Clerk of the Board August 11, 2011

California Air Resources Board

1001 I Street

Sacramento, CA 95814

Re: Comments on the proposed modified California cap and trade regulations with regard to the Improved Forest Management project type

Dear ARB staff,

Thank you for the opportunity to weigh in on the Cap-and-Trade rulemaking process.

It is clear that the supply of offsets from the four protocols under consideration for adoption and those from the Climate Action Reserve will surely fall short of the demand for them. Thus, I would like to echo the comments of the Verified Carbon Standard Association addressing the prospect of expanding the list of eligible protocols so that the supply of offset credits issued under the ARB-approved protocols are more capable of meeting demand.

I agree with the VCSA that “more clarity must be provided for how early action protocols can be brought forward for consideration and approval”, given that the study attached here finds CAR’s reversal compensation rule for improved forest management projects (and in effect the same rule ARB is adopting in § 95983(c)(3)) to be unnecessarily punitive for true working forest projects that do not choose to fully incur the incredible opportunity costs of sacrificing timber values and to therby strongly disincentivize forestland owners to concurrently improve forest management and supply legitimate offsets to the market. Please see pages 65-66, 75, 79 in the attached document for a more in depth discussion of these findings.

Because of the standing requirement that the credit liability of IFM project owners cover emissions beyond the credits issued prior to the reversal, it appears that protocols like those of the VCSA that do not impose such a punitive measure on AFOLU projects will never be compatible with the CA Compliance Offset Protocols. As stated in the VCS AFOLU Requirements, “all VCUs issued to AFOLU projects (as with all projects) are permanent…because the AFOLU pooled buffer account will always maintain an adequate surplus to cover unanticipated losses from individual project failures”, as the ARB buffer pool is designed to do. Under this line of reasoning, it seems inappropriately burdensome to enforce ARB’s current interpretation of project owner credit liability. Therefore, if compensation of reversals continues to be a requirement, as opposed to the VCS method of canceling credits from the buffer pool equal to the reversal, reversal compensation should be limited to the credits issued prior to the reversal. Such a rule would significantly improve the appeal of engaging in the CA offset market to forestland owners holding less than 1,000 acres because they wouldn’t be penalized for occasional silvicultural activities that temporarily push above-ground standing live carbon stocks below the minimum baseline level (MBL). It is important to note here that article § 95983(c)(4) contradicts the protocol with regard to these small landowners, which are allowed to let such carbon stocks fall to no more than 20% below the MBL for justified silvicultural activities.

It should be noted that this potential change in reversal compensation would also preserve the relevance of conservation easements because the protocol wouldn’t necessarily induce the level of conservation practices that are already incentivized by payments from land conservancies. Such compensation on top of what a landowner would commit to for carbon value would make participation in the CA offset market even more financially rewarding, thereby facilitating increased landowner engagement perhaps.

Not only do I recommend the reversal compensation rule be changed accordingly, but it seems that the VCS rule for which the reasoning quoted above is given should also be adopted:

* Although buffer credits are cancelled to cover carbon known, or believed to be lost, the VCUs already issued to projects that subsequently fail are not cancelled and do not have to be “paid back”.

–**AFOLU rule 3.6.11**

This would involve adopting the VCS approach to intentional reversals, which is as follows:

* Where an event occurs that is likely to qualify as a loss event and VCUs have been previously issued,…
  + at the verification even subsequent to the loss event, the monitoring report shall restate the loss from the loss event and calculate the net GHG benefit from the monitoring period in accordance with …the methodology applied. In addition, where the net GHG benefit of the project, compared to the baseline, for the monitoring period is negative, taking into account project emissions, removals and leakage, a reversal has occurred and buffer credits equivalent to the reversal shall be cancelled from the AFOLU pooled buffer account… –**AFOLU rule 3.6.7**
* At a verification event, where a reversal has occurred, the following applies: Where the reversal is a non-catastrophic reversal (eg, due to poor management or over-harvesting)…No further VCUs shall be issued to the project until the deficit is remedied. The deficit is equivalent to the full amount of the reversal, including GHG emissions from losses to project and baseline carbon stocks. –**AFOLU rule 3.6.8**

The forest protocol rules in the context of the attached study present an obvious paradox, as they clearly prohibit the long-term diminishment of species diversity but appear to afford quite limited prospects for silviculturally sound and sustainable timber production (in adherence to CAR criteria), which in Southern Appalachia is essential to the maintenance of current biodiversity levels. These results also revealed that limitations on even-aged opening size and project age-class distribution have no influence on even-age harvest levels, as barely complying with them in the first half of the study’s simulation produced more liabilities than credits. Furthermore, given that project viability necessitates low harvest levels to begin with, sustainable forestry certification will not be needed to ensure sustainable harvesting levels and may otherwise offer little value relative to its cost.

These suggested changes would not only allow for a more seamless process of incorporating VCS registered projects into the CA offset market, but more importantly, would make the ARB regulations significantly more workable for IFM project owners and developers, especially those with small acreages that altogether could increase the offset supply considerably. After all, the idea behind IFM offset protocols is to make improvements in forest management more attractive not to bring them into a relatively inflexible regulatory system that landowners or their heirs cannot escape from without bearing overwhelming costs.

Project Evaluation of Sustainable Upland Hardwood Management in the U.S. South with the Monetization of Carbon

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**Photo of study area by Kingsbury (**[**2008**](#_ENREF_76)**)**

by:

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Approved:

Dr. Brian Murray, Advisor

Masters project submitted in partial fulfillment of the requirements for the Master of

Environmental Management degree in the Nicholas School of the Environment and Earth

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## Abstract.

Many studies have demonstrated that working pine forests can be cost-effectively managed to enhance carbon sequestration under various, mostly hypothetical compensation frameworks but none have assessed the creditable carbon potential or financial viability of rarely employed sustainable forestry practices in upland hardwood forests, the South’s most abundant, complex and exploited forest type. This study examines the economics of sustainable forestry in the Southern Appalachian Mountains with and without the monetization of carbon due to the region’s importance to eastern hardwood timber production and its overarching ecological significance. The primary constituent of the landscape, upland oak forests, face a confluence of threats to their continued prevalence in the region and are declining in the absence of recommended oak-sustaining silviculture, which will have serious implications on the biota of these forests. This analysis was therefore conducted to assess the viability of oak-management at the project level for a hypothetical Appalachian hardwood forest according to the updated Climate Action Reserve (CAR) forestry protocol to see if this program lends itself to mitigating both greenhouse gas emissions and the potential ecological calamity associated with oak decline. A dynamic 100 year model was built with the Forest Vegetation Simulator to best approximate real world conditions. Even with an appreciable reduction in harvesting on 20 percent of project area and lower harvest intensities on the rest of the forest compared to business as usual (BAU), the CAR protocol gave little credit for doing so. Project implementation under all tested-variations of the protocol yielded lower value than the timber-only project scenario or BAU scenario at reasonable carbon and timber prices. These results cast doubt on the utility of the CAR protocol (version 3.2) as a catalyst for popularizing sustainable even-age forestry in medium to small size tracts of relatively mature upland hardwood forests, as was hypothesized. An alternative baseline linked to anticipated management with limited liability for carbon credit reversals was the only variation that rendered CAR participation more economic than the timber-only scenario at foreseeable prices. The pragmatism of different protocol elements called into question and potential solutions identified herein certainly need to be examined in future protocol revisions if CAR is to become widely applicable.

## INTRODUCTION

The annual sequestration or removal of atmospheric carbon dioxide (CO2) by U.S. forests[[1]](#footnote-1) significantly ameliorates the national account of greenhouse gas (GHG) emissions. In recent years, carbon removals resulting from wood utilization and forest growth have mitigated 12-15 percent of total U.S. emissions ([U.S. EPA 2008](#_ENREF_12); [2009](#_ENREF_13)). Domestic climate change mitigation actions that amplify biological carbon removals are particularly beneficial because many can be initiated with virtually no lag time as opposed to more fundamentally transformative emission abatement solutions requiring more exhaustive facilitation and underwriting by governments and capital markets. Sequestration activities can in turn help slow the rate of climate change as technologically driven emission reductions are scaled up or can be allowed to offset unabated emissions until compulsory emission reductions become cost-effective in comparison.

Of these activities, improved forest management (IFM) has been identified as one of the most rapidly deployable and cost effective ([Murray et al. 2005](#_ENREF_42); [Sohngen and Brown 2008](#_ENREF_61)). IFM in this context can involve slowing harvest cycles, increasing post-harvest retention levels, minimizing timber harvest impacts to the soil and residual growing stock, and/or preserving forestland to protect against timber extraction. Aside from direct carbon payments to landowners, concomitant benefits from the effective application of IFM can have multiplicative and cascading effects on both ecosystem and societal welfare at multiple scales and include: diversified and perhaps stabilized employment opportunity in forestry for managers, surveyors, equipment operators, entrepreneurs, researchers and others; reduced wildfire hazard; enhanced materials and energy recovery associated with forest treatments; advanced knowledge of forest ecosystems and their response to silvicultural treatments; enhanced and enlarged wildlife habitat; improved control of pests and invasive species; decreased erosion and nutrient loss; improved flood control and water quality; increased production of non-timber forest products; enhanced awareness of the natural features and history of locales; and augmented recreational values and related revenues.

###### *IFM Potential in the Southern United States[[2]](#footnote-2)*

Given the backdrop of mainstream media and political attention to GHG cap-and-trade policy and to its influence on forestry, the way in which IFM can be tapped for climate benefits has understandably become a key focal point for many entities with interests in domestic forestry (e.g. [Forest-Climate Working Group 2009](#_ENREF_5); [CAR 2009](#_ENREF_1)). As much of the nation’s, and indeed the world’s, investment-grade timberland lies in the southern U.S. ([Cascio and Clutter 2008](#_ENREF_35)) and accounts for the majority of national volume growth in both the hardwood and softwood resource ([Smith 2009](#_ENREF_130)), the viability of forest carbon projects in the region’s key ownerships, forest cover types and management types also appears to be of primary interest to its numerous and influential stakeholders.According to Birdsey and Lewis ([2003](#_ENREF_27)), U.S. forest statistics from 1987 to 1999 reveal that nearly half (~46 percent) of forest and wood product net carbon accrual occurred in or originated from the southern U.S.[[3]](#footnote-3) Of this growth, 70 percent was attributable to Non-Industrial Private Forests (NIPFs), 41 percent to wood products in use or in landfills, and 60 percent to planted loblolly pine (*Pinus taeda*) acreage. Future increases in the national share of timber production are projected ([Smith 2009](#_ENREF_130)), which are likely to further expand the share of U.S. forest carbon sequestration occurring in southern states. Under a national compensation scheme, empirical estimates of potential IFM-induced carbon sequestration in NIPFs show that the South holds the most mitigative potential by far ([Murray et al. 2005](#_ENREF_104)). Altogether, these estimates imply that national climate change mitigation programs can substantially benefit from encompassing the South’s NIPF owners, wood production chain, and actively managed timberlands[[4]](#footnote-4) assuming a careful balance is struck in their relative engagement.

