credits from not converting one hectare of mangrove to shrimp farm, the sellable avoided emissions (AE_S) equals the total net avoided emissions (AE) reduced by a discount buffer factor (ɣ).   The Forestry Carbon Standard discount factor of 30% of total credits was used, although reserve factors can range from 10-60% of total credits.

$$AE_S = (1-\gamma)*AE$$

$$AE_S = (1 - 0.30) * \frac{330\ \mathrm{mt\ CO^2e}}{\mathrm{ha} * \mathrm{yr}} = \frac{231\ \mathrm{mt\ CO^2e}}{\mathrm{ha} * \mathrm{yr}}$$

Therefore, 231 mt CO^2e emissions credits would be eligible for sale on regulatory or voluntary markets as abatement for other parties' emissions. Even with conservative estimates for the above- and below-ground carbon stocks, this value of sellable carbon credits is large compared to other estimates.

The price per ton CO^2e (P_C) that where forest conservation payments equal the net profits from shrimp farming calculated by multiplying profit (π) by the inverse of sellable carbon credits per hectare ($1/AE_S$) (Eq. 4). As seen in Eq. 4, given the calculation that one hectare of mangroves grants 231 carbon credits per year, for a shrimp farmer earning \$744.00/ha, the price per ton of CO^2e would have to equal \$3.22/mt CO^2e.

$$P_C = \pi \left(\frac{1}{AE_S}\right) \qquad \text{(Eq. 4)}$$

$$\boldsymbol{P_C = \frac{\$744}{\text{ha}} * \frac{\text{ha}}{231\ \text{mt}\ \text{CO}^2\text{e}} = \frac{\$3.22}{\text{mt}\ \text{CO}^2\text{e}}}$$

For the average shrimp farmer earning \$6,240.00/ha, a price of \$27.00/mt CO^2e would make forest conservation as profitable as shrimp farming. With a high income of \$36,000/ha, the price per ton of carbon would have to equal \$156.00/ mt CO^2e to compete with shrimp farming.

Conclusions

The current global area of mangrove is less than half of their original total cover. These increasingly threatened tropical coastal ecosystems rival their terrestrial counterparts as highly efficient blue carbon sinks that sequester and store large quantities of carbon in standing stock biomass and in sediments for long periods of time. In terms of long term sequestration in sediments, 1 km^2 of mangrove area results in the equivalent of 10 km^2 of temperate forest or 50 km^2 of tropical forests. Mangrove standing stock can hold 7990 g C/m^2 (293 mt CO^2e/ha) while the sediments can release 70 t C/ha/yr (256.6 mt CO^2e/ha/yr). The clearing of mangroves to other land uses, such as shrimp farming, releases these large amounts of carbon back into the atmosphere. The conversion of one hectare of mangrove in Thailand can release 330 mt CO^2e/ha/yr.

The emergence of carbon markets provides a valuable tool to account for the true carbon value of these blue carbon sinks and create tangible economic incentives for mangrove conservation. Reducing Emissions from Deforestation and Forest Degradation-Plus (REDD+) can provide international payments and assistance for avoiding anthropogenic emissions from deforestation. REDD must compensate land users for the opportunity costs (i.e. lost profits and income).

In Thailand, highly profitable shrimp farming resulted in rapid mangrove deforestation since the 1980s. Profits can range from $744/ha (low) upwards of $36,000/ha (high), with an average income of $6,235.58/ha. Of the 330 mt CO^2e/ha/yr of net avoided emissions, 231 credits are sellable on the carbon market given a 30% reserve buffer factor. Given the calculation that one hectare of mangroves grants 231 carbon credits per year, for a low profit shrimp farmer, the price per ton of CO^2e would have to equal $3.22/mt CO^2e. For the shrimp farmer earning an average profit, a price of $27.00/mt CO^2e would make forest conservation as profitable as shrimp farming. With a high income, the price per ton of carbon would have to equal $156.00/ mt CO^2e to compete with shrimp farming.

Given the prices per ton of carbon in voluntary and regulatory markets currently ranges between $5-23, carbon prices in existing carbon markets can cover the opportunity costs of *marginal* shrimp farmers with the lowest profit margins in Thailand. REDD+ carbon credits and incorporation into existing carbon markets present an opportunity to provide a substantial funding mechanism and tangible incentives for mangrove conservation. However, the high profits of shrimp aquaculture may hinder carbon payments for mangrove given current market conditions. With the prospect of other major greenhouse gas emitting countries, including the

US, entering into regulatory carbon markets, the future carbon markets could see increases in the price per ton of carbon equivalent as a result of increasing demand.

International payments and assistance can be used to overcome financial, technological, or institutional barriers to implementation. However, the design of REDD+ is still highly uncertain. REDD+ policies must ensure that (1) there are true carbon savings that are measureable and verifiable, (2) payments reach the community level, and (3) local communities are not excluded from the forests they depend upon. International capacity building and assistance will be crucial in preparing developing nations for REDD. Only by incorporating avoiding deforestation can mitigation efforts work towards true greenhouse gas reductions.

Carbon markets and economic mechanisms should be used in conjunction with regulation and proper governance to encourage wise resource use decisions. The 5 Policy Recommendations included in this report aim to promote a balance between development and stewardship. REDD+ will be a useful and necessary tool in promoting forest conservation, for mangroves as well as all terrestrial forests.

