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Land Use, Land-Use Change, and Forestry Offsets

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RESOURCES FOR THE FUTURE

Contents

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I. Introduction

According to the U.N. Framework Convention on Climate Change, land use, land-use change, and forestry (LULUCF) is a designation encompassing a broad range of activities including agricultural and forest land management, agricultural land conversion, afforestation, reforestation, and avoided deforestation. Emissions associated with LULUCF make up the second-largest source of carbon dioxide (CO_2) emissions, after fossil fuel combustion. Within LULUCF, tropical deforestation—due mainly to the conversion of forests to agricultural uses—is the main source of CO_2 emissions, accounting for around 10–15 percent of global CO_2 emissions (van der Werf et al. 2009; Harris et al. 2012). Reducing emissions from LULUCF activities is considered relatively inexpensive. The prospect of large and inexpensive reductions potentially available in the near term has caused LULUCF activities to become a central topic in climate policy.

Although the potential of LULUCF activities is enticing, constraints—technical, political and financial in nature—have limited emissions reductions thus far. Importantly, the monitoring and verification of emissions associated with LULUCF activities is a significant impediment to further reductions. Issues associated with the concepts of additionality, leakage, and permanence are also critical barriers.

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This backgrounder is one in a series prepared for the project "Planning for the Ex Post Analysis of U.S. Climate Policy" to inform discussions and assessments of U.S. climate policy. The backgrounders summarize research on the following topics: (i) competitiveness impacts of climate policy; (ii) climate policy, international trade, and emissions leakage; (iii) Kyoto flexibility mechanisms: the Clean Development Mechanism and joint implementation; (iv) land use, land-use change, and forestry; (v) EU Emissions Trading System, and (vi) the U.S. Environmental Protection Agency's Acid Rain Program. Taken together, these backgrounders summarize research on several key aspects of climate policy. In addition to helping inform discussions and assessments of climate policy, the backgrounders are intended to provide informative overviews of each topic to anybody interested in conducting or better understanding climate policy assessment, including researchers, students, and experts in academia, government, nongovernmental organizations, and industry. Funding for this project has been provided by the Alfred P. Sloan Foundation. The authors thank Daniel Morris for comments and suggestions on this backgrounder.

This backgrounder overviews LULUCF research, including analyses of from reduced emissions from deforestation and degradation (REDD) emissions offset projects. Our focus is on highlighting current research findings and discussing data needs and availability.

II. Research on LULUCF Offsets

Research on LULUCF offsets focuses on estimating the potential of certain offset types—including estimates of total reductions and economic costs—and on analyzing the challenges facing LULUCF offsets, especially additionality and leakage. Table 1 summarizes the data, methodologies, and results of studies that estimate the potential of LULUCF offsets.

A. Estimates of LULUCF Offset Potential

1. Afforestation and Reforestation

Currently, among LULUCF activities, the UNFCCC qualifies only afforestation and reforestation (AR) activities as eligible for Kyoto compliance. Afforestation occurs when trees are planted in lands that were not previously forested, whereas reforestation occurs when trees are planted on formerly forested land. Emissions from these activities are more easily verified and monitored relative to other LULUCF activities, such as reduced deforestation.

Many studies have estimated the potential land area that could be converted from agricultural or developed uses to forest cover. Trexler and Haugen (1995) estimate carbon sequestration potential in the tropics, and Nilsson and Schopfhauser (1995) estimate global afforestation potential. Together, these studies project that approximately 700 million hectares (Mha) of land are potentially available for AR. Zomer et al. (2008) calculate that, globally, 750 Mha of land may be suitable for AR under constraints dictated by the UNFCCC.

In addition to estimating available land, Benítez et al. (2007) estimate the cost and sequestration potential of AR. The authors estimate that between 2,600 and 3,500 Mha of land are suitable for AR. Assuming a carbon price of $50, the authors find that about 7 to 10 billion tons of carbon could be sequestered by AR offsets over 20 years. However, this sequestration estimate drops by up to 59 percent when the investment risks of candidate AR countries are taken into account. Regardless of this constraint, the authors conclude that AR can still play a "relevant role in global warming mitigation" (Benítez et al. 2006, 580).

Stavins (1999) uses panel data from Louisiana, Arkansas, and Mississippi for 1935–1984 to econometrically estimate the potential offset supply. At a carbon price of $66, the author finds additional sequestration of about 7 million tons in this region.

2. Reduced Emissions from Deforestation and Degradation Offsets

The Kyoto Protocol does not accept REDD emissions offset projects, which generate credits by avoiding emissions from deforestation and degradation. Although the exclusion of avoided emissions has several justifications, it is also controversial for several reasons. First, emissions from deforestation are estimated to account for a large portion (about 10–15 percent) of anthropogenic greenhouse gas (GHG) emissions (van der Werf et al. 2009; Harris et al. 2012). By disallowing REDD offsets, the Kyoto Protocol delays action in addressing a central source of carbon emissions. Second, many developing countries—where deforestation has continued, largely unabated—could potentially receive substantial economic and environmental benefits from selling REDD offsets. Third, developed countries incur Kyoto compliance costs that are higher than they would be if avoided deforestation were allowed.