###### *Focus on Upland Hardwoods*

Private landowners hold 78 percent of hardwood timber volume, 74 percent of which is located in the eastern U.S. Upland hardwood forests cover the majority of timberland in the South and nearly two-thirds of non-corporate southern timberland ([Smith 2009](#_ENREF_130)); the extent and concentration of upland hardwood forests can be seen in Figure 1. Therefore, the future of the hardwood resource and thereby most of the eastern forest resource is almost exclusively in the hands of the private sector. Yet many non-corporate private owners do not understand the implications that commonly chosen management decisions or lack thereof have on future plant and wildlife communities, management options, economic returns, and opportunities in emerging carbon markets. In fact, due to prevailing market incentives, upland hardwoods have historically been disfavored ([Siry 2002](#_ENREF_122)), converted ([Connor and Hartsell 2002](#_ENREF_41); [Mcgrath et al. 2004](#_ENREF_89)) or exploited without consideration for future renewal or value ([Fajvan et al. 1998](#_ENREF_50); [Miller 1993](#_ENREF_94)).

This paper examines upland hardwood forest management in the Southern Appalachian Mountains in the context of IFM project feasibility due to its importance to eastern hardwood timber production and the overarching ecological significance of these forests from the watershed to transcontinental scale. The region is comprised of some of the richest and most endemic tree and amphibian biotas in North America

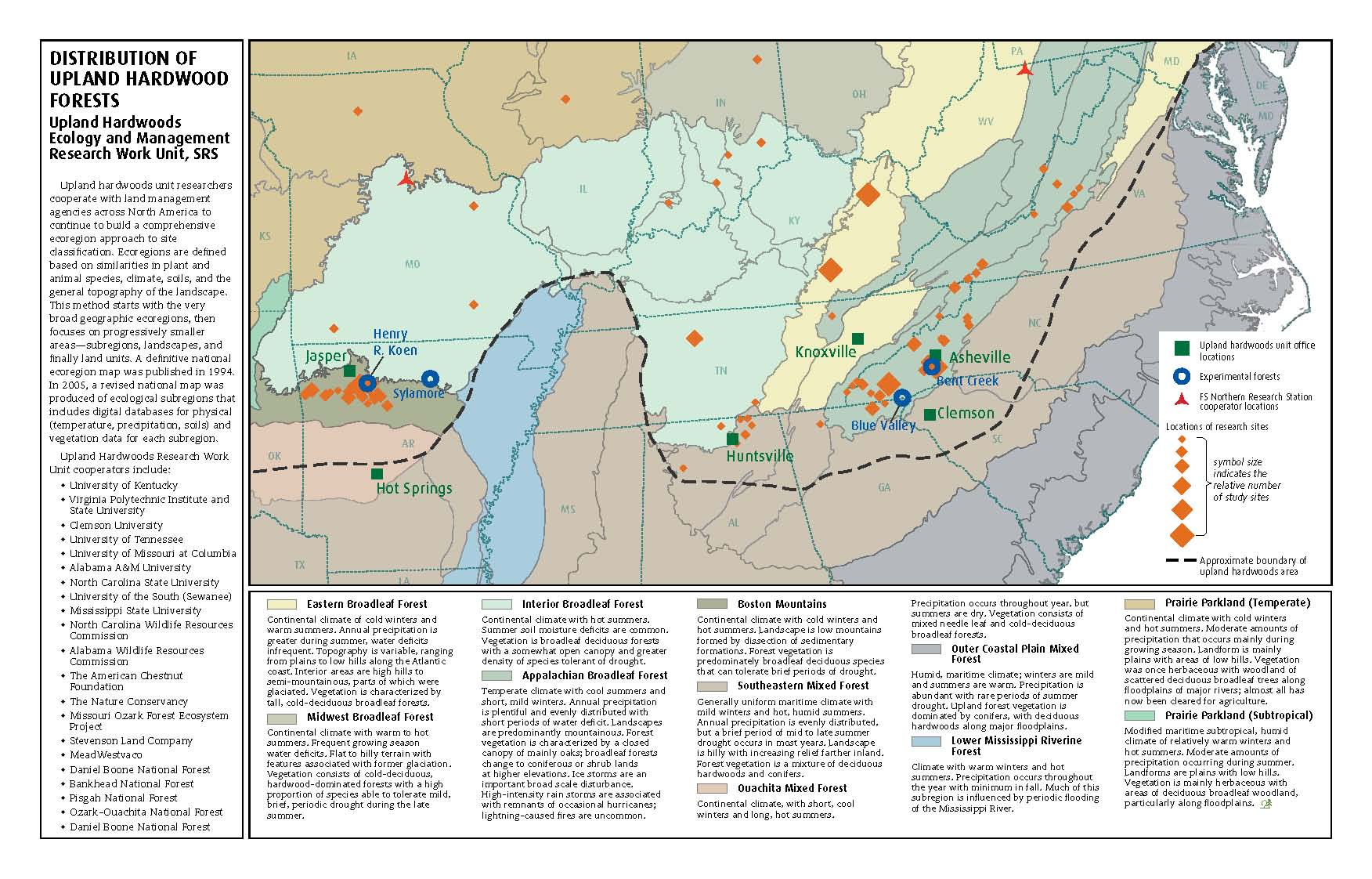


Figure 1. Spatial extent and concentration of upland hardwood forests in the U.S. South ([Source: USDA Forest Service 2007](#_ENREF_14))

([Ricketts et al. 1999](#_ENREF_113)) and constitutes one of the most complex timber markets ([Southern Appalachian Man and the Biosphere 1996](#_ENREF_9)), in which oaks (*Quercus* *sp.*) have been among the most valuable species. Upland oak forests have dominated the Appalachian landscape for the last 2000 years ([Delcourt and Delcourt 1987](#_ENREF_46)), and since the demise of the American chestnut (*Castanea dentata* Marsh.) in the early 20th century, have constituted the preponderance of the hard mast supply, a crucial pillar of the food web that numerous birds and mammals depend on as a food source in the dormant season ([Mcshea and Healy 2002](#_ENREF_90)). Now upland oaks face a confluence of threats to their continued prevalence in the region and are declining in the absence of recommended oak-sustaining silvicultural treatments ([Schuler 2004](#_ENREF_118); [Mcshea et al. 2007](#_ENREF_91)). As 80 percent of oak forests in the eastern U.S. are owned by NIPF owners ([Mcwilliams et al. 2002](#_ENREF_92)), their conservation will rely on widespread adoption of oak-management on NIPF land, a monumental challenge that has just begun to be proactively addressed ([see Mcshea et al. 2007](#_ENREF_91)). Whether existing and potentially government induced IFM programs can foster silvicultural operations at the requisite scale to sustain oak dominance in the South remains an open question.

###### *Coinciding Burdens on Upland Oak Forests*

Oak timber is still the most abundant, constituting 31 percent of total eastern hardwood growing stock, but Red maple (*Acer rubrum)* volume is the second most abundant and is growing rapidly, which has more than doubled (as has Yellow Poplar or *Liriodendron Tulipifera)* since 1963 ([Smith et al. 2009](#_ENREF_130)). What explains this trend? Aside from the advantages of seed dispersal via wind over gravity- or animal-dispersal, a chief driver of this trend is related to the fact that 60 percent of southern NIPF land has been treated with some sort of partial harvesting method exclusive of thinnings ([Connor and Hartsell 2002](#_ENREF_41)).

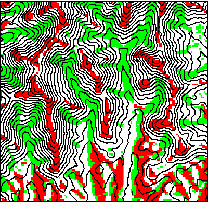
Research indicates that the silvicultural techniques required to sustain growth and maintain species composition in upland hardwood forests are less appealing on a short term financial basis than partial harvests based on a diameter limit ([Baumgras and Ledoux 1995](#_ENREF_24); [Smith and Miller 1987](#_ENREF_127)), the most commonly employed harvesting practice in the region ([Miller 1993](#_ENREF_41); [Fajvan et al. 1998](#_ENREF_23); [Stringer 2008](#_ENREF_62); [Oswalt et al. 2009](#_ENREF_46)), which removes all merchantable trees above a specific diameter at the stump or breast height (DBH). Diameter limit (DL) cuts are encompassed in the term “partial harvests”; however, unlike group selection partial harvests, DL cuts are not considered silvicultural practices because they are rarely administered by foresters and in turn typically result in high-grading, in which valuable trees are removed from the overstory without consideration for the effect that residual trees will have on the quality or growth of the future stand.

Prescribing appropriate silvicultural treatments in Appalachian hardwood forests is confounded by their inherent species and site diversity, as there are 20 commercial timber species that, due to silvical traits and historic disturbances, coexist in various relative abundances and structural associations within a similarly complex assortment of growing sites ([Miller and Kochenderfer 1998](#_ENREF_97)). As all-aged stands would dominate much of the eastern forested landscape without human disturbances ([Runkle 1985](#_ENREF_115)), many conservationists naturally believe that naturally regenerated forests should be managed to mirror such a state to the extent practicable, especially those in mountainous terrain where even-age harvests are unsightly and historically associated with poor logging practices. Although uneven-aged practices come the closest to mimicking small-scale natural disturbances, they ironically reduce species diversity by imposing stand conditions that favor a small shade-tolerant group of species ([Miller and Kochenderfer 1998](#_ENREF_97); [Schuler 2004](#_ENREF_118)).

Moreover, the longest-running experiment in hardwood silviculture portends the elimination of all oak seed sources and competitive advance regeneration in the near future if DL cuts are continued in stands subjected to DL cuts over the 45 year study ([Schuler 2004](#_ENREF_118)). When diameter limits control partial harvests on good to excellent quality sites (Red Oak site index 65+), subsequent stand dynamics precipitate a significantly less diverse species mix that is very similar to that resulting from single-tree selection harvests ([Trimble Jr. 1973](#_ENREF_139); [Miller and Smith 1991](#_ENREF_99); [Schuler 2004](#_ENREF_118)). These uneven-age practices diminish the value of future periodic harvests because they induce a proliferation of shade tolerant species in the understory that under such conditions produce less grade sawtimber and garner lower market prices than do relatively intolerant species ([Miller 1993](#_ENREF_94)) that are likely to be outcompeted when canopy openings occur ([Fajvan and Wood 1996](#_ENREF_52)). However, low-DL harvests can heavily reduce stocking, allowing the successful regeneration of well-formed less shade-tolerant species that are more desirable ([Smith and Lamson 1977](#_ENREF_125); [Fajvan 2006](#_ENREF_49)). While these intolerants out-compete their more tolerant neighbors outside of residual tree shade, the tolerant and pervasive maple population in the understory makes less tolerant species more scarce, especially oaks ([Fajvan 2006](#_ENREF_49)). Such outcomes are by definition unsustainable according to the Montréal Process Criteria and Indicators ([Montréal Process Working Group 2009](#_ENREF_7)). Indeed, if oak abundance declines by a significant extent, wildlife communities throughout the eastern forest region and especially in Southern Appalachia will be profoundly and adversely impacted ([Mcshea et al. 2007](#_ENREF_91)).