Co-benefits

The total economic value (TEV) of these ecosystems, not just carbon value, should be considered in land use planning. Nutrient cycling of carbon is only one of the many ecosystem goods and services provided by an intact, preserved mangrove ecosystem. Healthy mangroves provide many additional co-benefits include forestry and fisheries, coastal protection, water quality control and watershed protection, pollutant absorption, sediment retention, and housing biodiversity. The deforestation of mangroves in coastal areas can lead to losses in these goods and services and lead to detrimental effects to the health of the environment and human welfare.

Forestry

Wood products, fisheries and hunted meat, and recreation are examples of direct uses. Local communities have traditionally harvested wood products, fuel wood and charcoal, for subsistence and commercial sale in local markets. While subsistence extraction of these goods from mangroves may lead to minimal negative impacts on the mangrove, growing demand and pressure from increasing populations located close to mangroves has lead to overexploitation of these valuable resources. Sathirathai and Barbier (2001) estimated that local households in Thailand harvest $88/ha/yr. Costanza et al. (1997) found the value of wood production of $162/ha/yr.

Fisheries

Mangroves play a crucial role in the coastal ecosystem as a habitat and nursery for commercial and non-commercial fish and shellfish and nesting habitat for birds (Nagelkerken et al. 2008). Mumby et al (2004) found that mangroves provided intermediate nursery habitat for juvenile fish, including the vulnerable Rainbow parrotfish (*Scarus guacamaia*). Reefs in mangrove-rich systems demonstrated significantly increased biomass compared to mangrove-scarce systems (Mumby et al. 2004). The indirect linkage between mangrove cover and offshore fisheries in Thailand ranged in value from $21-69 per hectare per year (Sathirathai and Barbier 2001). Baran and Hambrey (1998) found that the presence of mangroves may enhance fish, shrimp, and prawn catches an estimated US $66-$3000 per hectare of mangroves. Aburto-Oropeza et al. (2008) found that one hectare of mangrove resulted in $37500 in fish and crab revenue for Gulf of California fisheries. In Florida, 80% of commercial and recreational harvested marine species depend on mangrove estuaries for at least a portion of their lifecycles (Hamilton and Snedaker 1984). The long term health and sustainability of these species depends upon the health and existence of mangrove ecosystems. Intact mangroves can result in external benefits to fishers by lowering the costs of catch and high fish abundances.

Coastal Protection

Following the 2004 tsunamis in the Indian Ocean, coastal protection was recognized as a valuable ecosystem service and international efforts began to reforest coastlines with mangroves. The thick trunks, dense foliage, and intertwined root systems of a healthy mangrove forest act as a buffer to protect coastal communities from the effects of wind, waves, and water currents. These "bioshields" save lives and reduce damages to coastal property. Das and Vincent (2009) found that the death toll would have been three-fold if not for the presence of a healthy mangrove greenbelt during the 1999 cyclone in Orissa, India. Sathirathai and Barbier (2001) estimated the cost of replacing the coastal protection of mangroves with a break wall in Thailand to be $3,679 per hectare per year. Compared to the $88 in wood products and $69 in offshore fisheries, ignoring the value of coastal protection will dramatically underestimate the benefits from mangrove preservation. In Vietnam, $7.3 million per year was saved in dyke maintenance and protected the local villages from Typhoon Wukong in 2000 while neighboring villages suffered loss of lives, property, and livelihoods (Reid and Swiderska 2008).

Watershed Protection

Mangroves protect coral reefs and sea grass beds from siltation minimizing/retaining sediment runoff and reducing coastal erosion. Excess nutrients and contaminants from upland sources increase the chances of eutrophication. In response to increased nutrient availability, plankton and algae communities bloom. During decomposition, increased dissolved oxygen use can result in dead zones for other fauna that rely on higher dissolved oxygen levels and losses to coastal fisheries. Pearl production in Guangxi Province, China experienced heavy economic losses from increased heavy metal contamination (Tam and Wong 1995). In Thailand alone, shrimp farms discharge up to 1.3 billion cubic meters (340 billion gallons) of effluent annually (Owen 2004). A one hectare intensive shrimp farm would need the equivalent of 22 hectares of mangrove to filter the nitrogen and phosphorus runoff from its operations (Robertson and Phillips 1995).

The value of this natural waste disposal service can be estimated by the replacement cost of constructing a waste water treatment facility to perform the same function as the mangrove ecosystem. In Fiji, the annual value of waste disposal cost $5820 per hectare (Lal 1990) and $1193 per hectare in Mexico (Cabrera et al. 1998). Costanza et al. (1997) estimates the annual waste treatment function of mangroves at $6700 per hectare.

Biodiversity

Within the past decades, the preservation of biodiversity has received considerable attention as critical hotspots face destruction. Positioned between the land and sea, mangrove forests provide valuable refuges, spawning and breeding grounds, and feeding grounds to over 1300 permanent and transient animal species (Duke 1992). The Royal Bengal tiger, Proboscis monkey, and Rainbow parrotfish are among more notable endangered megafauna known to inhabit mangrove areas (Macintosh and Ashton 2002). Migratory and wetland birds utilize the upper canopy as temporary flyways and permanent nesting as nesting and roosting perches. Marine crustaceans and mollusks burrow into the soft sediments. As mentioned earlier, 11 species of mangrove will be listed on the IUCN Red List of Threatened Species. These areas are ideal environments for REDD Plus (REDD+), which specifically includes consideration for the biodiversity value of ecosystems.