As an indication of increased emphasis on REDD offsets, recent climate proposals introduced in the United States—including H.R. 2454, the American Clean Energy and Security Act of 2009—have allowed for a potentially substantial amount of emissions reductions (up to 1 billion tons of CO_2 annually) to be achieved through avoided deforestation. If future legislation commits the United States to purchasing carbon offsets, currently approved Clean Development Mechanism (CDM) measures may not be capable of satisfying demand unless offset credits were expanded to include other measures, such as REDD. Even without the United States, a resolution at UNFCCC's 13th Conference of the Parties in 2007 signals international momentum toward the inclusion of REDD offsets. The resolution was to consider "policy approaches and positive incentive on issues relating to reducing emissions from deforestation and forest degradation in developing countries" (UNFCCC 2007, 3).

Several studies have estimated the costs, carbon sequestered, and potential land affected by a REDD offset market. These estimations typically use computational modeling approaches that require significant amounts of high-quality data; at times, such data are unavailable. Table 3 reproduces a table prepared by Macauley et al. (2009) that displays a summarization of current forestry models and highlights the data requirements for each model. These models have been used to estimate global and country-specific forest carbon sequestration supplies.

Table 3. Current Forestry Models and Data Requirements (Macauley et al. 2009)

Model	What does the model do?	Data needs	Regional detail
GTM/TSM (Sedjo and Lyon 1989; Sohngen et al. 1999)	Dynamic optimization model used to project forest land use, timber harvests, and biomass stock for the globe	Forest area and age class Forest yield functions Forest inventory	Globe divided into around 250 ecosystem types, which are aggregated into 16 geographical regions
CINTRAFOR (Kallio et al. 1987; Perez-Garcia and Lippke 1992; Perez-Garcia et al. 2002)	Projects timber harvests for the globe	Forest yield and inventory (stock)	Globe divided into 43 log-producing regions and 33 log-consuming regions 400 bilateral trade flows monitored
IIASA/DIMA/ G4M/GLOBIOM (Gusti et al. 2008)	Projects global land use in forests and agriculture (including biofuel crops)	Land use, forest inventory (stock), and forest productivity (e.g., NPP)	Gridded spatial resolution, so includes all regions of the world
GFPM (Buongiorno et al. 2003)	• Equilibrium model of market output, prices, and trade in timber products	Forest area, harvest, inventory (stock) Forest prices and trade	180 countries
GTAP (Hertel 1997; Hertel et al. 2009b)	• General equilibrium model of market output, prices, and trade in all products, including forestry and agricultural products	Forest area, harvest, inventory (stock) Forest prices and trade data	>150 countries, but users can specify the level of aggregation
GTEM (Ahammadand Mi 2005; see also ABARE n.d.)	• General equilibrium model of market output, prices, and trade in all products, including forestry and agricultural products	Forest area, harvest, inventory (stock) Forest prices and trade data	User-specified, but could be more than 150 countries

Notes: ABARE, Australian Bureau of Agricultural and Resource Economics; CINTRAFOR, Center for International Trade in Forest Product; DIMA, Dynamic Integrated Model of Forestry and Alternative Land Use; G4M, Global Forestry Model; GFPM, Global Forest Products Model; GTAP, Global Trade Analysis Project; GTEM, Global Trade and Environment Model; GTM, Global Timber Model; IIASA, International Institute for Applied Systems Analysis; TSM, Timber Supply Model.

On a global level, Sohngen and Mendelsohn (2003) estimate that between 416 and 963 Mha of land could enroll in a forest carbon offset market. This market would yield cumulative carbon sequestration of between 39 and 102 billion tons of CO_2 by 2100, for a carbon price between about \$60 and \$190. The majority (80 percent) of sequestration results primarily from REDD but also from afforestation.

Kindermann et al. (2008) use the three main computational models of global forest use to estimate the REDD carbon offset market over 25 years.[1] The authors estimate that, during 2005 and 2030, a carbon price of $20 would sequester about 2 to 4 billion tons of CO_2 annually. At a carbon price of $100, about 3 to 5 billion tons of CO_2 would be sequestered annually. Recently, Sohngen (2009) analyzed the potential costs of achieving reductions in deforestation using a global forestry model (detailed in Sohngen and Mendelsohn [2003] and Sohngen and Sedjo [2006]). The study finds that sequestration in the European Union and the United States is more expensive than in the tropics and that the magnitude of potential sequestration in the tropics is much larger. At a carbon price of $27, up to about 5 billion tons of CO_2 can be annually sequestered in the tropics, whereas, for the same cost, only about 0.5 to 2 billion tons of CO_2 can be sequestered annually in developed countries. The payments from carbon offsets correspond to about $600 per hectare annually in South America and about $500 per hectare annually in Central America and South Africa. This estimated rental value is much higher than that of Seo and Mendelsohn (2007), who estimate the rental rate of Latin American land at $1 to $130 per hectare per year.

