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policy

Where Is the Carbon? Carbon Sequestration Potential from Private Forestland in the Southern United States

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Uncertainty surrounding the future supply of timber in the southern United States prompted the question, "Where is all the wood?" (Cubbage et al. 1995). We ask a similar question about the potential of southern forests to mitigate greenhouse gas (GHG) emissions by sequestering carbon. Because significant carbon sequestration potential occurs on individual nonindustrial private forest (NIPF) lands owned by individuals, the accuracy of projections depends on how NIPF landowners respond to prices and their ability and willingness to participate in carbon offset programs. Striving to produce a more realistic assessment of the potential for southern forests to sequester carbon in response to future markets or policies, we use National Woodland Owner Survey data from the Forest Inventory and Analysis program to link landowner demographic and behavioral data with forest conditions. We also examine barriers to NIPF participation in carbon offset programs and offer recommendations for overcoming those barriers.

Keywords: carbon, nonindustrial private forestland (NIPF), southern United States, forest offset, National Woodland Owner Survey

If included in a larger GHG emissions reduction policy framework, such as an economywide cap-and-trade program, increasing the carbon stored in forests and other biological carbon sinks can provide a pool of low-cost mitigation options, lowering the overall cost of program compliance (Amano and Sedjo 2006). The US forest sector comprises a significant carbon sink, with US nonsoil forest and harvested wood product sequestration averaging approximately 700 million metric tons of carbon dioxide equivalent (tCO_2e) per year (US Environmental Protection Agency 2011). Several management options also exist to increase the GHG emission mitigation provided by US forest lands (Murray et al. 2005; Malmsheimer et al. 2008). Forest management can increase the amount of carbon stored in existing forests through changes in management and longer rotations, afforestation and reforestation can increase carbon storage through the planting of new trees, and avoided conversion prevents loss of carbon stored in existing forests. With a high enough carbon price, forest management and afforestation efforts alone might generate an additional 1.2 billion tCO_2e of forest carbon storage per year, nationwide (Murray et al. 2005). Management of existing forestland is thought to offer some of the lowest cost and highest volume opportunities in the South, representing over 400 million tCO_2e of annual potential sequestration (Figure 1).

Looking at aggregate potential can obscure several important factors, however. For example, total forest carbon storage is not distributed evenly across the country (Figure 2). The eastern United States contains higher total stocks of forest carbon and a larger proportion of carbon stocks on privately owned lands. Private ownership is particularly strong in the South, where timberland tends to be managed more intensively than in other regions. Southern forests will likely play a crucial role in any successful forest carbon market or program targeted to private landowners that includes forest management, but concerns have surfaced about the accuracy of estimates of the potential forest carbon supply from the region. These concerns are driven in part by highly variable results from estimates of the expected cost and magnitude of supply of forest carbon offsets in the United States (Stavins and

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Richards 2005) and the assumptions underlying the major carbon supply models.

Most supply models of aggregate carbon sequestration from US forests use a dynamic optimization framework (e.g., the FASOMGHG model used in Murray et al. 2005, Baker et al. 2010, Adams et al. 2011, and Latta et al. 2011) that assumes that all landowners seek to maximize land rents (profits) on their landholdings. Models that rely on strict profit maximization may overestimate actual mitigation supply potential by assuming that all forest landowners and their management responses to changing market conditions have the same objectives. This approach may be appropriate for large industrial forest ownerships but may not adequately account for the motivations of many NIPF landowners, who manage for diverse objectives, including, but not exclusively, profit maximization (Beach et al. 2005). As nearly half of all US forestland falls under individual NIPF (or "family") ownership (Butler 2008), understanding the behavior of these landowners is critical to our ability to design successful carbon offset programs.

Variations in both offset cost and supply can have dramatic implications for the performance of domestic climate policies (US Environmental Protection Agency 2009). Similar uncertainty surrounding the future supply of timber in the southern United States in 1995, prompted Cubbage et al. (1995) to ask rhetorically, "Where is all the wood?" Just as Cubbage et al. found that NIPF "nontimber motivations are apt to reduce the total . . . readily available timber supply," (p. 19) they also may reduce the readily available supply of carbon mitigation, a commodity that is less tangible and arguably far more uncertain. On one hand, these attributes could reduce supply incentives. But managing forests to store more carbon over time may also align with landowner nontimber objectives such as the provision of wildlife habitat and other ecosystem services that sometimes constrain timber supply.