5 Policy Recommendations for Mangrove Conservation

Government policies in countries with large mangrove forests have either encouraged land use practices that contribute to mangrove deforestation or protected areas only on paper. Carbon payments alone will not eliminate the problems of shrimp farming on mangroves. Systems of governance must institute and enforce wise economic and regulatory policies that are forward-thinking and increasingly progressive in scope. The local, national, and international community must create incentives and promote decisions that shun short term overexploitation and instead favor long term sustainable natural resource management. The following 5 REDD+ Policy Recommendations are actions that can be taken, in addition to international payments for environmental services, to promote development through wise decision-making with the hope of improving mangrove conservation and environmental stewardship.

1. Implement Coastal Zone Management (CMZ)

Coastal Zone Management (CZM) attempts to spatially delineate and manage different types of use within a coastal landscape. It attempts to balance use and non-use in order to maintain the flow of ecosystem goods and services provided by healthy natural ecosystems without alienating local populations and restricting economic development. CZM promotes land use planning by designating commercial use, sustainable harvest, subsistence use, and conservation areas. Regulating certain industries will be easier when commercial users are concentrated. However, monitoring and enforcement require government resources. State and community co-management and support for monitoring and enforcement will help to overcome financial and labor constraints. By appropriating certain areas to different interests, it allows activities to occur in some areas while tightly regulating activities in other areas. Conservation, or protected, zones may allow community (small-scale) harvesting or prohibit use entirely. When designating protected areas in coastal areas, it is important to consider the connectivity of mangroves to other adjacent coastal ecosystems such as coral reefs, and sea grass beds.

2. Encourage sustainable practices

The increasing international and domestic demand for shrimp cannot be met by wild capture fisheries. Aquaculture will have a growing role in meeting these demands. The question is not *if* it is going to happen; rather, it is *how* it is going to happen. Governments should encourage sustainable practices within industry by 1) promoting certification schemes for environmental stewardship and/or 2) removing subsidies from firms utilizing harmful practices and re-distributing them to firms utilizing good practices that promote environmental stewardship.

National and international aquaculture certification schemes have been proposed. On a national level, shrimp farmers comply with the Thai Good Aquaculture Practice (GAP). The Code of Conduct for Responsible Shrimp Aquaculture (CoC) and Bangladesh Shrimp Seal of Quality (SSoQ) are other recognized certification systems. Because of the inconsistencies between different certifications, there has been a push for a more universal, international certification scheme. The leader in international certification development is the Global Partnership for Good Aquaculture Practices (GLOBAL G.A.P.). Practices include farm siting above inter-tidal zones and out of sensitive habitats and treating wastewater effluent.

However, these certifications are voluntary. Farmers are unlikely to adopt practices unless there is evidence that consumers are willing to pay a price premium for certified product over non-certified product. Without this distinction, farmers are burdened with higher costs of production to implement these certification schemes. In addition, small scale operations may not have access to the technical or financial resources to make the necessary investment. Forming cooperatives, or social clubs, between shrimp farmers will open up resources.

If there is no clear advantage to certification, subsidies are also powerful tools for encouraging good land use practices and promoting sustainable activities. Eliminating subsidies to harmful, intensive shrimp farming while providing subsidies to sustainable forestry or poly-culture can shift development towards more sustainable harvesting by rewarding better resource management that does not require cutting mangroves. Investment in research and development for improved technologies of feeds, seed and broodstocks, energy and electrical equipment, and wastewater treatment can eliminate the need to cut down in mangrove ecosystems by substituting inputs that improve efficiency and productivity.

Subsidies distort the true costs and benefits from shrimp farming. Subsidized businesses are profitable because they artificially lower the costs of production. In some cases, farmers would have negative profits from shrimp farming if it were not for receiving government subsidies (Vandergeest, Flaherty, and Miller 2009). The Thai government facilitated the 1980s boom by offering subsidies and tax breaks, low interest loans and assistance, and land concessions or open access resources to spur economic development in shrimp aquaculture (Barbier and Cox 2004). International aid from the World Bank and Asian Development Bank also increased to $910 million from 1988 to 1993 (Primavera 1998).

Shrimp farming in mangrove environments provides a natural subsidy for utilizing highly productive mangrove without paying rents for land use (Naylor et al. 1998). Because these areas require less additional inputs, these businesses have lower production costs and higher profits. In the 1980s, the State would grant land concessions for 63 baht/ha/yr ($4/ha/yr) (Huitric, Folke, and Kautsky 2002). Land prices should capture this natural subsidy because higher productivity land is more valuable than marginal lands.

3. Levy a pigouvian tax that accounts for the social costs of externalities

The short term profits of shrimp farming are accompanied with long term losses to society as more intensive production results in greater potential for environmental degradation. If these environmental damages are not internalized by the firm, then businesses benefit with increased profits because they do not have to compensate for the social costs. Social costs are the opportunity costs of foregone benefits to society from mangrove deforestation. Since shrimp farmers they are not liable for the condition of the abandoned shrimp ponds, they do not pay the social costs, or externalities. A pigouvian tax attempts to correct for an externality by levying a tax on a polluting firm to compensate for the social cost to society.