Absent management and low intensity wildfire in these forests, species diversity also regresses ([Schuler 2004](#_ENREF_118); [Clark et al. 2007](#_ENREF_39)) and red oak species become increasingly vulnerable to “Oak decline” ([Shifley et al. 2006](#_ENREF_121)). “Oak decline” refers to usually clustered and relatively slow mortality events in aging hardwood forests brought on by a stress-induced disease complex whose incidence is notably high in Southern Appalachia ([Oak et al. 2004](#_ENREF_108)). Moreover, the European gypsy moth invasion from northern states (where it was introduced) is expected to exacerbate the incidence of “oak decline” because oaks are its preferred food source ([Kauffman and Clatterbuck 2006](#_ENREF_75)). In effect, halting or extensively deferring timber harvests on upland oak sites for carbon credit accrual may be as unsustainable as DL cutting. Furthermore, increases in stand density and corresponding increases in live tree carbon stocks accompany the transition to northern hardwood forest cover types. Therefore, financially rewarding the augmentation of forest carbon stocks indiscriminately may establish a perverse incentive to facilitate the transition to maple dominated forests.

In fact, DL harvests significantly stimulated periodic annual growth over the 45 year experiment described above, approaching the level of growth observed in even-aged stands on similar sites. This outcome contends with common wisdom that DL cutting hinders periodic growth due to the low-vigor of small-diameter residual trees. However, a dense understory dominated by shade-tolerant maples can respond to canopy openings with vigorous growth ([Tryon et al. 1992](#_ENREF_140)). Thus, it follows that if this response is replicable, despite common wisdom, DL cuts undertaken by landowners could perhaps qualify as IFM practices and generate creditable carbon just as easily if not more so than biodiversity supporting even-age silvicultural practices. Such a tradeoff between carbon and biological diversity is a significant one because it presents exceptionally undesirable implications for both carbon and other non-carbon forest values in the long run. For instance, oaks are more adept at surviving in dry growing conditions than associated maples and other species. Hence, oaks may be crucial to maintaining productive or perhaps cohesive forest cover, thereby stabilizing potential deterioration of carbon stocks in parts of Southern Appalachia that may experience a drier future climate. However, once oak parent trees are reduced to very low densities, artificially establishing oak reproduction becomes the only option for successful restoration, which is difficult and extremely expensive.

Due to impending and uncertain climate changes, forests must be managed with the recognition that they will have to adapt to a climate that may severely limit the productivity of many species and even threaten their existence. These uncertainties necessitate that IFM programs include rules that ensure sustainability in terms of future ecosystem productivity and resilience —the ability to recover from stress and persist through time, of which species diversity is a key indicator ([Franklin et al. 1989](#_ENREF_55)). Such measures are embedded in the Climate Action Reserve Forest Project Protocol, hereafter referred to as the CAR protocol, which compels an assessment of it in this analysis. The latest revision of the CAR protocol afforded the ability to encompass multiple forest community types in a project by removing a problematic rule dictating that proposed projects with fewer than 90 percent of total area in a single forest community were ineligible as a single project. In doing so, CAR expanded its applicability to Appalachia, where most properties large enough to be viable IFM projects are comprised of a mosaic of forest community patches determined by the great environmental heterogeneity and disparate disturbance history of the landscape. Figure 2 illustrates this point, depicting how forest composition relates to landform position and shape in the Appalachian Mountains. What’s more, the elimination of this rule now enables Appalachian CAR projects to restore mixed hardwood communities that have been overwhelmed by maples and associated species.

**Figure 2. Relation between forest community types and Appalachian topography mapped by Pearson (**[**2008**](#_ENREF_110)**)**

Moreover, forest loss to suburban sprawl is predicted to accelerate over the coming decades but most significantly in the Southern Appalachian Piedmont and to a lesser degree in the Southern Appalachian Mountains, notably areas surrounding Knoxville, TN[[5]](#footnote-5) ([Wear et al. 2004](#_ENREF_145)). Suburbanization is also increasingly fragmenting forested landscapes and thereby limiting the efficacy of forest management ([Alig et al. 2008](#_ENREF_19)). Stein et al. ([2010](#_ENREF_133)) report that most of the region’s watersheds rank at or above the 90th percentile for number of at risk species associated with private forests predicted to be developed in the next two decades. Timberlands in the Cumberland Mountainsv and Plateau (or Cumberlands) of Tennessee will therefore be increasingly impacted by development pressures, which also presents a threat to the region’s timber supply ([Smith 2009](#_ENREF_130)) due to the area’s high stocks of timber. Such effects have been incorporated into regional timber supply models in which they are assumed to primarily affect natural forests over pine plantations or other timberland investments ([Adams et al. 2005](#_ENREF_18)). However, the Cumberland Mountains are likely far enough from urban populations to largely escape significant appreciation in timberland values and thusly remain relevant for IFM as opposed to avoided deforestation assessment.

Not only do the Cumberland Mountains encompass one of the most diverse forest landscapes in North America ([Braun 1942](#_ENREF_28); [Muller 1982](#_ENREF_103); [Ricketts et al. 1999](#_ENREF_113)), they also comprise the headwaters of the Cumberland River, which is among the most diverse temperate freshwater communities in the world ([Natureserve 2010a](#_ENREF_105)). It should be noted that corporate ownership is high in the Cumberland Mountains and significantly comprises watersheds containing high numbers of at-risk species ([Stein et al. 2010](#_ENREF_133)). This may not bode well for such species given that many of these owners are timberland investment organizations that might only hold these investments for relatively short periods, after which such lands could become parcelized ([Alig et al. 2008](#_ENREF_19)). The coinciding fragmentation of timberland is likely to adversely affect the seriously declining cerulean warbler (*Dendroica cerulea*) population ([Buehler et al. 2006](#_ENREF_30)) and presents a grave threat to terrestrial biodiversity in general ([Armsworth et al. 2004](#_ENREF_20)). Thus, in addition to facilitating the adoption of more sustainable forestry practices, successful IFM deployment in such high conservation value forests would not only help maintain forest continuity and management efficacy but would also render large and distinctive non-carbon benefits.

###### *Ownership and Anticipated Behaviors/Opportunities*

Further insight into the practical and meaningful deployment of IFM activities in the South requires consideration of the makeup of timberland ownerships and recent economic impacts. First, it should be noted that the vast majority of southern timberland is privately held and 60 percent is held by non-corporate ownerships ([Smith 2009](#_ENREF_130)), or family forest ownerships (FFOs), which most applied forestry research is at least implicitly focused on informing or studying (including this paper). Second, nearly half of FFO land is comprised of 50-499ac (small to medium) tract sizes and another quarter is comprised of larger tracts, held by 12.1 percent and 0.7 percent of FFOs respectively[[6]](#footnote-6) ([Butler 2008a](#_ENREF_31)).The fact that this small fraction of FFOs controls three-fourths of family forest acreage and roughly half of all southern forestland seems to lend itself to a rapid deployment of IFM activities. In contrast to tract size-classes under 50 ac, the majority of land in these size-classes has undergone commercial treatments indicative of management for timber products ([Butler 2008a](#_ENREF_31)); hence, they generally define the floor of tract sizes relevant to IFM activities. While some find that only the latter size-class comprising under 1 percent of owners can plausibly benefit from existing voluntary IFM frameworks as individual projects ([Finite Carbon](#_ENREF_4) 2009), the likelihood of participation by those in the medium and smaller size-classes has improved greatly with the enabling of project aggregation by most IFM programs. Transaction costs are one of the key challenges that FFOs face in their ability to participate in emerging carbon markets due to the relatively high development and implementation costs, which are dampened by larger sized operations facilitated by aggregation ([e.g. Gunn et al. 2008](#_ENREF_63)). Recent analyses find that “cross-boundary coordination” further presents an opportunity to marginally improve both economic and ecological outcomes in privately owned landscapes ([Gass et al. 2009](#_ENREF_58); [Schulte et al. 2008](#_ENREF_119)). Forest carbon project aggregators may be able to play this role and improve forestry practices and conservation at a landscape level while combatting forest fragmentation and the hurdles to sustainable forestry.

Perhaps the most important statistics deserving attention are those describing the demographics of FFOs, market circumstances pointing to elevated timber harvests, and the effects on rural areas of the recent economic implosion. FFOs with maturing hardwood stands have undoubtedly experienced financial stress or setbacks recently for which timber revenues would compensate. These conditions appear likely to predicate an ensuing rise in harvest activity as timber prices recover with the economy, causing many forests to emit more carbon than they remove from the atmosphere. While it is impossible to precisely determine the prevalence of silviculturally informed management, recent survey data collected from 2002 to 2006 show that only 8.4 percent of southern 10+ acre FFO holdings controlling 25 percent of FFO forestland claimed past harvesting was part of a management or stewardship plan ([Butler 2008b](#_ENREF_32)). Thus, the influence of harvest strategy and execution on the future value of a forest tract and the consequent effect on long-term biodiversity, wildlife habitat, and water quality is probably not understood by most FFOs.

This widespread misunderstanding of forestry’s role in the continued supply of desired forest products and services, coupled with the fact that 57 percent of FFOs (at least 64 percent of southern forestland) are at or nearing retirement age ([Butler 2008a](#_ENREF_31)), could perpetuate short-sighted management practices such as DL cutting. At the same time, FIA data suggests that over 60 percent of even-aged timberlands in the region are mature enough to undergo partial harvesting ([USDA Forest Service 2010a](#_ENREF_15)). Smaller FFOs are by far the most prevalent timberland owners. They are also more likely to be dependent on the natural capital in their forest and to not have a written management plan ([Butler 2008b](#_ENREF_32)). Many of these smaller owners, especially those at or nearing retirement, with relatively mature and accessible timberland can therefore be expected to engage in DL cutting in the near future if timber prices continue to rebound from recent lows.

The overall ecological and economic situation of the Cumberland Mountains certainly appears to lend itself to the relevancy of “proof of concept” research undertaken in this study. Indeed, all counties in the Cumberland Mountains of Tennessee are among the most distressed in the nation as they and many others in Southern Appalachia rank in the top 20 percent of counties that had experienced relative unemployment increases in the 2007-2009 recession. As a consequence, the level of employment in these counties is not expected to recover for some time ([Greenstone and Looney 2010](#_ENREF_61)). Fortunately, IFM investments are already being made in the area and their continuation throughout the region may help the local forestry sector and related communities recover to some degree. Yet the potential for IFM projects to appreciably increase FFO income remains an open question.

Considering that a mere 5 percent of FFOs possess written management plans ([Butler 2008b](#_ENREF_32)), there seems to be potential for IFM programs to combat the widespread unsustainable management practices in the region that hasten the decline of oak. Even with a management plan, upland hardwood harvests are not likely to be spelled out in them, as most treatments are contingent on a complicated suite of factors. On the other hand, IFM programs are unlikely to shrink the profitability gap between imminent DL cuts and sustainable forestry given the value of grade sawtimber. The prospects for ending timberland degrading practices may ultimately depend on greater market demand for domestic low-grade wood products and outreach efforts that inform FFOs of the implications from conventional harvesting practices ([Mcshea et al. 2007](#_ENREF_91)). Nevertheless, considering that FFOs in the South consistently find property taxes to be a highly concerning limitation of land use ([Butler 2008b](#_ENREF_32)), IFM activities that could demonstrate net revenues in excess of property taxes would likely be quite attractive to most FFOs, especially if developers can cover the costs of project development and implementation or provide loans for them as some already do. Thus, an analysis of IFM’s marginal value in key southern forests is needed to determine if this win-win scenario is a likely outcome or just wishful thinking.