3. Agricultural Offsets

As with forested land, undisturbed agricultural land will sequester carbon. Neither the Kyoto Protocol nor the E.U. Emissions Trading System currently accepts credits generated by offsets that sequester carbon on agricultural lands. However, agricultural offsets could be particularly attractive because they can originate in developing as well as developed countries, whereas forest carbon offsets primarily originate in developing countries. For example, including agricultural offsets from the United States can be potentially useful in negotiating the passage of a domestic or international climate framework that includes the United States. To date, no country has yet made a significant push to include agricultural offsets in the international offset market. Nevertheless, some studies have attempted to quantify the potential of such a market.

Experience with U.S. programs, especially the Conservation Reserve Program (CRP), suggests that agricultural conservation programs can generate significant environmental benefits. CRP and the Wetlands Reserve Program work by paying farmers an annual rent to retire

[1] The three models are: the Dynamic Integrated Model of Forestry and Alternative Land Use, the Generalized Comprehensive Mitigation Assessment Process Model, and the Global Timber Model.

unproductive farmland and wetlands from production.[2] CRP is the largest federally funded conservation program in the United States (Ferris and Siikamäki 2009). As of 2009, CRP had enrolled over 30 million acres of land and had paid out nearly $2 billion annually. Although originally designed as a tool to combat soil erosion, the U.S. Department of Agriculture (USDA) Farm Service Agency estimates that 47 million metric tons of CO_2 are sequestered annually on CRP lands (USDA 2009). However, CRP is not without controversy. The permanence of environmental benefits has eroded as crop prices have increased and CRP lands get converted back to crop production. Leakage is also potentially prevalent in CRP. For example, Wu (2000) estimates that nearly 20 percent of enrolled land could be undermined by leakage—which Wu (2000) terms *slippage*—to other temporarily nonenrolled lands. Nonadditionality is also a concern as it is unknown whether the marginal croplands enrolled in CRP would have been farmed if farmers were not paid to retire them.

Researchers have estimated the total supply of agricultural offsets. Lee et al. (2005) estimate the potential for carbon sequestration on agricultural and timber lands in the United States, over a 100-year simulation and assuming a carbon price ranging from $0 to $50. The authors estimate an annual sequestration for agricultural offsets of 139 to 194 million tons of CO_2. Freibauer et al. (2004) estimate that the potential for economically viable agricultural carbon sequestration in Europe for the first Kyoto commitment period (2008–2012) is between 59 and 70 million tons of CO_2 per year—one-fifth of the theoretical sequestration potential of these lands and approximately 2 percent of Kyoto-mandated reductions for this period. Globally, the *Third Assessment Report of the Intergovernmental Panel on Climate Change* estimates global agricultural sequestration potential to be between 1.3 and 2.8 billion tons of CO_2 annually by 2020.

4. Conclusion

The studies reviewed above suggest that the potential for LULUCF projects to contribute to the global offset market is substantial. However, significant barriers block reductions from LULUCF from scaling up. The following section discusses these barriers.

[2] For more information about CRP and the Wetlands Reserve Program, see Ferris and Siikamaki (2009).

Table 1. Studies Estimating Land Use, Land-Use Change, and Forestry Offsets

Study	Region	Offset class	Data source	Results
Stavins (1999)	Arkansas, Louisiana, and Mississippi	AR	USDA Forest Service; U.S. Department of Energy; panel data for 36 counties in Arkansas, Louisiana, and Mississippi from 1935 to 1984.	At a carbon price of $66, annual sequestration increases 7 million tons from baseline.
Van Kooten et al. (2004)	Global	REDD, AR, plantations, and agroforestry	981 cost observations from 55 studies that provided estimates of the costs of carbon sequestration through forestry projects.	Costs per ton of CO_2 sequestered through REDD is about $13 to $71. Tree planting and agroforestry increases costs by more than 200%. When accounting for carbon in wood products or substitution of biomass for fossil fuels in energy production, costs are lowest when one takes into account (a) postharvest storage of carbon in wood products or (b) the substitution of biomass for fossil fuels in energy production. In such estimates, costs are roughly $3 to $19 per ton of CO_2 sequestered.
Kindermann et. al (2008)	Global	REDD	A variety of government sources and publications. For a full list of sources please see Kindermann et al. (2008)	For a carbon price of $20 and $100, about 2–4 billion tons and about 3–5 billion tons of carbon, respectively, are stored annually during 2005–2030.
Sohngen et al. (1999); Sohngen and Mendelsohn (2003)	Global	AR, REDD	Sohngen et al. (1999), using the Dynamic Integrated model of Climate and the Economy (Nordhaus and Boyer).	By 2100, about 420 to 960 Mha of forest land will participate. These forests will sequester around 1–4 billion tons of carbon annually, for a carbon price of about $16 to $510.