Alternatively, a user tax for temporary property rights similar to a permit system can be implemented. The mangroves in Thailand are owned by the state and managed by the Royal Department of Forestry. However, due to lack of enforcement and resources, these areas have become de-facto open access areas where users have no incentive to invest in the long term sustainability of the mangrove since they do not own the property and are not liable for the condition it is left in or the associated environmental damages. Rather than promoting a system of full property rights, the Thai government could establish user rights whereby users register and pay a fee to use the lands for a stated purpose. It is important to note that temporary property rights create an incentive for users to return the land to the State after the resources have been exhausted. However, if the fee is set at a high level, then revenues can be used to restore and maintain areas or deter use in the first place.

Since shrimp is predominantly exported and traded on the international market, an export tax could also be used to generate revenue and recycled for conservation measures, including mangrove reforestation. The effect of this export tax is ambiguous in regards to mangrove deforestation. While this does not have the direct effect of avoiding deforestation of mangroves, it could deter the expansion of shrimp farming. However, if mangrove habitat is significantly more productive, operations may shift toward mangroves to lower their costs, resulting in more pressure to mangroves.

4. Require mitigation for clearing mangroves

Setting national and international standards for shrimp farm siting and operations are necessary to solidify environmental protection in the long term. Mangroves are directly cut down for shrimp farming or killed by flooding by pond construction (Walters et al. 2008). There is no policy in Thailand that requires shrimp farmers to contribute to mangrove replanting and restoration (Barbier and Cox 2004). Requiring full mitigation for losses to mangrove area by shrimp farming or other development operations would provide developers the choice whether or not to cut the mangrove and capture the economic social costs of clearing mangroves. They are also indirectly affected by increased effluent from shrimp farming farther inland. Standards that are well enforced and best management practices that are self-promoting that can move the shrimp aquaculture industry closer to sustainability will ultimately improve the circumstances for mangroves.

5. Promote restoration efforts of degraded mangrove ecosystems

Afforestation and reforestation of previous mangrove areas should not be forsaken with the creation of REDD+. Following the hurricanes/tsunamis that devastated the South China Sea nearly two decades ago, efforts to reforest coastal zones began with hundreds of millions of mangrove seedlings planted over thousands of hectares (Malakoff 2008). In the Philippines, over 44,000 hectares of mangroves were planted. However, seedlings were planted in mudflats, sand flats, and sea grass meadows and actually altered existing healthy habitats (Lewis 2004). Instead, the 230,000 hectares of area that are previously mangrove forest should have priority for reforestation. Biologists Maricar Samson and Rene Rollon report that surveys of more than 70 restoration sites often found mostly dead, dying, or "dismally stunted" trees. The high mortality of seedlings was caused by planting seedlings in sub-optimal environments. Lack of nutrients for growth and high wave and wind energy are common reasons for failure of seedlings to settle and develop. Appropriate hydrologic regime is the necessary foundation to re-establish mangroves (Brockmeyer et al. 1997; Lewis 2004). Roy "Robin" Lewis III of Lewis Environmental Services, a private restoration firm in Florida, has shown that mangrove restorers around the globe routinely fail to understand the tree's biology and conflicts with landowners and political leaders can doom projects (Malakoff 2008). Low survivorship can result from selecting the inappropriate species or site for reforesting. Rhizophora seedlings are easier to handle and plant, but are not natural colonizing mangrove species.

Curbing deforestation may be more effective than reforestation for mangrove conservation because it is difficult to re-establish mangroves. Reforestation can be a very expensive process. The major expenses of wetland restoration projects, apart from land acquisition costs, are the degree of earthwork (moving soils to create hydrologic conditions) and the price of labor. For eight mangrove reforestation projects in Miami, Florida costs ranged from $5,300 to over $200,000 per hectare, with a mean of about $99,000 per hectare (Milano 1999). Without major excavation, hydrologic restoration costs can be as little as $250 per hectare, as shown in the Indian River Lagoon, Florida (Brockmeyer et al. 1997). The restoration costs of abandoned shrimp ponds in Thailand estimated at $13,750 per hectare (Sathirathai 1998).One effort included planting 440 million Rhizophora propogules at a density of 1 seedling per square meter (Samson and Rollon 2008). The effort cost $17.6 million at $400 per hectare. Sanyal (1998) recently reported 1.52 percent survival rates of mangroves planted in West Bengal, India; however, in general, expected survival rates will be around 50% of seedlings (Lewis 2004). Mangrove forest can naturally self-repair in 15-30 years with a normal tidal hydrology and seed bank or source from adjacent stands (Lewis 2004; Cintron-Molero 1992).

Deforestation is a quick release of carbon into the atmosphere while reforestation is a slower process of absorption and conversion to standing biomass over time. Ultimately, local community involvement and support may be the key to long term success of mangrove replanting efforts. It is important to both reduce deforestation and increase reforestation and afforestation globally to make significant steps in reducing overall carbon emissions.