As a first approximation response to the question, "Where is all the carbon?" we review previous literature on carbon supply models and potential for NIPF participation. The literature on NIPF landowner participation in carbon offset projects is informative but incomplete given the current scarcity of these projects. Significant literature exists on the influence of offset project requirements and benefits on landowner participation incentives and on the relationship between land and landowner attributes and NIPF participation in other, noncarbon related programs and activities (e.g., certification, wildlife habitat conservation, cost shares, conservation easements, etc.). What is missing, however, are analyses of potential NIPF contribution to future offset markets given present land and landowner attributes. We address this key information gap by investigating the distribution of carbon across the southern forest landscape, using Forest Inventory and Analysis (FIA) National Woodland Owner Survey (NWOS) data combined with plot-level forest inventory data.[1]

We begin with an assessment of the size and distribution of existing forest carbon stocks. Next, we use combined forest condition and landowner demographic and behavioral attributes to estimate the relative amount of carbon likely to be brought to market under a hypothetical carbon offset program. Although such efforts do not represent the final word in NIPF offset supply, they can help to focus attention on the role of private landowner behavior in driving aggregate carbon sequestration potential. This is, in turn, a necessary first step in designing programs and policies to successfully leverage the carbon storage potential of the private landowner base in the southern United States.

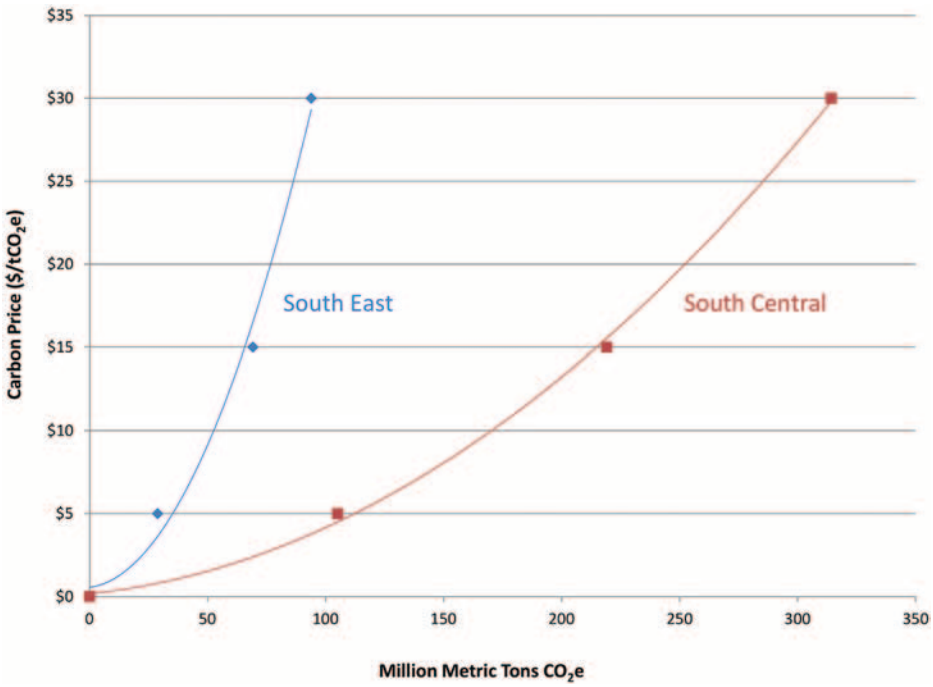

Figure 1. South-wide forest management potential at different carbon prices (derived from Murray et al. 2005). The southeast includes the states of Florida, Georgia, North Carolina, South Carolina, and Virginia, while the south central includes Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Eastern Oklahoma, Eastern Texas, and Tennessee.

Management and Policy Implications

This analysis facilitates individual nonindustrial private forest (NIPF) landowner access and participation in carbon markets by highlighting that portion of the landowner base most likely to participate in forest offset activities. This allows for appropriate outreach tools to be developed so as to connect with key components of the individual NIPF landowner community. It can also help in the development of measurement and verification processes and carbon offset project aggregation services to further facilitate the involvement of these landowners. From a policymaker perspective, the analysis refines estimates of potential greenhouse gas (GHG) mitigation supply by examining landowner behavior, an aspect often absent in existing national models. By helping to target policy design and outreach efforts to the needs of landowners most likely to participate in an eventual carbon market, the findings also facilitate greater production of forest offset credits, which in turn lowers the overall cost of climate policy.