Benítez et al. (2007)	Global	AR	International Geosphere Biosphere Project, University of Maryland, Global Land Cover 2000, Moderate-Resolution Imaging Spectroradiometer, World Bank, Erb et. al. (1996), International Country Risk Guide.	Assuming a carbon price of $50-, the authors find that around 6 to 10 billion tons of carbon is sequestered over 20 years. When country-specific risks are accounted for, this estimate drops by up to 59%.
Sohngen (2009)	Global	REDD	Sohngen and Mendelsohn (2003); Sohngen and Sedjo (2006).	At a carbon price of $27, the tropics and developed countries annually sequester up to about 5 billion tons of carbon and up to about 2 billion tons of carbon, respectively.

B. Barriers to Realizing the Potential of Land Use, Land-Use Change, and Forestry Offsets

The decision to exclude many types of LULUCF activities and their potential offset provisions as CDM-eligible offset projects seems motivated by four concerns over GHG accounting: measurability, additionality, emissions leakage, and permanence. Rewarding LULUCF offset credits requires the ability to measure changes in forest area and carbon content. In addition, it requires the establishment of a baseline level of deforestation, from which credits are rewarded. Only activities that provide reductions below the baseline level of deforestation—and that therefore represent additional reductions—should be awarded. Moreover, rewarding LULUCF offsets requires verification that emissions reductions do not induce emissions increases in neighboring areas; that is, that the emissions reductions do not leak. Lastly, forest areas that are rewarded LULUCF offsets cannot be deforested later; forestation must be permanent. Shortcomings in technologies to monitor, report, and verify these four aspects of GHG accounting have prevented a LULUCF offset market.

1. Measuring Deforestation and Carbon Sequestration

LULUCF offsets necessitate accurate and continuous monitoring of forest cover and sequestered carbon. These assessments are necessary to provide a baseline measure for the level of deforestation and degradation, and to ensure that forests enrolled are not surreptitiously cleared. Fortunately, recent advances in satellite and remote-sensing technologies allow verifiable and accurate assessments of global forest stocks (DeFries et al. 2006). However, these technologies require a level of expertise and implementation costs that can be prohibitive (Johns and Schlamadinger 2009). Without support from developed nations, developing countries have little capacity to access or analyze high-resolution forest cover data as a part of a LULUCF offset program. Consequently, "carbon stock estimates of forests undergoing deforestation and the subsequent carbon dynamics are uncertain for many developing countries" (DeFries et al. 2006, 3).

Olander et al. (2008) review data needs and availability for constructing baseline emissions levels for deforestation and degradation. The authors assess the effectiveness of one database and three satellites in measuring changes in deforestation and degradation. They find that a longstanding database—the Food and Agriculture Organization of the United Nation's database of global forest cover and deforestation (FAO 2010)—is not detailed enough to inform modern simulations of REDD baselines. However, the authors find promise in the Japanese Advanced Land Observing Satellite, which provides yearly forest coverage data at very high resolutions and, because it is radar-based, can detect changes through forest cover. Two additional technologies are less promising: modern imagery from Landsat and the Advanced Very High Resolution Radiometer provide daily and hourly forest coverage, but at a comparatively coarse resolution, with data obscured by cloud cover.

Studies often come to differing conclusions about the carbon content of the exact same location. For instance, even in a relatively small nation, such as Costa Rica,[3] researchers cannot agree whether deforestation is rising, declining, or staying the same. Employing differing satellite data alone may result in widely differing results: estimates of deforestation in Costa Rica using data from the MODIS satellite are 87 to 94 percent lower than those relying on the Landsat satellite (Waggoner 2009).

Although remote-sensing technologies can detect forest cover, they cannot be used to directly estimate the forest carbon content of forests. Rather, carbon content of forests is calculated based on biomass and forest volume estimates (Macauley et al. 2009). Currently, researchers classify forest cover into broad categories of forest type because these estimates are not available for all forests. This aggregation produces inherent uncertainty in forest model estimates that cannot be overcome using current research tools (Olander et al. 2008). Moreover,

[3] Costa Rica encompasses only 5 Mha of land.

uncertainties in parameters for the forest cover, biomass, and carbon content of forests can be extreme and can be compounded because they are multiplied together (Waggoner 2009). Given all of these uncertainties, researchers can generate significantly different forest carbon estimates for the same location.

2. Emissions Leakage

Forest carbon leakage occurs when the conservation of forests in one area results in increased harvests or land conversion elsewhere. By shifting, and not altogether avoiding, activities that reduce forest carbon storage, forest conservation results in diminished carbon benefits. Table 2 summarizes studies on leakage.