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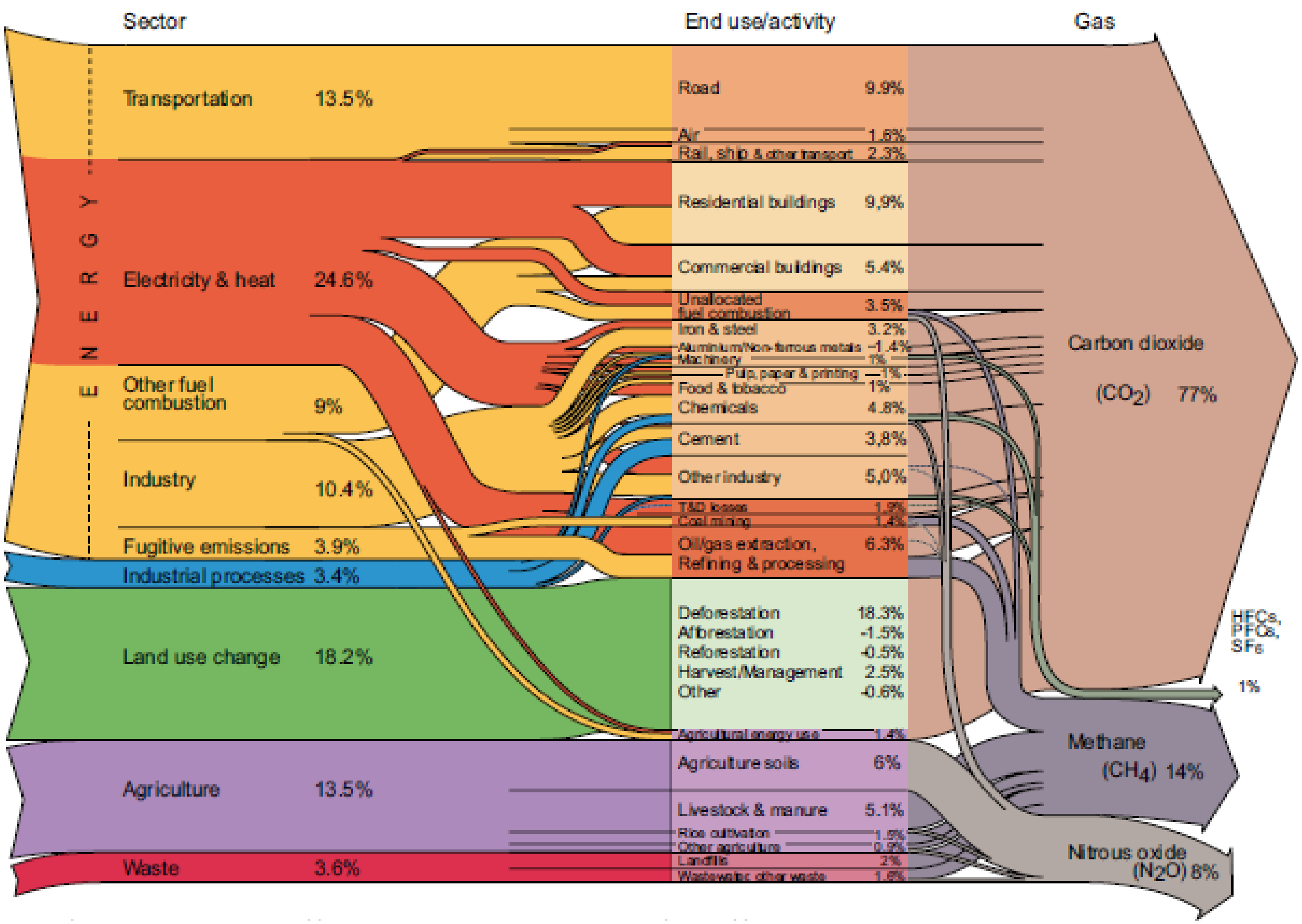
Appendix: List of Figures and Tables

Figure 1. World Greenhouse Gas Emissions (by Sector)



Source: World Resources Institute, Climate Analysis Indicator Tool; Navigating the Numbers: greenhouse Gas Data and International Climate Policy, December 2005; Intergovernmental Panel on Climate Change, 1996

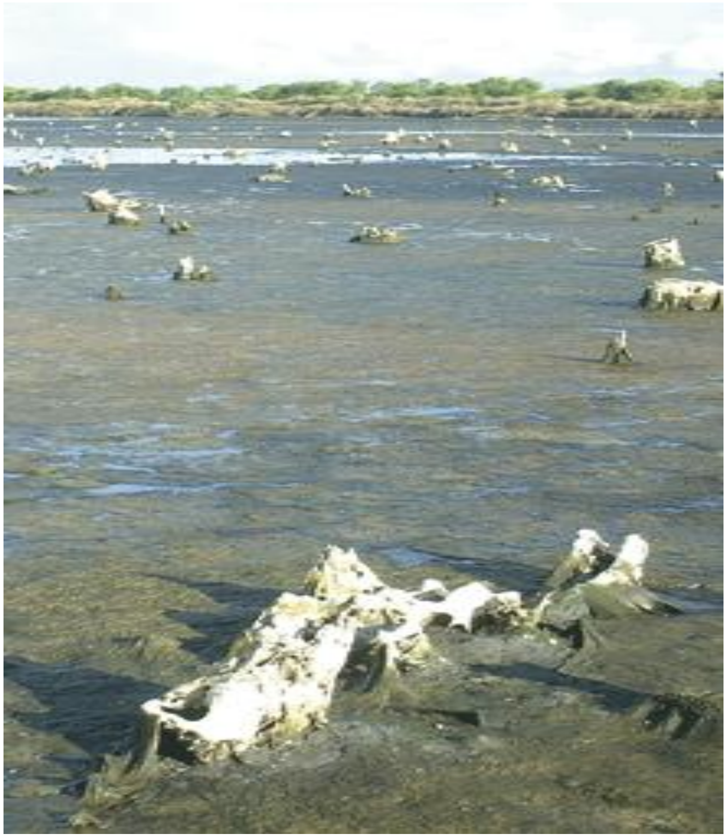
Figure 2. Photographs of Complex Root Systems of Mangroves