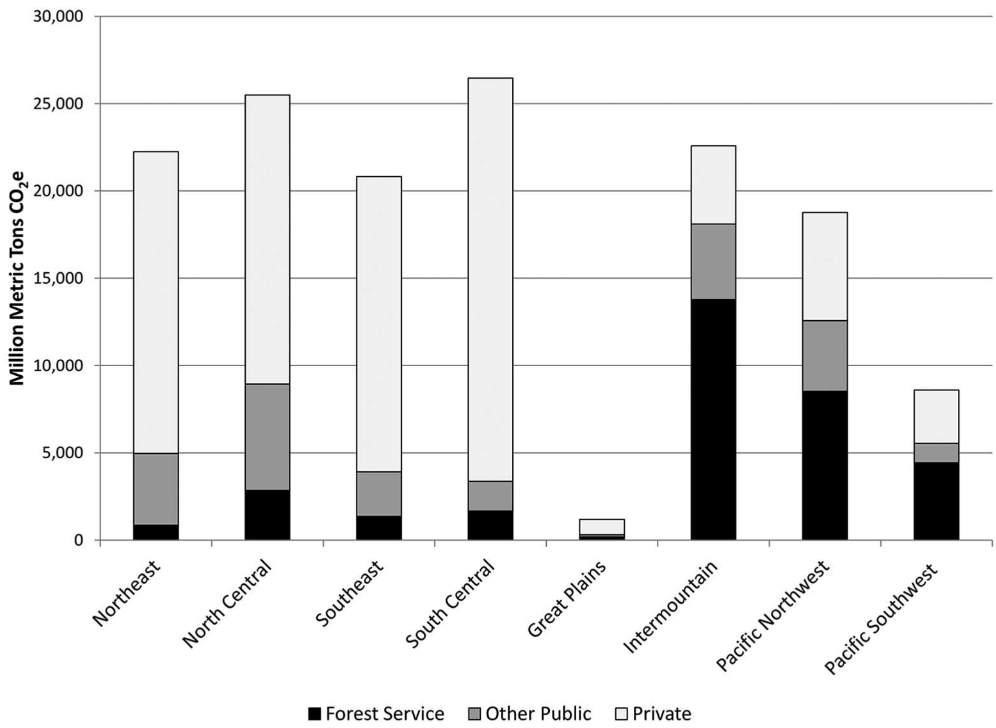

Figure 2. Total forest carbon by owner and region. Source: USDA Forest Service (2010).

What Does Existing Research Tell Us?

Forest offsets were a key part of multiple pieces of comprehensive climate legislation offered in recent years in both the US House of Representatives (e.g., H.R. 2454, American Clean Energy and Security Act of 2009) and the Senate (S.3036, The Lieberman-Warner Climate Security Act of 2008; S.1733, The Clean Energy Jobs and American Power Act of 2009). Though none became law, these legislative efforts were accompanied by a great deal of work by academics, consultants, government agencies, and other stakeholders to estimate the supply of forest carbon sequestration, generally finding that US forests are capable of generating significant, relatively low-cost GHG mitigation services.[2] Even in the absence of comprehensive climate policy, several voluntary and compliance-based markets and registries either have provided or presently provide landowners with opportunities to market recorded gains in carbon sequestration (e.g., Chicago Climate Exchange [CCX], American Carbon Registry [ACR], Climate Action Reserve [CAR], Regional Greenhouse Gas Initiative [RGGI], Verified Carbon Standard [VCS]).

As noted previously, most models used to assess national and regional carbon supply assume that all landowners are profit maximizers. For example, Murray (2003) expresses the aggregate supply of carbon sequestration in forests across a supply region (e.g., the Southeast, the United States) as a function of the share of land allocated to forest and the carbon density of the forest, each of which are a function of the price paid for carbon in a carbon market or other pricing scheme such as a tax, the price of competing noncarbon commodities such as timber or agriculture, and land quality. Following the framework of Hartman (1976), Murray (2000) developed a forest stand-level model that captures the joint output of carbon and timber and their contribution to the stand's bare land value. This takes into account the timber value when the land is harvested, replanting costs, the value of carbon sequestration revenues received over the length of the rotation, and the penalty or "payout" costs of releasing carbon at the time of harvest. Maximizing the bare land value develops the supply of carbon as a function of the prices of timber, carbon, and other land characteristics. This framework is similar to those used in large aggregate models of forest supply such as FASOMGHG (cited earlier) and other global timber models (Sohngen and Mendelsohn 2003).

Our goal is to indirectly assess the impacts of assuming all landowners want to and are able to be profit maximizers. They may wish to maximize the benefits they receive from producing a range of goods and services from their land, some of which are not typically traded in markets (e.g., scenic beauty) and do not generate profits per se. Moreover, some landowners may be constrained by financial or human capital shortfalls from maximizing financial profits. With these factors in mind, we first examine the literature on NIPF behavior to assess the likelihood that different types of NIPF landowners would participate in future carbon sequestration markets or government programs that paid specifically for changes in carbon storage.

In addition to purely financial motives, research suggests that willingness to participate in carbon sequestration activities is also a function of program attributes and landowner characteristics. The few studies directed specifically at NIPF participation in carbon markets find that carbon revenue is positively associated with willingness to participate but differ on the effect of program length (Dickinson et al. 2012, Fletcher et al. 2009, van Kooten et al. 2002). Thompson and Hansen (2012) find that NIPF attitudes toward carbon markets vary by a number of forest, management, and demographic characteristics, with those actively managing their lands and those on smaller parcels having a more favorable opinion of sequestration opportunities. Others (Markowski-Lindsay et al. 2011,Wade and Moseley 2011) find that carbon price and the opportunity to earn additional revenue could encourage participation, while accounting and compliance procedures and potential restrictions on property rights or future management options tend to discourage it.