In general, leakage occurs when conservation efforts are not universally adopted, allowing timber production to "leak" out of regulated areas into unregulated regions. For example, Wear and Murray (2004) show that policy-induced land-use shifts in one location are highly likely to cause a land-use change in other locations, unless specifically prohibited by policy. Current REDD policies attempt to address leakage issues by proposing country-level, rather than project-level, deforestation targets (Murray 2009). Although this policy reduces leakage within a country, the interconnectedness of the global timber market means that intercountry leakage can also easily occur. Researchers have estimated leakage rates for REDD offset programs, sometimes informing estimates with previous conservation efforts. Table 2 summarizes current studies analyzing leakage from forest carbon initiatives.[4] The existing studies have focused primarily on country-level estimates of leakage. Estimates of leakage rates range from slightly negative—meaning that no leakage is occurring—to up to 92 percent. The former estimate indicates that essentially all reductions from the offset are eroded by increases in unregulated regions. Overall, leakage rates seem significantly lower under afforestation projects than they are under reforestation projects. Among these studies, a chief finding is that policies that are less geographically inclusive tend to result in more emissions leakage. In addition, the following three conditions tend to amplify estimates of leakage rates: (a) when the demand for timber is relatively inelastic; (b) when unregulated regions have higher carbon concentrations per unit output than do regulated regions; and (c) when regulated regions constitute only a small share of the world market (Murray 2009).

[4] Adapted from Sathaye and Androsko (2007) and Murray (2009).

Table 2. Issues Challenging Land-Use Land-Use-Change and Forestry Offsets: Emissions Leakage

Study	Region	Activity	Estimation method	Leakage rate
Ravidrathanath et al. (2006)	Kolar district, Karnataka, India (hypothetical)	Afforestation of degraded lands	Household wood demand survey	About 0%
De Jong et al. (2007)	Scolel Té project, Chiapas, Mexico	Afforestation on small landowner parcels	Household wood demand survey	0% (some positive leakage)
Hooda et al. (2007)	Betalghat, Uttaranchal, India (hypothetical)	Afforestation	Household wood demand survey	10% from fuel wood, fodder; 20% from fuel wood, poles about
Sedjo and Sohngen (2000)	Global	Afforestation (plantation establishment)	Partial equilibrium model	0%–16%
Murray et al. (2004)	United States	Avoided deforestation and logging set aside on private lands	Ex ante partial equilibrium model	Northeast USA: 41%–43%; Pacific Northwest: 8%–9%; Pacific Northwest: 16%; South: 64%; rest of USA: 0%–92%
U.S. Environmental Protection Agency (2005)	United States	Afforestation and forest management	Partial equilibrium model	Afforestation only: 24%; afforestation and forest management jointly: about –3%
Sohngen and Brown (2004)	Bolivia, Noel Kempff project and national	Avoided deforestation	Ex ante partial equilibrium model	Undiscounted: 5%–42%; discounted: 2%–38%
Wear and Murray (2004)	Pacific Northwest, USA	Avoided deforestation	Ex post partial equilibrium model	Within-region: 43%; national: 58%; continental: 84%
Gan and McCarl (2007)	Global	Reduced forest output	Ex ante global computable general equilibrium model	45%–92%

3. Additionality of Emissions Reductions

Nonadditional crediting occurs when forests that are not threatened by deforestation receive carbon offset credits. REDD policies that establish accurate baseline rates of deforestation can minimize the degree of nonadditional crediting. However, establishing baselines and ensuring additionality is difficult in practice, as evidenced by recent studies.

Two comprehensive additionality studies—Pfaff et al. (2008) and Robalino et al. (2008)—analyzed Costa Rica's environmental services payment program (Pagos por Servicios Ambientales, or PSA). These studies analyzed historical satellite data from 1997 to 2000 and from 2000 to 2005 to estimate nonadditionality. The authors find that PSA prevented deforestation in less than 0.1 percent of all enrolled forests in the 1997–2000 period and in only 0.4 percent of enrolled forests during the 2000–2005 period.

III. Limitations to Research

Estimates of LULUCF offset potential and analyses of barriers facing LULUCF offsets face limitations regarding political foresight, research methodology, and data.