###### *IFM Research History and Relevance*

Approximations of forest carbon stocks corresponding to broadly defined geographical areas, forest types and site quality by Birdsey ([1996](#_ENREF_26)) provided the first clear demonstration of C sequestration resulting from even-age management. These tables and methods described for their use became the cornerstone of subsequent analyses, technical guides ([J.E. Smith et al. 2006](#_ENREF_129)), accounting protocols, and online tools ([Van Deusen and Heath. 2007](#_ENREF_141)) that inform the ballpark quantification of carbon sequestration for a given forest type (or type group), age and locale. These updated and digestible data and guidance have fostered numerous assessments of sequestration opportunity in forestry ([e.g. Foley et al. 2009](#_ENREF_54)). Yet most studies are rarely executed at scales or within tangible frameworks and circumstances meaningful to typical forest owners and managers that may be knowledgeable or curious about the opportunities presented by carbon offset markets.

Despite the fact that planted yellow pine area comprises about one-fifth of southern private timberland and only about 12 percent of non-corporate private timberland ([Smith 2009](#_ENREF_130)), most IFM studies are narrowly focused on industrial plantation management (i.e. intensively managed southern yellow pine) and/or simplistic scenarios (e.g. [Walker et al. 2005](#_ENREF_66); [Cason et al. 2006](#_ENREF_14); [Sohngen and Brown 2008](#_ENREF_61); [Dwivedi et al. 2009](#_ENREF_22); [Galik et al. 2009](#_ENREF_26)a; [Nepal et al. 2009](#_ENREF_45)). Applied IFM research has indeed addressed important questions pertaining to the magnitude of potential carbon removals, costs, and returns that can be expected from lengthened pine rotations induced by current or anticipated IFM programs. Nevertheless, research addressing similar questions or other IFM tactics for hardwood forests is exceptionally lacking. Case studies of key forestry offset protocols that evaluate IFM practices for important forest conditions in the South are critical to filling this void. While protocols remain in a state of considerable flux causing this important subset of the literature to perhaps lose relevance, it should be noted that plantation forestry particularly appears to be on the losing end of IFM rulemaking as the dust settles ([e.g. CAR 2010](#_ENREF_2)). Accordingly, this study builds onto recent research by Nunery and Keeton ([2010](#_ENREF_107)), which quantified the individual and coupled effects of harvest frequency and post-harvest retention on carbon sequestration in mature forests in the northern hardwood region using the Forest Vegetation Simulator. Alternative even-age management practices similar to those evaluated by Nunery and Keeton ([2010](#_ENREF_107)) are simulated herein. But in addition, an examination of the economic outcomes generated from the pragmatic application of such activity under a widely recognized IFM standard was the primary intention of this assessment.

## OBJECTIVES

This study sought to undertake the first real-world project-scale assessment of sustainable upland hardwood management under the new national CAR Forest Project Protocol (version 3.2) for the benefit of managed forest owners that may consider such an investment. It was also intended to contribute to the sparse documentation on applied IFM offset economics and long-term modeling with the Forest Vegetation Simulator, the model maintained and supported by the U.S. Department of Agriculture, Forest Service (USFS). The vast majority of landowners and foresters are either not familiar with the processes required to monetize forest carbon sequestration, let alone other ecosystem services, or are deterred by low carbon prices. The significant upfront costs and technical expertise required at project inception coupled with uncertainty in the ultimate outcome are major impediments to landowner engagement in these voluntary markets. Hence, another primary intention was to examine the discernable impacts of key features and costs of the given management regime, forest carbon accounting, and certification procedures on IFM project economics to help define the limiting factors in implementation.

###### *Commodity Driven Sustainable Forestry with Carbon Value*

The simulated IFM regime was intended to reflect silviculturally and economically justified timber-focused management given that potential earnings from carbon sequestration are not likely to outweigh those of timber harvesting for relatively mature timberlands as long as carbon prices are low to modest. Project management was particularly colored by the rarely sought aim at maintaining oak dominance across the landscape. Contemporaneously balancing age-classes was an essential element of IFM simulations in that it kept average per acre carbon stocks elevated and because the forests in this study are approximately the same age, owing to the fact that a plurality of the region’s forests were cleared in the 1910s and 1920s ([Hall 1910](#_ENREF_65); [Hinkle et al. 1993](#_ENREF_72); [Southern Appalachian Man and the Biosphere 1996](#_ENREF_10)). Galik et al. ([2009a](#_ENREF_57)) conducted a similar analysis of IFM viability under various protocols for a Piedmont old-field loblolly pine (*Pinus taeda*) plantation, albeit with already balanced age-classes. While Gunn et al. ([2008](#_ENREF_63)) evaluated a potential IFM project in Maine under a hypothetical methodology for aggregated projects, the approach of Galik et al. ([2009b](#_ENREF_56)) and this paper appear to be the only localized project-level feasibility studies of IFM applications in the South to date. It is fitting then that this study examines the counterpart to softwood plantation management in the South. As in Gunn et al. ([2008](#_ENREF_63)) and Nunery and Keeton ([2010](#_ENREF_107)), the modeling approach necessitated for this analysis is more closely linked with forest ecology than past IFM studies and consequently lent itself to ecological considerations in simulated treatments and more accurate accounting of harvested wood product (HWP) sequestration and earnings.

Specifically, the hypothesis of this analysis was that adoption of oak-sustaining silviculture and otherwise sustainable commodity-driven forestry —administered per CAR-constraints on the distribution of age-classes, canopy opening size, and minimum live tree carbon stocks― could render gains in net present value (over timber-only focused oak management) at carbon prices foreseeable in the near future. Other important notions and assumptions that predicate this exercise include: A) the hypothetical study area is medium size FFO timberland just mature enough for profitable harvests and thereby prone to mismanagement; B) development considerations of “higher and better use” and related impacts on forest management are ignored; C) management attitudes and behaviors of the hypothetical owner(s) and heir(s) result in short-term profit maximization and remain the same over time; D) the same operational best management practices are applied in each scenario; E) property taxes are ignored since they presumably would not differ between scenarios given that TN forestlands are not required to have written management plans to receive present-use tax treatment; F) timber prices do not climb to levels that induce harvesting for two years; G) significant natural disturbances and environmental changes are ignored; H) changes in unmeasured carbon pools are not big enough to warrant their measurement; and I) the project is part of an aggregate of similar IFM projects. While the goal is to quantify the marginal benefit from CAR participation as an IFM project in this geographic region, the relative differences brought to light from scenario comparisons should be more instructive and meaningful than absolute values.

## METHODS

* 1. ***Forest Model******ing***
     1. ***Forest Vegetation Simulator***

Numerous empirical models forged over the last several decades to predict various features and underlying function of forest ecosystems in the U.S. are now integrated in a free-ware system called the Forest Vegetation Simulator (FVS), which is maintained by the USFS. FVS emanated from the Prognosis Model for Stand Development, which was designed to simulate mixed forest stand-dynamics in the mountains of northern Idaho and western Montana with an inherent capacity for interacting with applicable disturbance models ([Crookston and Dixon 2005](#_ENREF_42)). Despite the base model’s original geographic scope, FVS has emerged as the core framework in the national forest management planning system due to its ability to dovetail with other regional growth models. As a result, an array of software tools has consolidated around the FVS platform enabling the examination of a variety of biological processes in relation to silvicultural activities. Consequently, FVS allows robust and dynamic projections over centuries (e.g. Vandendriesche and Haugen 2006; Nunery and Keeton 2010) and is a powerful tool for land managers with the gumption, patience, and inventory data to make management prescriptions and evaluate their effects.

As the utility of the FVS modeling system appears to be unparalleled, it was evident at this project’s inception that the Southern Variant (SN-variant) of FVS was the only model sophisticated enough to simulate the long term management of some of the most complex forests in North America. It is however not as well developed as western variants and requires a substantial amount of parameterization and augmentation. Despite the advanced capabilities of FVS, it shares a common limitation with other growth models in that it only renders reasonably accurate growth projections in the short- term using default parameters ([Rauscher et al. 2000](#_ENREF_111); [Davis et al. 2009](#_ENREF_45)). At the same time, many model features employable for FVS simulations may inject far more uncertainty into model outputs. For this reason and because uncertainty in stand predictions increase with time, it is more incumbent upon the modeler of long-term forest projections to parameterize the model to the fullest extent practicable with comprehensive/rigorous site measurements and/or conservative assumptions if stakeholders are to have sufficient confidence in the results. It is also paramount to manually estimate sawtimber volumes in order to obtain more reliable estimates than those provided by the Sn-variant at the present time (for reasons mentioned later in this section). Inadvertently overstating the potential timber and carbon quantities could spell financial disaster for owners of smaller tracts that place too much credence in analyses based on simulations. Prudence therefore dictates that simulations be parameterized with accurate and/or conservative values and assumptions due to the acute sensitivity of eastern FVS-variants to density-influencing adjustments ([Nunery and Keeton 2010](#_ENREF_107)) and due to the significant investments that could be leveraged on favorable model results. However, making simulations overly conservative at every step is also unwise.

FVS’s usefulness is more demonstrable in its suitability for performing sensitivity or comparative analyses that reveal the relative effects that various model parameters or scenarios have on stand conditions; though, in large simulations such as this, model parameters are too numerous for sensitivity analysis. As such, those embedded in the forest simulation model here represent best guesses informed from the forestry literature and trial and error; these include natural regeneration parameters, adjusted small-tree height growth, adjusted growth and survival responses to release treatments, simulated logging damage to residual stems, and adjusted stand density constraints. Others were derived from onsite inventory data or public soil records which include site index, percent defect, and large tree diameter growth parameters. For example, the precise diameter increments provided by the inventory data enabled the calibration of the large-tree diameter increment model.

* + 1. ***Study Area and Data***

The Tennessee Valley Authority instituted a Continuous Forest Inventory (CFI) program in the 1960s and 1970s consisting of over 9,000 permanent forest plots in Eastern TN ([Batteson and Hitchcock 1976](#_ENREF_23)), from which the inventory data used in this study originated. The site of the plots utilized was located in the Wartburg Basin (Morgan County, TN) at the southwestern edge of the Cumberland Mountain section of the Appalachian Plateaus physiographic province ([Fenneman 1938](#_ENREF_53)). This region of Southern Appalachia was once the area that best exemplified the forest type with the highest tree diversity in North America, the mixed mesophytic forest association ([Braun 1942](#_ENREF_28)). These mountains have a humid mesothermal climate characterized by long, moderately hot summers and short, mild to moderately cold winters ([Thornthwaite 1948](#_ENREF_136)) with usually 50 percent of the annual average precipitation (55 inches) falling in April through September[[7]](#footnote-7) ([Davis and Yaeger 2007](#_ENREF_44)). The mean temperature is 54°F and the frost-free growing season is 163 days long 50 percentvii of the time. According to Smalley ([1984](#_ENREF_123)), soils are representative of a portion of the Muskingum-Gilpin-Jefferson soil association and are mostly pale, loamy, friable, acidic, well-drained, and vary in content of sandstone and shale fragments. Contour surface-mining operations in the past established a relatively extensive road network through the Wartburg Basin’s rugged mountains and created a new mining-spoil based soil type containing 35-80 percent rock and coal fragments.