Source: Mangrove Action Project; Octavio Aburto

Figure 3. Map of the Global Distribution of Mangroves, including Top 5 Country Percentages of Total Global Cover

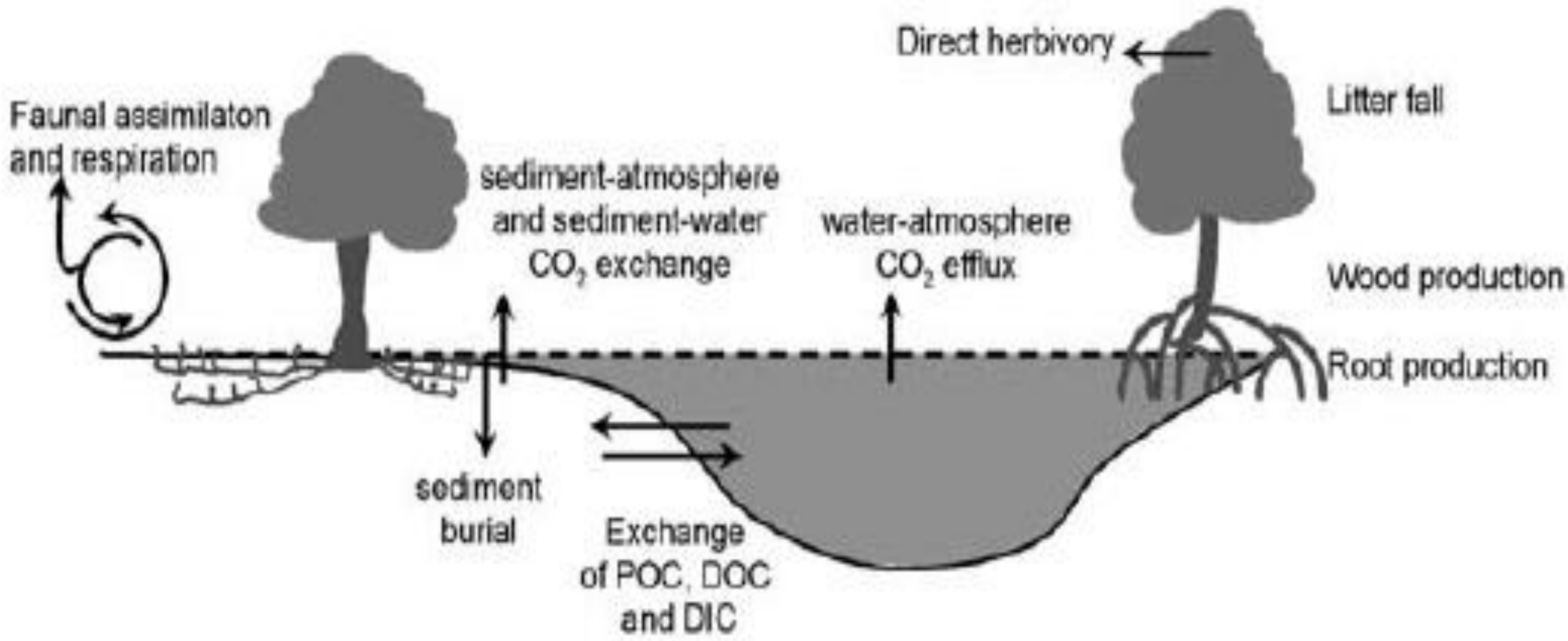
Source: UN Environment Programme, WCMC 2009, FAO 2007, and Valiela et al. 2001

Figure 4. Photographs of Cleared (Top) and Logged (Bottom) Mangroves from Shrimp Farming