Compared to carbon market participation, a vast literature exists on NIPF forest management behavior, participation in timber markets, nontimber objectives, and utilization of easements, cost-share, or other forest-related programs that may provide indirect insight into NIPF carbon market participation. Not surprisingly, timber price is generally positively associated with increased harvesting (e.g., Prestemon and Wear 2000). In a meta-analysis of the NIPF literature, Beach et al. (2005) find that forest management activity is generally positively associated with the availability of cost-share and other incentives. Factors other than timber price and harvest cost that may also influence landowner harvest decisions include parcel size, absenteeism, landowner income, education, and bequest intentions, all of which are significant in explaining harvest activity (Conway et al. 2003, Beach et al. 2005, Størdal et al. 2008).

Participation in nontimber forest management programs, such as those fostering biodiversity conservation and provision of other ecosystem services, is also influenced by a variety of factors, including absenteeism and parcel size (Conway et al. 2003), education (Matta et al. 2009, Kramer and Jenkins 2009), and nonforest income (Layton and Siikamaki 2009). Previous management experience, including the use of professional consultants or foresters (Rossi et al. 2010), the importance of nontimber attributes of their forest (Langpap 2004, Layton and Siikamaki 2009), and participation in other conservation programs (Kramer and Jenkins 2009) are also associated with increased probability of program participation. Alternatively, male landowners (Layton and Siikamaki 2009, Sullivan et al. 2005) and those interested in bequeathing land to heirs (Sullivan et al. 2005) are less likely to participate in programs. Conflicting results have been found on the influence of income and wealth (e.g., Matta et al. 2009, Shaikh et al. 2007, Kramer and Jenkins 2009), respondent age (e.g., Layton and Siikamaki 2009, Shaikh et al. 2007, Matta et al. 2009, Langpap 2004, Kramer and Jenkins 2009), length of landownership (e.g., Matta et al. 2009, Langpap 2004), and size of holding (e.g., Rossi et al. 2010, Kilgore et al. 2008, Langpap 2004).

The specific requirements of programs also have a strong influence on landowner participation. For example, restrictions on forest management options reduce the likelihood of participation in forest conservation programs (Kilgore et al. 2008, Matta et al. 2009). Longer contract lengths are also associated with decreased probabilities of program participation (Layton and Siikamaki 2009, Kramer and Jenkins 2009), and higher payments with increased participation (Matta et al. 2009, Layton and Siikamaki 2009, Kramer and Jenkins 2009).

A variety of factors thus influence NIPF management behavior, participation in timber markets, nontimber outputs, and participation in easements, cost-share, or other forest-related programs. Economic factors such as timber price and harvest cost play a prominent role, but so do landowner demographics (e.g., age, income, education), parcel size, and previous experience with either timber management or government program participation. Of these, parcel size and previous management or program experience are perhaps the most likely predictors of participation in a yet-to-be-defined carbon market, as these are both attributes that can lower the relative cost of participation. Demographic factors are inconsistent in the direction of their association, while economic variables will be most applicable to landowners actively seeking profits.

Observed Patterns of Carbon Storage

Using FIA forest inventory and landowner survey data we next assess the potential impact of forest and landowner attributes on carbon supply in the southern United States by comparing the distribution of existing carbon stock across these attributes. In doing so, we note that the available literature on NIPF behavior is incomplete and at times conflicting (Langpap and Kim 2010), and that even consistent results derived from research in other regions of the country may not be directly applicable to forests landowners in the southern states. Nonetheless, the exercise is helpful in identifying general trends and associations, refining and targeting future research, and assisting in future carbon market development and outreach efforts.

Methods and Materials

To examine the distribution of forest carbon across the South, we use NWOS data on private landowner demographics and behavior linked with FIA inventory data on forest conditions and management for thirteen southern states—Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. Raw NWOS data were obtained directly from the USDA Forest Service, while carbon estimates were compiled using state FIA data tables downloaded via the US Forest Service DataMart website (USDA Forest Service 2011). These data are not publicly available and were acquired only after entering into a memorandum of understanding with the US Forest Service and agreeing to abide by specific security and confidentiality requirements. Even with access to unique plot sequence numbers, the data cannot be used to identify specific landowners.

For each condition within a forest inventory plot, aboveground and belowground carbon totals were compiled for all trees. Carbon in down deadwood, litter, soil, standing dead, understory aboveground, and understory belowground pools was compiled in a similar fashion. All eight pools were then summed across conditions within each plot to generate carbon totals at the plot level. A plot's noncarbon attributes were derived from the NWOS survey data. When a plot had multiple conditions, attributes of the dominant condition were assigned to it. Plots with conditions of equal proportion had one condition selected at random to represent the plot, as it is not possible to simply take the average of "forest type" and other characteristics that together define a condition.