All studies suffer from regulatory uncertainty, in that they often attempt to estimate programs that are not yet specified or implemented and must make assumptions about the specific design elements of the program in question. For example, the organizational structure of any future REDD offset crediting program is highly uncertain. Such programs generally use one of three approaches: subnational (project-level), national-level management, or a nested approach that combines elements of the two. Angelsen et al. (2008) assessed the effectiveness, efficiency, and equity of each approach. The authors find that, although subnational approaches are more flexible than the other two approaches, they have potentially higher transaction costs and have the potential for significant leakage. They also find that national approaches are likely to invest in broader, more strategic targeting of forest conservation, so these offsets tend to be longer lasting; however, this approach favors middle-income countries (such as Brazil) that have some infrastructure in place to monitor forests and may result in policy failure if not implemented correctly. Lastly, they find that a nested approach, resulting in a system combining subnational and national approaches, may improve flexibility but may also result in higher marginal costs, and it is unclear how such a system would work in practice. The challenge for researchers is that each regulatory regime is idiosyncratic and necessitates radically different assumptions for simulation analysis. Until some consensus is reached on the preferred regulatory structure, REDD researchers will be unable to calibrate their estimates to policy-specific guidelines.

Studies that estimate LULUCF offset potential suffer from at least four broad sources of uncertainty. First, uncertainty in parameter values—such as forest cover and carbon uptake rate, the latter of which depends heavily on forest growth rate—impact the accuracy of the results. Second, incorporating feedback effects—including the impact of REDD offsets on development and agricultural prices—is limited, which may lead to overly optimistic estimates. Third, the models have perfect foresight, which may not be realistic; in other words, the models can predict and observe future deforestation rates and reward offsets that sequester carbon accordingly. In reality, regulators can only attempt to measure deforestation and consider uncertainty perfectly. Finally, studies suffer from a general lack of knowledge surrounding deforestation. For example, although the multiple causes of deforestation are widely studied, they are not perfectly understood. These causes include conversion to agricultural land; illegal and legal development, especially road building; and cyclical fluctuations of the timber market. To properly calibrate deforestation models, these fundamental drivers must be better understood. However, in many developing nations, relevant socioeconomic data are not widely available. Therefore, researchers make do with a more limited understanding of, and capacity to model, the drivers of deforestation.

IV. Discussion

LULUCF offsets remain a largely untapped potential of relatively low-cost emissions reductions. Although the UNFCCC allows the use of AR offsets, no mandatory carbon pricing system has yet allowed the use of the offset type with greatest potential supply—REDD offsets. This reluctance can be explained by concerns over measurement, emissions leakage, additionality and permanence. Regarding measurement, technological advancements are promising and may eventually quell concerns. Regarding emissions leakage, it seems that carefully designed policies can mitigate high leakage rates to some extent. Additionality may be the most persistent concern, especially given the high rates of nonadditionality in Costa Rica's environmental services payment program. Improvements in these areas and others—including an improved understanding of the drivers of deforestation—will increase the chances of large-scale investments in a future REDD offset market.

References

Ahammad, H., and R. Mi. 2005. Land Use Change Modeling in GTEM: Accounting for Forest Sinks. Paper presented at EMF22: Climate Change Control Scenarios. May 25–27, 2005, Tresider Memorial Union, Stanford University, Stanford, CA.

Angelsen, A., C. Streck, L. Peskett, J. Brown, and C. Luttrell. 2008. What Is the Right Scale for REDD? In *Moving Ahead with REDD: Issues, Options, and Implications,* edited by A. Angelsen. Bogor, Indonesia: Center for International Forestry Research.

Benítez, P.C., I. McCallum, M. Obersteiner, and Y. Yamagata. 2007. Global Potential for Carbon Sequestration: Geographical Distribution, Country Risk and Policy Implications. *Ecological Economics* 60(3): 572–583.

Buongiorno, J., S. Zhu, D. Zhang, J. Turner, and D. Tomberlin. 2003. *The Global Forest Products Model*.San Diego, CA: Academic Press, Elsevier, 310 p.

DeFries, R., F. Achard, S. Brown, M. Herold, D. Murdiyarso, B. Schlamadinger, and C. de Souza. 2006. *Reducing Greenhouse Gas Emissions from Deforestation in Developing Countries: Considerations for Monitoring and Measuring*. GOFC-GOLD report no. 26; GTOS report no. 46. Rome, Italy: Global Terrestrial Observing System.

De Jong, B., E.E. Bazán, and S.Q. Montalvo. 2007. Application of the "Climafor" Baseline To Determine Leakage: The Case of Scolel Té. *Mitigation and Adaptation Strategies for Global Change* 12(6): 1153–1168.

EPA (U.S. Environmental Protection Agency). 2005. *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*. EPA 430-R-05-006. Washington, DC: EPA.

Erb, C.B., Harvey, C.R. and T.E. Viskanta. 1996. Expected returns and volatilities in 135 countries. Portfolio Management 46-58 (Spring).

FAO (Food and Agriculture Organization of the United Nations (FAO). 2010. *Global Forest Resource Assessment 2010*. Rome, Italy: FAO. http://www.fao.org/forestry/fra/fra2010/en/ (.Aaccessed Julyon 7/ 21, /2011).