The land was held by the Emory River Land Company during the time CFI plots were created/revisited and was later sold to The Forestland Group, LLC. The data used in this analysis originated from 1994 CFI field sampling sheets supplied by The Forestland Group, on which plot condition and sampling data from the previous 1984 sampling were printed (see field sheet copy in appendix A); plots from one of many compartments were initially selected for modeling. The 1984 data were lost for one CFI plot on a mining-spoil site, leaving 11 plots. Two nearly monotonic Yellow poplar dominated plots were paired to represent one stand in FVS since they also shared similar stand structure and carbon stocks. Likewise, the remaining CFI plots were modeled as individual stands whose tree lists were similarly paired with plots from other compartments that were the closest matches (in the 1994 inventory); the intention was to inject variation into each simulated stand. Such variability is carried throughout the simulations as each treatment instigates differential responses from the two conditions for each stand similar to what would be observed in real forests.

CFI plots spanned 13 compartments but those from one compartment were originally chosen for analysis because it had been sampled (including regeneration) to a high degree of precision and accuracy nine years after the CFI sampling in 1994. The database of this 2003 inventory was used for its seedling and sapling data because the SN-variant is not yet capable of predicting a seedling and sapling sample from a large tree plot tree list, as is the case in some western FVS variants. While the CFI plots were used in the 2003 sampling design calculations, they were not sought out for re-measurement since the new survey instituted a new sampling grid of variable-radius plots for merchantable trees. The CFI data were critical to this study in several ways. The collection of merchantability metrics permitted sound (non-rotten) timber volume estimation by tree grade, which was essential for tracking the disposition of harvested wood. In addition, DBHs from previously sampled trees allowed for calibration of the growth model to local growth rates. Tree status, source of present injury, and risk of mortality or defect were also recorded for each tree, enabling the simulation of real-world management.

The relation between initial above-ground live (AGL) carbon stocks per acre (ac-1) and the applicable CAR common practice (CP) statistic determines the requisite approach to follow for estimating a baseline carbon stock, the value that annual project stocks are compared to in the computation of annual carbon removals. Utilizing the latter set of CFI measurements with higher initial AGL stocks ac-1 would have provided a helpful jumpstart in earned credits from having initial AGL stocks above the CP statistic. Conversely, the 1984 data were less likely to earn this head-start at the outset and in effect were better suited to address the proof of concept question. Thus, the forest simulation model was constructed from the 1984 inventory, which was assumed to be conducted in 2011 for this hypothetical project.

All CFI plots were classified by topographical position, stand type, and stand size as displayed in appendix B. They were on moderate to steep slopes between approximately 1,200 and 2,600 feet (′) in elevation, congruent with general conditions in the Cumberland Mountains ([Smalley 1984](#_ENREF_123)), and were classed as “dry uplands” (upper slopes, southerly mid-slopes, or ridgetops) or “moist uplands” (lower slopes, northerly mid-slopes, coves, ravines, or lower bottoms). Plot conditions corresponded with the Upper Mountain Slope and the Colluvial Mountain Slopes, Benches, and Coves landtype associations ([Smalley 1984](#_ENREF_123)). There were equal numbers of Oak-Hickory and Yellow Poplar stand types (four each) and of Northern Hardwood and White Pine-Hardwood stand types (one each). Although these labels are not synonymous with classifications used presently by the USFS, they provide a general description of the surrounding forest’s composition. The classifications given by the USFS’s Forest Inventory and Analysis (FIA) forest cover typing algorithm and other stand characteristics are also shown in appendix B. The fact that some of these plots contain or are co-dominated by species that are mostly found in higher latitudes owes to the diversity of micro-environmental conditions in the Cumberland Mountains ([Hart and Grissino-Mayer 2008](#_ENREF_67)).

Unfortunately, increment boring and total height measurement were not part of the sampling procedure, so site indices were partly inferred from those published in the National Resource Conservation Service soil survey of the area ([Davis and Yaeger 2007](#_ENREF_44)) by locating the soil map unit on which each plot lay. While the site indices of species found by NRCS to be good site trees are provided for each taxonomic soil class, map units of this area are soil complexes comprised of more than one taxonomic class of soil but are not delineated at such a scale. As the soil classes differed appreciably in potential productivity, the species composition of the plot was relied upon as an indicator of which set of site indices was relevant; site index approximations were further refined in the process of estimating missing heights (in next section). It should be noted that one validation study of NE-TWIGS, the basis of the northeastern FVS variant growth equations, somewhat overestimated biomass in stands in the same region and of similar stand structure as those modeled in this study but was found to predict volumes to within 10-15 percent of actual volumes ([Yaussy 2000](#_ENREF_147)). Assuming the Sn-variant is equally apt at simulating upland hardwood growth and capable of the same overstating bias, it seemed reasonable to reduce the site indices of the most productive plots by 5′, which may be manifested by the warming climate.

Individual CFI plots were comprised of nested plots (concentric circles of differing radii from plot center) in which sampling was based on size class. All sawtimber size trees (≥11″DBH and above) were measured on 1/5 acres (ac) plots and all poletimber (5-10.9″DBH) on 1/20ac plots. Field sheets included a tally box for advance reproduction in 1/100ac plots but surveyors were not instructed to measure their diameters or heights. Hence, four fixed-area regeneration plots sampled in 2003 were chosen as substitute CFI regeneration plots to populate each CFI plot’s small-tree list. In most cases where a cruise point landed very close to a CFI plot, the corresponding regeneration tallies were added to the tree list of that plot. Otherwise, regeneration plots were selected if the parent plot was found to match the conditions of the given CFI plot.

Regeneration plots were also nested, in which seedlings (under 1″DBH) that fell in a 1/1000 ac plot were counted by species while saplings were counted in 1/200 ac plots by species. In such microplots, stems were tallied by the number of seedlings in 3 different height classes (<1′; 1-3.9′; and ≥4′) and the number of saplings one inch DBH or more, distinguishing between which would likely become part of the future overstory (acceptable growing stock) or not (unacceptable growing stock) as a result of form, species or competition. All seedlings in the medium height class were assumed to be 1.4′ because it is near the low end of the height class and is the SN-variant’s suggested minimum height for oak and maple advance regeneration. All trees greater than 4′ classified as acceptable growing stock were not given heights and were allowed to be defined by the height-diameter relationship employed by FVS because this relationship was found to accurately predict heights when compared with CFI data obtained from Duke Forest (Durham, NC). Because the majority of saplings classed as unacceptable growing stock were Red maple, these trees were given heights equal those of the medium seedling height (1.4′) to ensure that they were given less of an advantage at becoming part of the overstory. The diameters of seedlings and saplings were approximated since they were not measured.

Upper merchantable heights were measured to a four inch top diameter outside bark (DOB) with a clinometer and pentaprism caliper. Precision is vaguely mentioned for merchantable heights in the CFI field manual but called for them to be “measured to the nearest two feet” ([Batteson and Hitchcock 1976](#_ENREF_23)); though, heights were measured in one foot (ft.) increments. Thus, upper merchantable height data were assumed to be accurate to ± one ft. The pentaprism caliper not only allowed surveyors to ensure merchantable heights were precisely measured to the correct top diameter, but more importantly, it allowed for measurements of the variable top-diameter dividing a stem’s sawlog and pulpwood portions. Although these top diameters were meant to be inside bark (DIB) estimates, there was no indication that the cruisers were equipped with a bark gauge in addition to the pentaprism caliper to estimate DIB of upper merchantable heights. The resulting estimates of sawtimber merchantable heights enabled sawlog volume to be more accurately quantified. Because sawtimber merchantable heights were closer to the surveyor than upper heights, they were assumed to be exact measurements. While timber volume equations employed herein were derived from trees cut one ft. off the ground and implicitly assume merchantable heights include a one ft. stump, survey documents did not indicate whether stumps were included or excluded in CFI height measurements. By contrast, merchantable height of sawtimber is defined by Cassens ([2001](#_ENREF_36)) as “that portion of a tree from stump height to a point on the stem at which merchantability for sawtimber is limited by branches, deformity, or minimum diameter”. Given that many small sawtimber trees in the data have sawtimber heights of 16′, the universal butt log length, it was assumed that merchantable heights were representative of timber above the stump.

* + 1. ***Adjustments and Surrogates for Modeling***

New trees, or ingrowth, appeared in every plot’s second inventory. These trees were missing in the previous sampling because the breakpoint diameter of the given plot was greater than the tree’s DBH, precluding it from being recorded; no ingrowth had grown into the plot from outside the plot radius. Ingrowth becomes problematic when comparing inventories because large changes in poletimber volume, sawtimber volume, and other total stand measures may occur as trees in a small or medium size-class grow into a larger size-class where trees represent fewer trees ac-1 than those of the smaller size-class. This complication emerges regardless of whether such trees were ignored or tallied in the past inventory. In effect, the treatment of ingrowth had major implications in the determination of baseline carbon stocks, since the minimum-baseline level of AGL carbon stocks had to be set to initial stocks in accordance with the protocol. To err on the side of conservatism, surrogates for all ingrowth appearing only in 1994 were created for the 1984 inventory and given DBHs that reflected diameter increments of a similarly sized tree of that species observed on the same plot or one with similar conditions.

Because the initial seedlings and saplings in each stand were imputed from the separate inventory at a later stage of stand maturity, their numbers were systematically reduced. Their large numbers were deflated until approximate parity was achieved between relative stand density based on Stand Density Index (SDI) and the relative stand density measure created specifically for these forests ([Brose et al. 2008](#_ENREF_29)), in an effort to temporarily calibrate the SDI-based FVS mortality model with empirical density models used in practice[[8]](#footnote-8). Such adjustments were necessary in some stands to prevent significant augmentation of density constraints, which tried to automatically accommodate for the artificially high initial densities. Despite these adjustments, stand density rose quickly in growth-only test simulations and caused mortality to significantly impede sawtimber growth. Still, a jump in sawtimber volume occurred in the latter years of the forecast. This was the result of the small-trees in the initial tree-list growing into sawtimber trees under complete suppression. The Sn-variant (unadjusted) erroneously allowed small trees to eventually reach the midstory and mature there, despite the absence of simulated canopy openings. To prevent this unwarranted small-tree height growth, a pragmatic growth modifier was administered to the small-tree growth model based on the approximated height growth potential of oak recruits in shade. Equation 1 characterizes the multiplier constructed for this purpose, which determined the fraction of predicted small-tree height growth that was applied in each cycle. Considering that this modification was only necessary for poletimber and sawtimber stands with closed canopies, no multiplier was applied if stand age was less than 30 or if basal area was less than 20 square ft. (ft2) ac-1. The multiplier was ignored (i.e. applied growth was 100% of predicted growth) at values at or above 90 percent.

This multiplier has a starting value of five percent before accounting for stand density or percent canopy cover (CC). The rest of this equation consists of a relative density (percent stocking) term multiplied by a relative CC term. This relative CC term is made more influential by an internal multiplier equal to the ratio of the equation’s fixed SDI value to the CC value of the given cycle, reflecting the fact that small-tree growth is largely influenced by light intensity. For further control, another height growth multiplier was applied to large saplings (ten ft. or more), the magnitude of which was a function of stand size-class. However, this was only administered if relative density demonstrated moderate stocking levels or better.