Once plot-level values for carbon and all other attributes were estimated, the data were grouped by landowner and management attributes. Based on the literature review of forest management behavior and nontimber program participation, we assume that different types of landowners will respond differently to forest carbon offset program opportunities. To understand the influence on carbon offset program participation, we apply several management, demographic, and land attribute filters that could shape the pool of landowners most likely to participate.

The first filter distinguishes between landowner type. Not all private landowners can be expected to manage their lands in a similar fashion. A distinction can be drawn, for example, between forest industry, firms, timber investment management organization (TIMOs), real estate investment trusts (REITs), and individual NIPF (or "family forest") owners. The first three can be expected to manage their lands in a traditional profit-maximizing fashion, while the behavior of individual NIPFs is less certain. As the NWOS data represent only a portion of the total private carbon supply, namely the individual NIPF portion, we first generate a rough approximation of the magnitude of the individual NIPF contribution to the total carbon pool. To do so, we estimate the mean per-hectare carbon storage associated with individual NIPF NWOS survey records and then multiply that by family forest acreages reported in Butler (2008). We then compare this to the total nonsoil forest carbon for all other private ownerships in the region (retrieved from USDA Forest Service 2012) to estimate individual NIPF contribution to total carbon storage.

A second important filter is management history. Participation in future forest management offset market activity will likely require landowners to either actively manage their lands, increase rotation ages, or otherwise *change* management to generate additional carbon storage. Accordingly, we expect landowners with a history of actively managing their lands would be more likely (and perhaps more eligible) to participate than those without a history of management. We assume that individual NIPF landowners identified in the NWOS database as having either conducted a timber harvest or completed a management plan were actively managing at least some portion of their lands.[3]

A third important filter is parcel size. Scale economies suggest landowners on larger parcels will be more likely to participate in carbon markets or programs (Galik et al. 2012). Although recent research suggests that smaller landowners may be more motivated to participate in emerging carbon markets than larger ones (Thompson and Hansen 2012), landowners on small parcels are also likely to face significant transaction costs, sampling costs, and other barriers to participation (Galik et al. 2012, Mooney et al. 2004). In light of these expected barriers, we assume that ownerships of less than 100 acres are unlikely to participate in offset markets.[4]

Results

Comparing carbon storage from NWOS survey records to all other private lands suggests that the individual NIPF portion comprises roughly 60% of total private carbon storage in the region. Note that this is only current stock, and programs designed to mitigate GHG emissions will require that "additional" mitigation be made to be eligible for participation. In other words, offset credits can be generated only for reducing emissions below (or increasing sequestration above) what would be found under normal ("baseline") conditions. So it is not simply a matter of how much carbon is on the ground now but how much extra can be added.

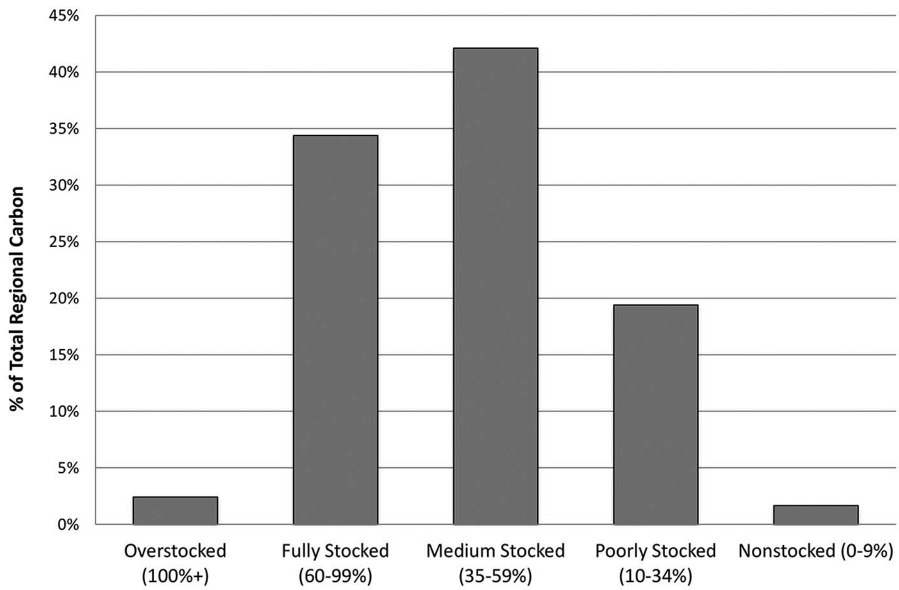

Figure 3. Distribution of total nonsoil carbon in the US South by growing stock level.