Ferris, J., and J. Siikamäki. 2009. *Conservation Reserve Program and Wetland Reserve Program: Primary Land Retirement Programs for Promoting Farmland Conservation*. Washington, DC: Resources for the Future. http://www.rff.org/RFF/Documents/RFF-BCK-ORRG_CRP_and_WRP.pdf (accessed October 18, 2012).

Freibauer, A., M.D.A. Rounsevell, P. Smith, and J. Verhagen. 2004. Carbon Sequestration in Agricultural Soils of Europe. *Geoderma* 122: 1–23.

Gan, J., and B.A. McCarl. 2007. Measuring Transnational Leakage from Forest Conservation. *Ecological Economics* 64(2): 423–432.

Gusti, M., P. Havlik, and M. Obersteiner. 2008. *Technical Description of the IIASA Model Cluster. TheEliasch Review* London, , UK: Office of Climate Change. http://www.occ.gov.uk/activities/eliasch/Gusti_IIASA_model_cluster.pdf (accessed December 12, 2009).

Harris, N.L., S. Brown, S.C. Hagen, S.S. Saatchi, S. Petrova, W. Salas, M.C. Hansen, P.V. Potapov, and A. Lotsch. 2012. Baseline Map of Carbon Emissions from Deforestation in Tropical Regions. *Science* 336(6088): 1573–1576.

Hertel, T.W. (ed.). 1997. *Global Trade Analysis Modeling and Applications*. Cambridge, UK: Cambridge University Press.

Hertel, T., S.K. Rose, and R.S.J. Tol. 2009b. *Economic Analysis of Land Use in Global Climate ChangePolicy*. NY: Routledge.

Hooda, N., M. Gera, K. Andrasko, J. Sathaye, M.K. Gupta, H.B. Vasistha, M. Chandran, and S.S. Rassaily. 2007. Community and Farm Forestry Climate Mitigation Projects: Case Studies from Uttaranchal, India. *Mitigation and Adaptation Strategies for Global Change* 12: 1099–1130.

Johns, T., and B. Schlamadinger. 2009. International Policy and Institutional Barriers to Reducing Emissions from Deforestation and Degradation in Developing Countries. In *Avoided Deforestation: Prospects for Mitigating Climate Change*, edited by C. Palmer and S. Engel. New York, NY: Routledge, 71.Kallio, M., D.P. Dykstra, and C.S. Binkley. 1987. *The Global Forest Sector: An Analytical Perspective*. New York: Wiley, 703 p.

Kindermann, G., M. Obersteiner, B. Sohngen, J. Sathaye, K. Andrasko, E. Ramesteiner, B. Schlamadinger, S. Wunder, and R. Beach. 2008. Global Cost Estimates of Reducing Carbon Emissions through Avoided Deforestation. *Proceedings of the National Academy of Sciences of the USA* 105(30): 10302–10307.

Lee H.-C., B.A. McCarl, and D. Gillig. 2005. The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration. *Canadian Journal of Agricultural Economics* 53: 343–357.

Macauley, M.K., D. Morris, R. Sedjo, K. Farley, and B. Sohngen. 2009. *Forest Measurement and Monitoring: Technical Capacity and "How Good Is Good Enough?*" Washington, DC: Resources for the Future.

Murray, B.C. 2009. Leakage from Avoided Deforestation Compensation Policy: Concepts, Corresponding Evidence and Corrective Policy Options. In *Avoided Deforestation: Prospects for Mitigating Climate Change*, edited by C. Palmer and S. Engel. New York, NY: Routledge, 49.

Murray, B.C., B.A. McCarl, and H. Lee. 2004. Estimating Leakage from Forest Carbon Sequestration Programmes. *Land Economics* 80(1): 109–124.

Nilsson, S., and W. Schopfhauser. 1995. The Carbon-Sequestration Potential of a Global Afforestation Program. *Climatic Change* 30: 267–293.

Olander, L.P., H.K. Gibbs, M. Steininger, J.J. Swenson, and B.C. Murray. 2008. Reference Scenarios for Deforestation and Forest Degradation in Support of REDD: A Review of Data and Methods. *Environmental Research Letters* 3(2): 025011. http://iopscience.iop.org/1748-9326/3/2/025011/pdf/1748-9326_3_2_025011.pdf (accessed October 20, 2012).

Perez-Garcia, John M., Linda A. Joyce, A. David McGuire, and Xiangming Xiao. 2002. Impacts of Climate Change on the Global Forest Sector. *Climatic Change* 54: 439–461.

Perez-Garcia, John M., and B.R. Lippke. 1992. *The Timber Trade and Tropical Forests: Modeling the Impacts of Supply Constraints, Trade Constraints and Trade Liberalization*. London Economics Centre Paper DP 93-03. London, UK: International Institute for Environment and Development.

Pfaff, A., J. Robilano, and G.A. Sanchez-Azofeifa. 2008. Payments for Environmental Services: Empirical Analysis for Costa Rica. Working paper SAN08-05. Durham, NC: Sanford Institute of Public Policy, Duke University.