Moreover, in an effort to automatically program regeneration into simulations, the FIA data from the Cumberlands of TN, KY, and VA were manually transformed into an FVS input database[[9]](#footnote-9) and run through FVS in order to generate stand tables that in turn were converted into ingrowth keyword files by the Repute post-processor[[10]](#footnote-10). This empirical approach was taken by Vandendriesche and Haugen ([2006](#_ENREF_143)) in which the process is described in more detail. Regardless of management history, seedlings and saplings up to 20′ tall were periodically added to the tree list according to embedded criteria from the Repute program. Saplings added in the cycles immediately after final harvests (< age 10) or during the stem-exclusion phase ([Oliver 1980](#_ENREF_109)) of stand development (age 15-50) were precluded so that advance regeneration inputs were realistic and did not cause an immediate spike in the regenerating stand’s carbon stocks. Aside from the ecological importance of ingrowth, its addition to simulations provided a restraint on forecasted AGL biomass growth in that the resultant increases in stand density caused mortality levels to be relatively elevated, which moderated net growth. Such density increasing measures were necessary considering that rates of carbon uptake reported by Nunery and Keeton ([2010](#_ENREF_107)) were up to 12.5 times larger in management scenarios without regeneration inputs.

Nunery and Keeton ([2010](#_ENREF_107)) asserted that “simulations lacking well researched, user-defined regeneration inputs may not realistically reflect stand development processes.” While this is true, there is no FVS guidance available for modeling the regeneration dynamics of hardwood forests under managed or unmanaged conditions other than the Repute program’s generalized, empirical estimation system developed for all forest types ([Vandendriesche 2010](#_ENREF_142)). Thus, there is no way of knowing how much regeneration is necessary to realistically regulate FVS stand mortality and species composition at various stages of stand development and management. While additional regeneration inputs in harvested stands were necessary, best approximations seemed more appropriate than overly conservative estimates in such uncertainty.

Even though the initial small-tree list combined with imputed ingrowth provided enough advance regeneration to simulate forest regrowth, a greater multitude of seedlings were needed at stand initiation to achieve stocking levels able to moderate net growth over several cycles of thinning in the regenerated stands. Therefore, in order to guarantee the re-establishment of all species in sufficient numbers, natural regeneration from both stump sprout and seed origin was simulated after each final harvest according to the number of harvested trees assumed to be coppice-capable and seed-bearing respectively. Stump sprouting occurred after every simulated thinning, whereas seed origin regeneration was only added in cycles coinciding with final harvests to ensure FVS data storage limitations were not exceeded. As a consequence, seedling flushes associated with final harvests usually did not produce trees large enough to be favored in subsequent simulated thinnings but did serve to keep stand density at appropriate levels in later cycles. Although adjustments made to default stump-sprouting parameters were based on available information from silviculture literature, differences in initial spout heights among species were made less meaningful by the insensitivity of small-tree height growth to species-specific shade tolerances.

Percent unsound (or rotten) defect grew between inventories for many trees, but data were not changed unless a tree’s measurements differed dramatically between inventories (indicative of measurement error), in which case the latter was assigned. Depending on whether a tree is defective due to form or injury and the severity and location of the flaw, percent defect may decrease as the tree grows or increase until the tree is considered cull. Although all tree records in FVS can be assigned a defect percentage that varies with DBH, relative volume deductions for records with non-zero defect measurements are constant over time because defect inputs cannot be altered by FVS simulations unless replaced by the DBH-predicted defect. This FVS function discounts gross volumes according to a curve fit to a percent defect vs. DBH table using linear interpolation, helping to prevent upward bias in sound wood estimates associated with extensive rotations.

|  |  |  |
| --- | --- | --- |
| **Table 1. Percent Rot Parameter Estimation** | | |
| DBH class (in.) | Average Rot | Sample size |
| 9-12.5″ | 5.2% | 1,266 |
| 12.6-17.5″ | 8.3% | 1,676 |
| 17.6-22.5″ | 12.9% | 508 |
| 22.6-27.5″ | 16.2% | 156 |
| 27.6+″ | 32.2% | 35 |

This function was parameterized using the CFI database of all 13 compartments of the Emory River property as shown in table 1, which generated similar results to those found by Vandendriesche and Haugen ([2006](#_ENREF_143)). These estimates were derived from live trees from both inventory years, including the sample trees with high defect percentages in 1984 that were later found dead. The entire CFI database[[11]](#footnote-11) was also utilized in computing multipliers for large-tree DBH growth according to the “moist uplands” or “dry uplands” designation using the Calibration Statistics post-processing program of FVS.

With site indices and total heights unknown, stand ages could only be inferred from published averages in stand (diameter distribution) and yield (volume) tables for even-aged upland oak and yellow poplar stands ([Schnur 1937](#_ENREF_117); [Beck and Della-Bianca 1981](#_ENREF_25)). Nevertheless, the variation in structure and composition within and among stands gave conflicting indications of age despite the likelihood that the entire area was originally harvested at about the same time. Such unconformities are most likely relics of the discriminate way in which the parent stands were originally harvested and of post-harvest disturbances such as wildfire and cattle grazing. Still, stand conditions were generally indicative of the 61-70 year age-class, which agrees with Hart and Grissino-Mayer’s ([2008](#_ENREF_67)) findings for a Cumberland Plateau mixed-oak forest comprised of canopy trees established around 1920, when logging activity in the Cumberlands was at its peak ([Hinkle et al. 1993](#_ENREF_72)).

While this slight age ambiguity confounded the approximation of site index, the height estimation procedure employed to approximate missing total height measurements proved useful in corroborating site index estimates because it involved three different methods for determining height, one of which depended on site index. Merchantable height to a 4″DOB top informed one method’s estimates but was the most volatile measure, given that merchantable heights can vary substantially all else equal. The resulting merchantable height-informed total heights were compared to those given by the species-specific height-diameter equations imbedded in the Sn-variant and those provided by similar equations for a given site index constituted by Lamson ([1991](#_ENREF_38) ). Canopy class was used as a surrogate for height class, helping to determine which of the three height estimates for a given tree was chosen. This time consuming process was deemed necessary by the fact that tree height is the second most critical tree-attribute in FVS and that the inventory data provided the metrics to do so.

It should be noted that the site classification and productivity information presented in Smalley ([1984](#_ENREF_123)) was not discovered until after simulations were completed. Although this productivity information was largely drawn from adjacent regions, it represented the best information and collective judgment available in the region and provided greater detail than recent county soil maps. Suggested site indices for each land type association diverged from the site index relationships between species expressed by the site index transformation equations developed by Doolittle (1958) for southern Appalachian forests, which are embedded in the Sn-variant. As a result, the assumed site indices (before any 5′ deduction for conservativeness) were up to ten ft. less than those in Smalley ([1984](#_ENREF_123)) for some oak species, up to 15′ less for black cherry (*Prunus serotina*) and black walnut (*Juglans nigra*), and up to 20′ less for yellow poplar (*Liriodendron Tulipifera*). The level of difficulty in understanding the context of NRCS soil productivity data was the primary cause of this potential error. Consequently, the simulation model was even more favorable to the relative height-growth of oak regeneration because oak regeneration exhibits a much more conservative growth strategy than intolerant species on good to excellent sites. This height-growth advantage was perhaps justified by the oak-promoting intention of simulated treatments. Likewise, forecasted stand growth was more conservative than what was originally intended. However, the overall degree of conservatism is unclear given that the exact effects of other adjusted parameters and augmentations of the model, contributing to and detracting from this negative bias, were not evaluated.

* 1. ***Simulation Assumptions***

First it is important to point out that management simulated from the 84’ CFI data set did not take 94’ measurements into account to the extent practicable since this information would not be known in reality at the outset of an IFM project[[12]](#footnote-12). The hypothetical FFO timberland assessed was assumed to be 400ac given the ten-stand simulation design and the CAR 40ac limit to contiguous even-age treatments. Best management practices (BMPs) for both scenarios were assumed to include practices found by Shaffer et al. ([1998](#_ENREF_120)) to be employed on harvest sites in the Virginia mountains in average intensities, which included about half a mile of haul road construction. Findings by Kochenderfer ([1977](#_ENREF_78)) suggest that this distance would be enough to harvest only about 25 percent of each stand, as all stands had slopes of 30 percent or greater. Although the steep terrain modeled here would require some amount of road (re)construction preceding harvest operations, it was assumed that road construction beyond that described here was not required. In effect, this implies that all additional BMP and other logging costs are assumed by the logging company and are included in the applied stumpage (value above the stump) rates.

* + - 1. ***Harvesting System, Schedule, and Economics***

Timber extraction via ground based yarding on steep Appalachian terrain requires the construction of a network of skidroads spaced roughly 150′ apart ([Kochenderfer 1977](#_ENREF_78)). Combined with the area converted to landings and truck roads, such an operation can permanently disturb over 10 percent of a tract. Germain and Munsell ([2005](#_ENREF_59)) found that a high degree of BMP implementation does not necessarily reduce surface area disturbance and thereby might not be enough to prevent significant stream sedimentation. In addition, steep slopes and silty loam soils make logging more dangerous and expensive in the Cumberland Mountains. Cable yarding can markedly reduce the surface area disturbed by equipment and haul roads ([Kochenderfer and Wendel 1978](#_ENREF_79)), but simulating it would have overcomplicated forest modeling, requiring more assumptions and separate simulations to model yarding corridors. In light of these findings, it was assumed that productivity was not diminished on the area disturbed in harvest operations and that roads and landings were reconstructed on previously disturbed areas such as former coal mining areas/roads (as opposed to construction on forested land). This notion inherently rests on the assumption that contracted logging companies employ safer and lower-impact equipment with highly skilled operators, such as steep-terrain harvesters with a carefully managed ground-based yarding system[[13]](#footnote-13). This non-conventional system would make logging operations relatively expensive, especially for small-diameter mechanical thinnings ([Li et al. 2006](#_ENREF_87)), but the extra expense could be somewhat or entirely offset by increases in delimbing and log extraction efficiency ([Rummer and Erwin 2008](#_ENREF_114)).

The most critical piece of this experiment’s design is the construction of harvest schedules. Harvest schedules of the two contrasted scenarios and their underlying approaches to forest management were drawn from behaviors and trends observed in the forestry sector (including silvicultural guides) but were not determined empirically or based upon pre-existing models. While starkly different attitudes and preferences may be ascribed to the hypothetical FFO in the business as usual management (BAU) scenario compared to the sustainable oak-management (or project) scenario, economic considerations were the principal drivers of harvest timing in each. In particular, simulated harvest timing was guided by the volume of potential removals, percent stocking (growing space per tree), mean diameter of overstory trees, risk of defect or mortality, and maximum diameters[[14]](#footnote-14). For obvious reasons, it had to be assumed that simulated harvest years coincided with sufficiently good timber markets. It should also be noted that aggregate merchantable volume may be indicative of the opportunity for commercial (i.e. profitable) treatments but is just one of many determinants of whether timber extraction operations are indeed commercial. Aside from volume ac-1, the viability of commercial thinning operations is largely influenced by timber markets, average tree size, proximity to a road, distance to mills, logging crew efficiency, and extraction equipment utilized, among other factors ([Ledoux 2000](#_ENREF_82)). Software that uses such variables to predict harvesting costs exists but was not deemed necessary.