Stocking levels, defined as the "basal area and/or number of trees in a stand compared with the basal area and/or number of trees required to fully use the growth potential of the land (or the stocking standard)" (USDA Forest Service 2004), can help to shed light on the potential additional carbon that could be brought to market. Of the data available from the FIA data sets, stocking level is perhaps the most appropriate for indicating rough potential for future carbon sequestration, as it can provide insight into the magnitude of opportunities for offsetting carbon through improved forest management activities. In the FIA NWOS data set, the majority of nonsoil forest carbon—that portion found in aboveground and belowground live trees, aboveground and below ground understory, standing deadwood, and litter—lies in medium-to-fully stocked stands (Figure 3). Poorly stocked stands also make up a sizable portion of total NIPF holdings. Together, these two stocking levels likely hold the greatest potential for additional carbon storage, and collectively hold 60.6% of current carbon stocks.

Turning to parcel size, slightly more than half of the total nonsoil carbon in the South is found on larger land holdings (Figure 4); carbon on medium (100–999 acres) and large (greater than 999 acres) is approximately 60.2% of total NIPF carbon. If one assumes that only those landowners holding larger parcels of land *and* with some history of management (e.g., management plan or recent harvest activity) will participate in carbon markets, the potential carbon stock is reduced to approximately 52% (Figure 5). What this implies is that a good deal of the South's private forest carbon remains even after removing the potentially nonparticipating smaller parcels. In this respect at least, the small landowner "problem" for market participation may be overstated. Adjusting for those individual NIPF landowners not actively managing their land likewise has little additional impact on the available carbon stock.

In addition to the contribution to total carbon stock by individual NIPF landowners, Figure 5 also includes the expected contribution from all other private landowners in the South, such as industrial holdings, TIMOs, and REITs. This "other" portion includes those larger landowners expected to exhibit greater profit-maximizing behavior. Although a gross oversimplification, we assume here that these "other" landowners are price responsive and so require less filtering to gauge potential participation in carbon markets.

Discussion and Conclusions

Returning to the original forest management supply curves produced by Murray

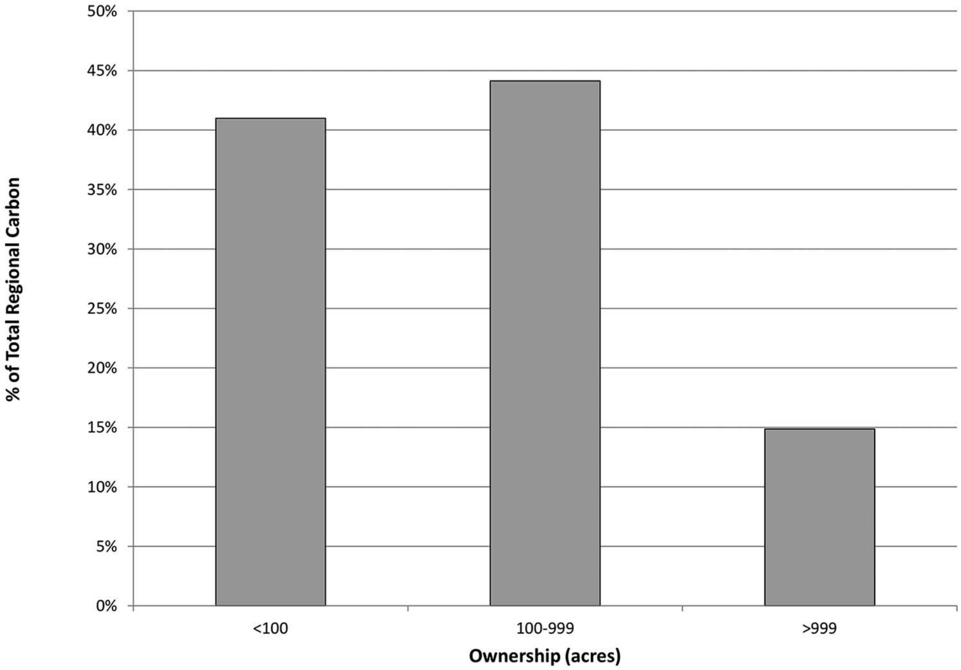

Figure 4. Distribution of total nonsoil forest carbon on individual NIPF land holdings in the US South by landowner size class.