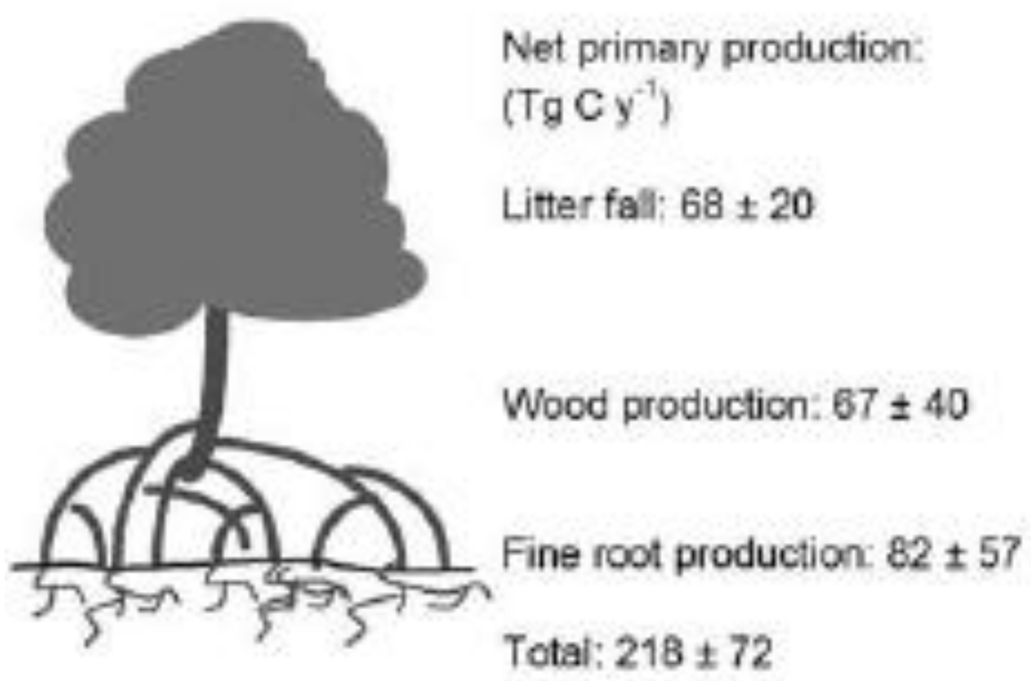
Source: Nellemann et al. 2009; JH Primavera

Figure 5. Diagram of Carbon Cycling and Storage in a Mangrove Ecosystem



Source: Bouillon et al. 2008

Figure 6. Vertical Distribution of Net Primary Production (NPP) within a Mangrove



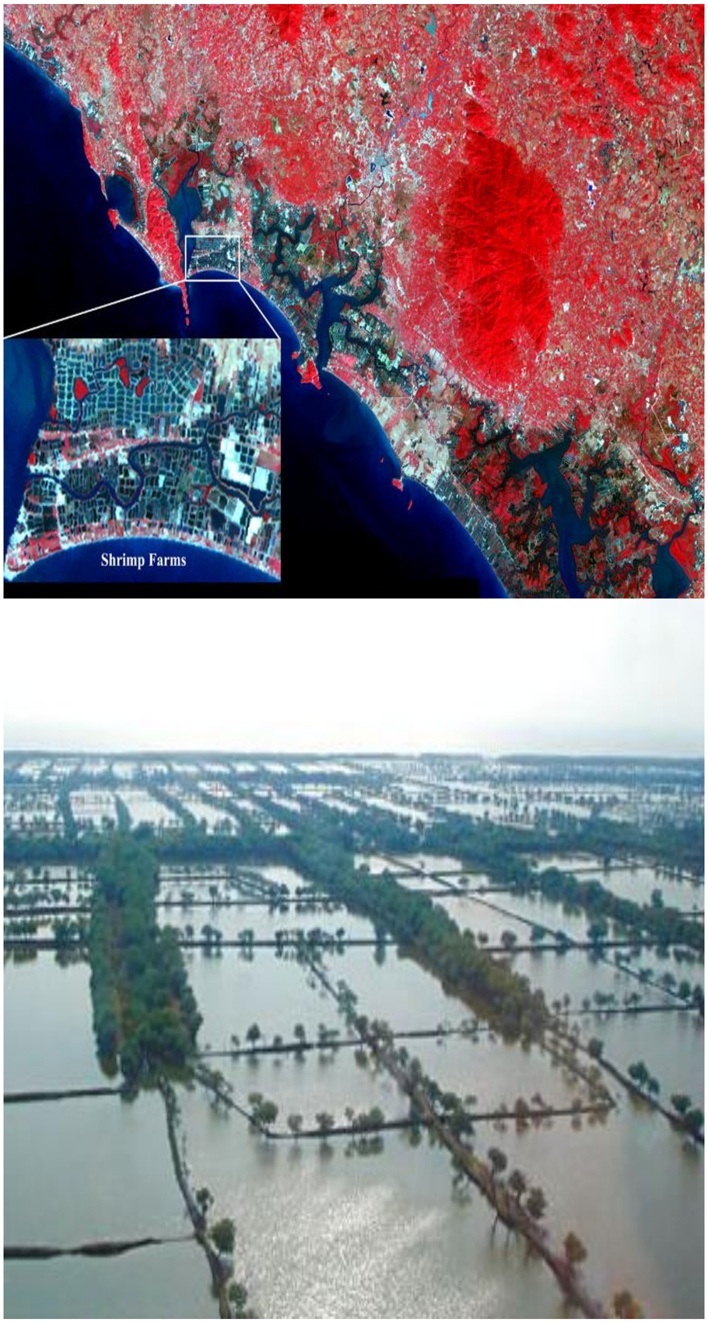
Litter fall: ~31% NPP

Above-ground Wood Production: ~38% NPP

Below-ground Wood Production: ~38% NPP

Source: Bouillon et al. 2008

Figure 7. Satellite and Aerial Photographs of Intensive Shrimp Farming



Source: http://www.isprs.org/proceedings/XXXIII/congress/part7/504_XXXIII-part7.pdf

Table 1. Mangrove Species Additions and Noted "Vulnerable" Species to IUCN Red List of Threatened Species in June 2010