Instead, logging costs were ignored for commercial thinning treatments performed during years in which regeneration harvests occurred, because appreciable sawtimber removals provide cost advantages in harvesting poletimber. At least 75 percent of Southern Appalachian private forests were estimated to have harvesting and hauling costs of over $1,000 ac-1 ([Southern Appalachian Man and the Biosphere 1996](#_ENREF_9)). These costs are largely influenced by slope steepness and are relatively high owing to the fact that over one-third of Southern Appalachian forests occupy slopes of 35 percent and above. Such felling and removal costs of common yields and field conditions are naturally incorporated into reported stumpage rates, so there is no need for further accounting of these costs for regeneration harvests and coinciding sawtimber yielding treatments.

Likewise, harvested volumes from stream-side management zones (SMZs) in both scenarios appear large enough to assume their removal cost does not exceed those already embedded in stumpage rates. In treatment years yielding low commercial volumes, stumpage rates were used to estimate gross revenues from removals while associated costs of tree felling and chemical treatments were accounted for separately. Given that reported mean-prices emanate from a wide array of sources and on the ground circumstances, recent and optimistic stumpage rates, from the James Sewall Company first quarter 2011 and second quarter 2007 eastern TN reports[[15]](#footnote-15) respectfully, were used for year-one values and grown at a 1 percent rate annually thereafter. This growth rate was inferred from projected real hardwood-sawtimber stumpage prices reported in Haynes et al. ([2007](#_ENREF_68)), which could be too optimistic if the stagnant sawtimber price projections of Abt et al. ([2009](#_ENREF_17)) become a reality (over the 17 years following their assumed post-recession price recovery). In addition, this economic analysis employed common financial accounting methods; revenues (timber/carbon) were computed with prices given by the assumed price growth trajectory and all cash flows (positive/negative) were converted to present values using the discount rate.

* + - 1. ***Timber Volume Calculations and Merchantability Assumptions***

The SN-variant computes board foot (BF) volumes from equations that were developed by Ted Lasher and are a function of DBH, merchantable height, relative height, total height, site index, and basal area variables. The coefficients of these predictors are known but all records of the corresponding data and analysis were lost. As a result, the log scale (or rule) in which it predicts volumes is unknown, though it is thought to be either the Scribner or International ¼ inch rule[[16]](#footnote-16). Regardless, sawlog stumpage rates for eastern hardwood species are primarily defined in dollars per thousand BF on the Doyle scale. Despite the multiple sources that imply or offer average conversion factors to use for volume conversion between common log rules, volumes from another log rule cannot be systematically adjusted to account for the discrepancies between it and the Doyle rule due to the associated inconsistent bias and causal factors ([Spelter 2004](#_ENREF_132)). Thus, Sn-variant BF volumes are not useful.

The standardized method of estimating Doyle volume is to use form-class volume tables that, for a given Girard form-class, provide BF values by DBH and the number of 16′ sawlogs (½ log increments). However, the Doyle formula shown in equation 2 was used to compute BF volumes directly in the interest of accurately reflecting reality (i.e. delivered volumes). Because the Doyle scale is less accurate if applied to longer logs, the pricing scheme adopted at most sawmills incentivize length maximizing hardwood bucking strategies[[17]](#footnote-17). Therefore, in a separate model built in Microsoft Excel based on a unique method of computing log taper from initial sawtimber measurements using tree profile equations from Clark III et al. (1991) and the Smailian formula expressed in equation 3, sawtimber volume was estimated for each tree’s 16′ log(s) and for progressively shorter logs in 2′ increments up to the greater of a 9″ scaling diameter or 8′ log[[18]](#footnote-18).

*Equation 2*: Board feet (Doyle) =

Merchantable sawtimber height growth was ignored in the first four decades of the simulation. Merchantable sawtimber heights thereafter were assumed to be the greater of the initial measurement or one-third of total height (minus a one ft. stump), which is the fraction that best approximates merchantable bole length between the stump and live limbs or dead branch stubs for oaks (i.e. the high grade portion) ([Carmean and Boyce 1974](#_ENREF_34)). As most hardwood trees in mature stands have merchantable sawtimber above this high grade fraction, this merchantable height growth assumption made stumpage and HWP carbon values for hardwood lumber more conservative. Because it is unclear whether stumpage rates were based on actual harvested volumes or sawn volumes, Doyle volume calculations were adjusted to exclude the assumed 4″ of trim (extra length) on each sawlog. All cut poletimber and the pulpwood portion of sawtimber trees (to 4″DOBs) were assumed to be harvested in the project scenario but not in the BAU scenario. In addition, sawtimber trees under 19″ DBH with more than 35 percent cull or larger trees with more than 40 percent cull contributed only to pulpwood sales[[19]](#footnote-19) since it is uncommon for sawmills to apply the requisite time-consuming scaling rules for defective logs ([Cassens 2001](#_ENREF_36)).

To inform management decisions and wood product allocation, FVS tree value codes were used to distinguish between tree conditions on a tree grade or canopy class basis. Under the assumption that the future condition of each merchantable tree was more than likely predictable from indicators present at the first sampling, conditions from both inventories were considered in the assignment of tree values.Other than some cases where trees in the first inventory showed compelling signs of impending mortality, mortality observed in-between inventories was not reflected in simulations. As a consequence, trees that were actually dying instead lived on in the management scenarios until harvested, which helped keep stand SDI elevated, thereby helping to counteract potentially excessive net growth induced by the small-tree growth reductions mentioned earlier.

* + 1. ***BAU Simulation***

The timber market situation mentioned earlier could fortuitously set the stage for many FFOs who presumably have recently experienced some degree of financial limitation or stress to look favorably on the opportunity to earn supplementary income from timber harvesting. Although retaining a seemingly adequate amount of sizable trees on steep but accessible terrain portrays (to the untrained eye) a compromise between timber and amenity values, “thinning” sawtimber stands from above down to a diameter limit can ironically render higher net revenues than clearcutting ([Baumgras and Ledoux 1995](#_ENREF_24); [Miller 1993](#_ENREF_94)). Therefore, the BAU scenario was built to simulate a series of DL harvests for each of two harvest groups. The five stands with the largest mean DBH (trees 5+″DBH) comprised the first harvest group and were scheduled to be cut initially at the end of year two of the simulation (2013); the second group of five received the same treatment ten years later. Both groups were subjected to DL cuts every 40 years thereafter (2053/2063/2093/2103). Harvest areas of this size (200ac) are relatively common compared to those observed on the south end of the TN Cumberlands ([Mcgrath et al. 2004](#_ENREF_89)). Only trees under 60 percent cull and above a 12.5″ DBH diameter limit were targeted in BAU harvests in consideration of the fact that a 12″ DBH diameter limit is commonly observed in the region ([Miller 1993](#_ENREF_41); [Fajvanet al. 2002](#_ENREF_24)). The extra half inch was added to buffer the potential for slight upward bias in measurements and to reflect the concern from a logger’s perspective that trees near 12″ DBH are likely to have low marketability. Low grade sawtimber was only harvested when a substantial volume of grade sawtimber was simultaneously cut but only if the low grade tree was 19″ DBH or larger.

Two stands were duplicated to explicitly characterize SMZ effects on timber and carbon stocks in the model because the plots they represented fell near apparent streams. The affected stands (ER34 and ER35) had slopes suggesting 85′ and 125′ minimum SMZ buffers for compliance with voluntary Tennessee BMPs ([TN Dept. of Agriculture 2003](#_ENREF_11)), which constitute at least 40 and 60 percent of an acre (perfectly square). These four stands were assigned weights of 50 percent (of 10ac stand), the average of the minimum weights above, although most SMZ minimum buffers observed in the Cumberlands exceed those recommended by the state of TN as well as those required by Forest Stewardship Council (FSC) certification ([Lemoine et al. 2006](#_ENREF_86)). Hence, in harvest years, the two duplicates (or SMZ stands) were thinned from above to 50 percent of initial canopy cover as recommended by TN BMPs while the others received a DL cut.

There was no use of a forester and no bidding process assumed for timber sales, congruent with common anecdotal accounts, particularly in the case of harvests instigated by solicitation from loggers. Moreover, considering that the trees retained in DL harvests are likely to be deformed and/or slow-growing and that their shade causes saplings to bend or lean, rendering them low value stems at best, the net value to the landowner of repeat-harvests would clearly be overstated without amending the model further. To account for the likelihood that a typical landowner would receive stumpage rates below prevailing market rates in this scenario, felling and removal costs ac-1 in addition to BMP costs were applied at each harvest, equal to the medium estimate for such costs found in western North Carolina ([NC Division of Forest Resources 2010](#_ENREF_8)). In order to account for the inexorable degradation of residual stands, sawtimber volume was discounted by half for all large low grade trees cut and those that were harvested during repeat DL cuts but originated from small or non-crop trees during the simulation.

Bole and limb damage inflicted on residual trees by felled trees and harvesting equipment is positively correlated with harvest intensity in Appalachian hardwood stands ([Fajvan et al. 2002](#_ENREF_51); [Miller et al. 1984](#_ENREF_98)). In fact, a partial harvesting study of Appalachian mixed hardwood stands involving diameter limit and shelterwood establishment cuts found that lower DL harvests knock down a higher fraction of unmarked and non-merchantable trees than high DL harvests, demand more area for skid trails, and require more frequent incursions into the stand off of the skid trail, resulting in higher residual tree damage incidence and severity ([Fajvan et al. 2002](#_ENREF_51)). As this is the only meticulous case-study to date on residual stand damage resulting from DL cutting, its residual damage statistics were used in BAU simulations to approximate the number and distribution of trees that would be knocked down. Such trees were ignored in BAU stumpage and harvested wood carbon calculations because they along with cull trees, poletimber, and pulpwood tops were not removed. Damage was only intentionally applied to poletimber and smaller trees because knock down of sawtimber trees happens much less frequently ([Miller et al. 1984](#_ENREF_98)).

It should be noted that damage to residual trees would be greater than that which was simulated, owing to the fact that Fajvan et al.’s ([2002](#_ENREF_51)) study was conducted on gently-sloped stands; however, intentionally simulating a larger number of destroyed trees would have been speculative. Even though the amount of severe damage to residual trees (if approximated) would have been significant, volume or tree grade deductions were not made to characterize it more than the aforementioned 50 percent sawlog volume discount of trees that had regenerated under full and/or partial canopies. Considering that the commercial value of affected trees or lack thereof was not manifested until years 42, 52, 82 or 92 of the projection, the deducted volume would have changed the present value of these harvests very little due to the effect of time-discounting.

* + 1. ***Project Simulation***

It is important to note that an ecological approach to upland hardwood forestry is not nearly as straight forward as basic plantation forestry. Moreover, the determinants of harvest timing on FFO lands are numerous and extremely variable and the existence of a mixed-oak cohort further confounds sustainable management planning. Given the inherent species diversity and so many important and varying parameters, modeling natural forest management (i.e. with species composition as an important consideration) in Appalachian hardwood forests in a methodical and automated fashion was found to be exceedingly difficult if not impossible. As a result, each harvest in the project management regime was uniquely constructed taking pre-harvest forest conditions and long-term management aims into account and informed by the silviculture literature. SMZ-stand simulations were an exception to this rule because they involved simple definitive prescriptions. Treatment timing and parameters were somewhat simplified in the model for convenience and useful insights. Moreover, despite the potential for prescribed fire treatments to help render the conditions necessary for successful oak recruitment ([Arthur et al. 2009](#_ENREF_21)), prescribed fire was not one of the silvicultural applications simulated due to the complexity it would have added to the model.