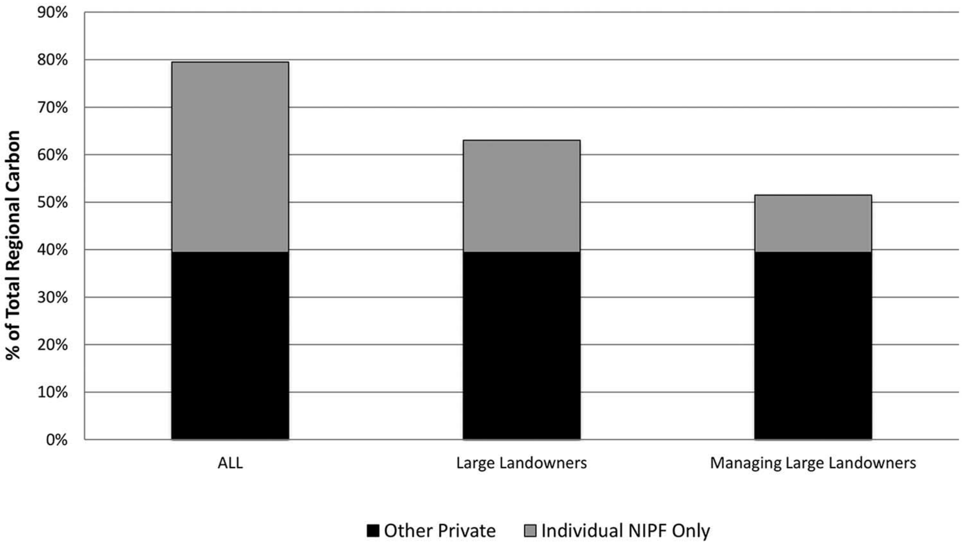

Figure 5. Distribution of total nonsoil carbon on individual NIPF land holdings in the US South by landowner grouping. "Large landowners" are those individual NIPF landowners holding 100 or more acres. "Managing landowners" are those individual NIPF landowners having either conducted a timber harvest or completed a management plan. "Other private" indicates that portion of total southern nonsoil forest carbon estimated to be held by all other private entities (i.e., those not classified as "individual NIPF").

et al. (2005) and shown in Figure 1, we can attempt a rough first approximation of offset supply based on the lessons learned here. We do not estimate a new supply curve but rather adjust the existing one to deduct the proportion of carbon on fully stocked and overstocked stands, lands without a management plan or harvest activity, and landowners owning less than 100 acres. In other words, we assume that the distribution of current carbon stocks on those remaining lands can be used to qualify future supply. We assume that individual NIPF landowners on large parcels with a history of management and with poorly or medium stocked stands are both profit maximizing and capable of generating additional carbon storage and, therefore, that the original curve calculated by Murray et al. (2005) applies to this portion of the carbon stock. We also include here a proportion of carbon stored on "other private" lands, likewise assuming that this portion of landowners is also profit maximizing and capable of generating carbon.

The forest carbon supply curve shown in Figure 6 thus represents a first attempt at answering the question, "Where is the carbon?," or rather, "Where is the carbon storage potential, and at what price is it available?" It represents a point of departure, the beginning of a deeper conversation of how to refine economic estimates of private landowner potential, though admittedly much remains to be done. For one, the sequestration supply curve in Figure 6 represents a hypothetical maximum potential at differ-

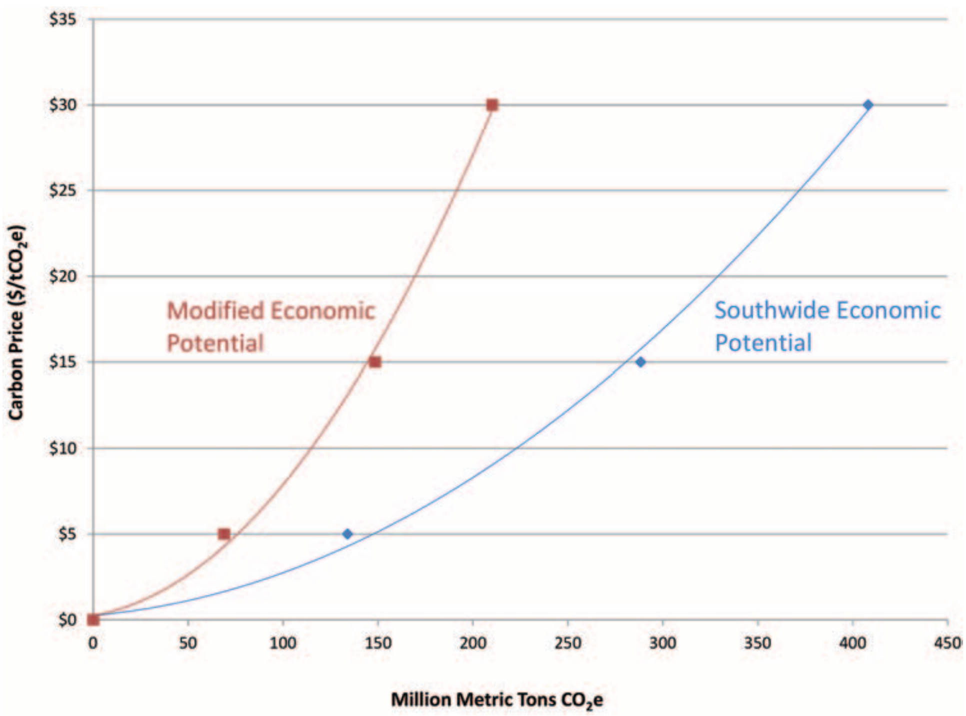

Figure 6. Total forest management potential at different carbon prices for previous estimates (Murray et al. 2005 Southwide potential) compared to a modified adjusted Southwide potential estimated here. The latter adjusts the Murray et al. Southwide total curve to deduct fully stocked and overstocked stands, landowners without a management plan or recent timber harvest activity, and landowners owning less than 100 acres.