Species	Status		Countries of Occurrence
Bruguiera hainesii	Critically Endangered	CR	Indonesia, Malaysia, Papua New Guinea, Singapore
Sonneratia griffithii	Critically Endangered	CR	Indonesia, Malaysia, Bangladesh, India, Thailand, Myanmar
Camptostemon philippinens	Endangered	EN	Indonesia, Malaysia, Philippines
Heritiera globosa	Endangered	EN	Indonesia, Malaysia
Heritiera fomes	Endangered	EN	Malaysia, Bangladesh, India, Thailand, Myanmar
Rhizophora samoensis	Near Threatened	NT	Ecuador, Costa Rica, Panama, Colombia, Nicaragua, El Salvador, Guatemala, Honduras, Mexico, American Samoa, Fiji, New Caledonia, Samoa, Tonga, Peru
Aegiceras floridum	Near Threatened	NT	Indonesia, Malaysia, Philippines, Vietnam
Brownlowia tersa	Near Threatened	NT	Indonesia, Malaysia, Philippines, Brunei Darussalam, Cambodia, Singapore, Bangladesh, India, Thailand, Myanmar
Ceriops decandra	Near Threatened	NT	Malaysia, Bangladesh, India, Thailand, Myanmar
Phoenix paludosa	Near Threatened	NT	Malaysia, Vietnam, Bangladesh, India, Thailand
Pelliciera rhizophorae	Vulnerable	VU	Ecuador, Costa Rica, Panama, Colombia, Nicaragua
Avicennia rumphiana	Vulnerable	VU	Indonesia, Malaysia, Philippines
Avicennia bicolor	Vulnerable	VU	Costa Rica, Panama, Colombia, Nicaragua, El Salvador, Guatemala, Honduras, Mexico
Tabebuia palustris	Vulnerable	VU	Costa Rica, Panama, Colombia
Avicennia integra	Vulnerable	VU	Australia
Avicennia rumphiana	Vulnerable	VU	Papua New Guinea

Source: International Union for the Conservation of Nature (IUCN)

Table 2. Mangrove Ecosystem Goods and Services and Associated Values Estimates (Source)

Co-benefit	**Value Estimates**
Forestry/Wood Products	$88/ha/yr in Thailand (Sathirathai and Barbier 2001) $162/ha/yr (Costanza et al. 1997)
Fisheries	$21-69/ha/yr in Thailand (Sathirathai and Barbier 2001) $37,500/ha in Gulf of CA (Aburto-Oropezaet al. 2008)
Storm Protection	$3,679/ha/yr in Thailand (Sathirathai and Barbier 2001) $7.3 million/yr in Vietnam (Reid and Swiderska 2008)
Watershed Protection (Water Quality)	$1,193/ha in Mexico (Cabrera et al. 1998) $5,820/ha in Fiji (Lal 1990) $6,700/ha (Costanza et al. 1997)
Biodiversity	
Coastal Stabilization	
Sediment and Pollutant Retention	
Aesthetics, Ecotourism, Cultural and Spiritual Value	$658/ha/yr (recreation) (Costanza et al. 1997)

Table 3. Comparison of Carbon Stocks and Accumulation of Carbon in Soils in Terrestrial and Coastal Ecosystems

Ecosystem type	Standing Carbon Stock (g C/m^2) Plants	Soil	Total Global Area (*10^{12} m^2)	Global Stocks (*10^{15} g C) Plants	Soil	Soil Carbon Accumulation Rate (g C/m^2/yr)
Tropical forests	12045	12273	17.6	212	216	2.3-2.5
Temperate forests	5673	9615	10.4	59	100	1.4-12.0
Boreal forests	6423	34380	13.7	88	471	0.8-2.2
Tropical savanna and grassland	2933	11733	22.5	66	264	
Temperate grassland and shrublands	720	23600	12.5	9	295	2.2
Deserts	176	4198	45.5	8	191	0.8
Tundra	632	12737	9.5	6	121	0.2-5.7
Croplands	188	8000	16.0	3	128	
Wetlands	4286	72857	3.5	15	225	20
Tidal Salt Marshes			Unknown (0.22)			210
Mangroves	**7990**		**0.152**	**1.2**		**139**
Seagrasses	184	7000	0.3	0.06	2.1	83
Kelp forests	120-720	na	0.02-0.4	0.009-0.02	na	na

Source: Laffoley, D.d'A. and Grimsditch, G. (eds). 2009.

Table 4. Comparison between Intensive and Extensive Shrimp Farming

	Extensive	Intensive
Size (ha)	12.2	2
Ownership	Local peoples and families	Foreign Investors
Major Expenditure	Overhead costs (equipment and maintenance)	Input intensive: Seed, feed, fertilizers, labor
Productivity (tons/ha/yr)	0.5-1.5	7-15
Profits ($/ha/yr)	$744	$36,000
Environmental Impact (apart from mangrove clearing)	Minimal impact	Decreased water quality (disease, pollutants) Acidic soils in abandoned farms

Table5. Results of Price per Metric Ton of CO^{2}e from Shrimp Farming in Thailand and Comparison with Current Prices in Carbon Markets

Profit ($/ha)	**Farmer Status**	**Price per mt CO^{2}e**	**Can current carbon markets meet the price per ton CO^{2}e/ha to promote forest conservation?**
$744	Marginal	$3.22/mt CO^{2}e	Yes, voluntary and compliance
$6,235.58	Average	$27.00/mt CO^{2}e	No, current compliance upper bound is $23.00/mt CO^{2}e
$36,000	High	$156.00/mt CO^{2}e	No