Ravindranath N. H., Murthy I. K ., Sudha, P., Ramprasad V., Nagendra, M.D.V., Sahana, C.A., Khan, H. and Srivathsa, K.G. 2006. Methodological Issues in Forestry Mitigation Projects: A Case Study of Kolar District, "Mitigation and Adaptation Strategies for Global Change." Working paper LBLNL-61459. Bangalore, India. Center for Sustainable Technologies and Center for Ecological Sciences, Indian Institute of Science.

Robalino, J., A. Pfaff, A. Sanchez, F. Alpizar, C. Leon, and C.M. Rodriguez. 2008. Changing the Deforestation Impacts of Ecopayments: Evolution (2000-2995)inosta Rica's PSA Program. Working paper. http://www.duke.edu/~asp9/files/PSApost2000-v12ap.pdf (accessed July 30, 2010).

Sathaye, J., and K. Andrasko. 2007. Special Issue on Estimation of Baselines and Leakage in Carbon Mitigation Forestry Projects. *Mitigation and Adaptation Strategies for Global Change* 12(6): 963–970.

Sedjo, R.A., and K.S. Lyon. 1989 *The Long Term Adequacy of the World Timber Supply*. Washington, DC: Resources for the Future, 230 p.

Sedjo, R., and B. Sohngen. 2000. Forestry Sequestration of CO_2 and Markets for Timber. Discussion paper 00-03. Washington, DC: Resources for the Future.

Seo, N., and R. Mendelsohn. 2007. A Ricardian Analysis of the Impact of Climate Change on Latin American Farms. Policy research working paper 4163. Washington DC: World Bank.

Sohngen, B. 2009. Assessing the Economic Potential for Reducing Deforestation in Developing Countries. In *Avoided Deforestation: Prospects for Mitigating Climate Change*, edited by C. Palmer and S. Engel. New York, NY: Routledge, 49.

Sohngen, B., and S. Brown. 2004. Measuring Leakage from Carbon Projects in Open Economies: A Stop Timber Harvesting Project in Bolivia as a Case Study. *Canada Journal of Forestry Research* 34(4): 829–839.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 1999. Forest Management, Conservation, and Global

Timber Markets. *American Journal of Agricultural Economics* 81:1–13.

Sohngen, B., and R. Mendelsohn. 2003. An Optimal Control Model of Forest Carbon Sequestration. *American Journal of Agricultural Economics* 85: 448–457.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 1999. Forest Management, Conservation, and Global Timber Markets. *American Journal of Agricultural Economics* 81: 1–13.

Sohngen, B., and R. Sedjo. 2006. Carbon Sequestration in Global Forests under Different Carbon Pricing Regimes. *The Energy Journal* 27(1): 109–126.

Stavins, R. 1999. The Costs of Carbon Sequestration: A Revealed-Preference Approach. *American Economic Review* 89: 994–1009.

Trexler, M.C., and C. Haugen. 1995. *Keeping It Green: Evaluating Tropical Forestry Strategies To Mitigate Global Warming*. Washington DC: World Resources Institute.

UNFCCC (U.N. Framework Convention on Climate Change). 2007. Revised Draft Decision-/CP.13. Ad Hoc Working Group on Long-Term Cooperative Action under the Convention. Conference of the Parties, 13th session. December 3–14, Bali, Indonesia.

———. 2007. Report of the Conference of the Parties on Its Thirteenth Session, Held in Bali from 3 to 15 December 2007. http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf (accessed July 21, 2011).

Van Kooten, G.C., A.J. Eagle, J. Manley, and T. Smolak. 2004. How Costly Are Carbon Offsets? A Meta-Analysis of Carbon Forest Sinks. *Environmental Science and Policy* 7(4): 239–251.

van der Werf, G.R., D.C. Morton, R.S. DeFries, J.G.J. Olivier, P.S. Kasibhatla, R.B. Jackson, and G.J. Collatz. 2009. CO_2 Emissions from Forest Loss. *Nature Geoscience* 2: 737–738.

Waggoner, P. 2009. Forest Inventories: Discrepancies and Uncertainties. Discussion paper 09-29. Washington DC: Resources for the Future. http://www.rff.org/rff/documents/rff-dp-09-29.pdf (accessed October 20, 2012).

Wear, D., and B. Murray. 2004. Federal Timber Restrictions, Interregional Spillovers, and the Impacts on U.S. Softwood Markets. *Journal of Environmental Economics and Management* 47(2): 307–330.

Wu, J.J. 2000. Slippage Effects of the Conservation Reserve Program. *American Journal of Agricultural Economics* 82: 979–992.

Zomer, R.J., A. Trabucco, D.A. Bossio, and L.V. Verchot. 2008. Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation. *Agriculture, Ecosystems and Environment* 126: 67–80.