ent prices from changes in forest management. Recall that we are adjusting the curve by percentages of current carbon stock, whereas offset potential is determined by how much additional storage can be generated. Although the figure attempts to adjust potential to account for stocking levels, the link between current carbon stock, stocking levels, and future potential is complex. For example, fully stocked stands could still be managed so as to generate additional carbon benefits through extended rotation or stand improvement interventions (e.g., Galik and Cooley 2012). The extent of additional carbon potential in understocked stands is likewise unclear. Likewise, the present analysis does not directly address leakage and other market phenomena capable of reducing aggregate storage, though these are present in the original Murray et al. (2005) curve. Efforts should, therefore, turn to integrating behavioral and attribute screens such as those employed here into traditional modeling approaches capable of assessing the impact of these larger market effects.

Furthermore, we argue that a sizable portion of sequestration potential may not be fully price responsive, but a large portion will be, implying that total mitigation delivered will depend on the market for both carbon and other agricultural and forest products (Mercer et al. 2011). Tied to pricing are the program design elements that define the rules for participation in forest offset programs. Program design can influence the manner in which carbon is measured and reported, which in turn can have direct effects on the financial viability of individual offset projects (Galik and Cooley 2012).The voluntary carbon market has likewise shown some price preference for offsets sold under more rigorous participation rules.

Program design can also affect participation in other ways, especially as it pertains to long-term commitment requirements or additional management encumbrances. Targeted research on the willingness to participate in carbon markets confirms landowner hesitance to accept such restrictions, even when compensated (van Kooten et al. 2002, Markowski-Lindsay et al. 2011). Unfortunately, the data to explore such limitations at the regional level are limited.[5] Until this question can be answered definitively, it is worthwhile exploring other options for promoting sequestration on private lands, including incentive-based policies and support programs (see, e.g., Langpap and Kim 2010, Mercer et al. 2011). Regardless of the approach taken, outreach and education will play an important role, especially in light of documented gaps in landowner awareness of carbon and other conservation programs (e.g., Wade and Moseley 2011, Van Fleet et al. 2012).

The information generated by this study nonetheless has a strong and clear role in the development of national carbon policy. From a forest landowner perspective, a properly designed offset program may provide an additional revenue stream for working forests and promote forest retention. Information generated from this analysis can further assist individual NIPF landowner access and participation to carbon markets by identifying the outreach tools and methods needed to connect with key components of the individual NIPF landowner community, the measurement and verification processes likely necessary for adoption of offset projects, and the need for and role of carbon offset project aggregation services. From a policymaker perspective, the findings serve two primary purposes. First, they help to refocus efforts on the refinement of potential GHG mitigation supply by examining an aspect, landowner behavior, often absent in existing national models. Second, in helping to maximize individual NIPF landowner participation in a forest carbon offset program, the findings can also help to lower the overall cost of climate policy by facilitating the generation of greater amounts of relatively low-cost GHG reduction credits.

Endnotes

1. See www.fia.fs.fed.us/nwos/ (last accessed May 16, 2012) and www.fia.fs.fed.us/ (last accessed May 16, 2012) for further information on the National Woodland Owner Survey database and plot-level forest inventory data, respectively.
2. A full review of this voluminous work is beyond the scope of this short article. Reviews can be found elsewhere (Lewandrowski et al. 2004, Stavins and Richards 2005, van Kooten and Sohngen 2007). Stavins and Richards (2005) find fairly wide agreement on estimates of offset price and quantity up to approximately 1.1 billion tCO_2e of additional carbon supplied per year. Beyond that quantity, cost estimates begin to diverge, but some studies suggest a potential for low-cost mitigation opportunities to exceed 1.8 billion tCO_2e/year or more.
3. This can be viewed as a relatively benign cutoff, as "harvest" is a catchall for a number of activities, including the simple harvest of firewood. Further exploration of the data, however, show that limiting harvest activity to post, veneer, pulp, or sawlog removal retains over 93% of carbon in lands between 100 and 999 acres in size, and 99% of the carbon in holdings over 999 acres. Harvests only consisting of firewood and other materials, therefore, make up a small portion of the sample.
4. The 100-acre cutoff is somewhat arbitrary but is grounded in the increasing costs faced by smaller landowners as noted in the referenced studies.
5. One could attempt to gauge the potential of such requirements to limit aggregate participation, but the closest proxies for carbon market participation available in the NWOS database are past experience with or future willingness to enter into conservation easements and third party certification (e.g., Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), American Tree Farm System, etc.). There are similarities between both (e.g., long-term commitments with easements; verification requirements with certification), but the pool of landowners willing or even able to participate in these two activities may be significantly less than those willing to sell carbon. We thank an anonymous reviewer for clearly articulating this last point.

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