Management costs were obtained from the published prevailing rates for sub-practices in western North Carolina but did not include the felling and removal costs applied in the BAU scenario for the reasons previously mentioned ([NC Division of Forest Resources 2010](#_ENREF_8)). Costs for administering timber sales were assumed to be $12 BF-1 based on the findings of Hersey and Kittredge ([2005](#_ENREF_70)) and marking costs were assumed to be $90 ac-1 in agreement with the 2008 mean marking cost reported by Barlow et al. ([2009](#_ENREF_22)). Management planning during the project was assumed to be covered by these costs. A one-time initial management planning cost for the timber-only project case was accounted for explicitly with the $500 base fee and $10ac-1 charge[[20]](#footnote-20) suggested by Hersey and Kittredge ([2005](#_ENREF_70)). While a corresponding tract-size was not indicated, the resulting cost ac-1 mirrored that reported by Gunn et al. ([2008](#_ENREF_63)) for a 13-member forest carbon aggregate made up of forest tracts similar in size to this hypothetical project area.

* + - 1. ***SMZ-Stands***

Partial harvesting practices in compliance with the Forest Stewardship Council-US standard’s rules governing SMZs were adopted for the project scenario in lieu of those recommended by BMPs. Even though SMZ weights of 65 percent and 80 percent for each respective 10ac stand were suggested by lengthier SMZ buffers required by the FSC standard, the 50 percent weights that the two SMZ-stands represented before were expanded to 100 percent in this scenario as a way of keeping AGL stocks elevated and since large SMZs are common in the region. Additionally, instead of a canopy cover reduction limit of 50 percent, harvests in the project SMZ-stands were only allowed to reduce canopy cover by ten percent to again parallel practices deemed acceptable by the FSC ([Forest Stewardship Council 2010](#_ENREF_6)). Even though the primary goal of the project scenario is to maintain hard mast producing species, this FSC-compliant practice facilitates a compositional shift of the upland oak SMZ to a Maple-Beech-Birch forest cover type as one would expect with uneven-age management. This compromise was made for what was thought to enhance the accrual of creditable carbon. Conversely, increases in oak regeneration stocking were pursued in the Yellow poplar stand, which was meant to offset this effect. The importance of species diversity in the face of an uncertain future climate necessitates that mitigation activities do not buttress the forces driving maple dominance in these forests. Accordingly, even-age management was simulated for all other 40ac stands.

* + - 1. ***Mature Oak Management Prescriptions and Silvicultural Rationale***

The economics of hardwood forestry is driven by the production of grade sawtimber from species with consistently dependable and valuable markets. Yet, findings from research and field experience over the last several decades show that most passively managed hardwood stands are minimally stocked with the most desirable healthy trees (or crop trees) that will constitute the vast majority of stand value at rotation age ([Miller et al. 2007](#_ENREF_101); [Gingrich 1971](#_ENREF_60)). The capacity of these stands to produce high grade sawtimber is constrained by the non-linear decline in the number of crop trees as upland hardwoods mature ([Miller et al. 2007](#_ENREF_101)). The implication of this fact is that if and when an intermediate thinning is attempted, fewer stems of desirable species and quality will exist ([Ledoux and Miller 2008](#_ENREF_85)) and will have a lower capacity for growth response ([Miller 1997](#_ENREF_95)). For managed upland oak stands, Gingrich ([1971](#_ENREF_60)) estimated that physical yields produced over 20 years following an area-wide thinning at age 60[[21]](#footnote-21) (including initial removals) were marginally greater than those of unthinned stands. Thinning beyond this age was not recommended. Yet, research indicates that different commercial area-wide thinnings in intermediate-site, gentle to moderate sloped Appalachian hardwood stands with 100 year optimal rotations do not become optimal (i.e. most cost-effective) until age 60[[22]](#footnote-22) or 70[[23]](#footnote-23) ([Ledoux 2000](#_ENREF_82), [2007](#_ENREF_83)). The outcomes of these optimal thinning case-studies cannot be generally inferred, but considering that they do not account for opportunity costs prior to mid-rotation, they clearly contend with the practicality of such practices at the present time in immature hardwood forests as suggested by traditional upland oak management guides ([Hilt and Dale 1989](#_ENREF_71); [Gingrich 1971](#_ENREF_60)). This traditional area-wide thinning strategy primarily targets the removal of subordinate canopy classes in pursuit of an average area-wide residual stocking-level; however, it has been abandoned in contemporary silvicultural guidance ([e.g. Miller et al. 2007](#_ENREF_101)) in favor of the improvements in efficacy and growth found in crown-touching release studies.

Crown-touching or crop-tree release (CTR) is now considered by most as the superior method for manipulating stand growth at almost any age or age-structure, whereby the best candidates for high grade sawtimber and the requisite ascendance to or persistence in a competitive canopy position are released by eliminating crown-touching neighbors on three to four sides (270-360⁰). Stocking levels in the immediate vicinity of fully released crop trees consequently fall beneath those recommended for area-wide thinnings ([Lamson et al. 1990](#_ENREF_81)) but have not been found to affect tree grade in mature stands ([Miller and Stringer 2004](#_ENREF_100)); though, CTR was found to reduce clear stem length ([Miller 1997](#_ENREF_95)) and temporarily increase the risk of wind-throw and snow/ice damage as trees adjust to augmented site resources ([Miller et al. 2007](#_ENREF_101)). While such mortality and defect-inducing disturbances are major concerns to managers of maturing upland hardwood forests, particularly those with a substantial red oak cohort vulnerable to oak decline ([Clatterbuck and Kauffman 2006](#_ENREF_40)), CTR facilitates the enlargement of crop tree crowns and root systems, which improves long-term resilience to drought, pathogens, insects, wind, and ice damage ([Miller et al. 2007](#_ENREF_101)). Even though carbon sequestered[[24]](#footnote-24) in unthinned hardwood forests is likely to exceed that of commercially managed forests ([Hoover and Stout 2007](#_ENREF_73)), crop-tree focused forestry produces much greater economic value ([Miller et al. 2007](#_ENREF_101)) in the absence of carbon incentives, which is a key IFM tradeoff in need of examination.

Considering the information above, four of the simulated upland oak stands were thinned via CTR within the first seven years of the project scenario; another was thinned in year 20 of the project (see Table 2). Combined CTR and stocking-focused thinnings (to ~60 percent stocking) as suggested by Miller and Stringer ([2004](#_ENREF_100)) were employed to simulate the open conditions needed to encourage oak seedling establishment and survival in addition to a desirable increase in sawtimber growth. Doing so diminished AGL carbon stocks but also decreased mortality rates in the long-run. Thinnings were prioritized by initial stocking levels since lower relative densities reduce the risk of oak decline ([Clatterbuck and Kauffman 2006](#_ENREF_40)), Gypsy moth attack ([Kauffman and Clatterbuck 2006](#_ENREF_75)) and conflagrations and because the balancing of age-classes necessitated extensive harvest deferments in which stocking could rebound to risky levels. Given that tree mortality may be under-predicted by simulations with long time horizons ([Vandendriesche and Haugen 2006](#_ENREF_143)), it was important to simulate such active management throughout the projection as a way to avoid assumptions about the incidence and intensity of significant mortality-inducing events.

Moreover, the mechanics of the Sn-variant also necessitated active management given that maples dominated the understory. In the BAU simulation, the area of Sugar maple-American Beach-Yellow Birch types increased from 20 to 65 percent of project area. Because the mortality submodel of the Sn-variant is calibrated to the FIA forest typing algorithm, the density-based mortality imposed on a stand is diminished as the forest cover type changes to northern hardwood types. This sudden transition allows for higher stand density (i.e. carbon stocks) and net growth. Thus, the intensity of simulated management was not only needed to sustain the relative abundance of oak species but also to prevent abnormal surges in stand growth.

CTR is not easily simulated in FVS because post-harvest live tree records are essentially treated as if they are evenly distributed on the plot. Thus, all trees are provided a growth boost and density-based mortality reduction if tree density decreases anywhere in the virtual stand. Nevertheless, the simulation of each upland oak stand’s initial CTR treatment was attempted by amplifying the growth multipliers for crop trees and reducing mortality. This approach involved determining the FVS growth multipliers that enhanced growth congruent to the growth increases observed[[25]](#footnote-25) by Miller ([1997](#_ENREF_95), [2000](#_ENREF_96)). The amount and distribution of tree knock down was estimated for all commercial CTR treatments preceding regeneration harvests based on inferences made from all relevant studies ([Miller et al. 1984](#_ENREF_98); [Stringer et al. 1988](#_ENREF_135); [Lamson et al. 1984](#_ENREF_80)). From these initial thinnings to the regeneration harvest of each stand, DBHs and assigned tree values informed the removal of trees taking up more growing space than their value or canopy position warranted, the selection of reserve trees to be retained in regeneration harvests in accordance with Stringer ([2006](#_ENREF_134)), and the realistic allocation of harvested logs to the relevant “wood pile”.Commercial operations that involved the removal of merchantable poletimber (5.5″DBH+ with under 60% rot) were assumed to harvest all felled, knocked down, and severely damaged merchantable trees in the project scenario.

The harvesting schedule of the second ten-year period of this scenario was defined by a clearcut harvest of the most valuable stand, midstory removals (or prep-treatments) initiating a irregular shelterwood sequence, and a second CTR thinning for one of the first treated stands, as shown in Table 2. Aside from the need to compensate for the thinning costs incurred in the first ten years of the simulation, the regeneration harvest (or final cut) was justified by the 19.4″ mean DBH of harvested sawtimber and the impressive amount of large black cherry trees, which were found by Smith and Miller ([1991](#_ENREF_128)) not to respond to CTR at this age. Subsequent final cuts were spread out in an effort to balance age-classes across the project in agreement with the protocol’s 40 percent constraint on project area in the 0-19 age-class, while also following silvicultural guidance for oak regeneration and removals of financially mature timber according to the SILVAH decision-support system ([Brose et al. 2008](#_ENREF_29)). It should be noted that the scarcity of red oaks in the stands regenerated in the 20 years after the initial set of CTR thinnings was also an important factor in final harvest timing considering that natural red oak restoration is contingent on having a sufficient parent tree population. Overall, a conservative approach was taken in scheduling regeneration harvests with regard to the 18″ mean diameter suggested for rotations ([Brose et al. 2008](#_ENREF_29)), as demonstrated by the harvest-year conditions displayed in appendix B.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 2. Project Treatment Schedule Key:**  Stand ID | | | | | Revenue = | Green | Revenue & Cost = | Yellow | Cost = | Pink |
| Year | **ER24** | **ER152** | **ER3** | **ER25** | **ER4** | **ER33** | **ER1** | **ER26** | **ER34** | **ER35** |
| 2013 |  |  |  |  | CTR |  | CTR |  |  |  |
| 2018 |  |  |  | CTR cut |  |  |  | CTR cut |  |  |
| 2021 | Final Cut | prep spraying |  |  |  |  |  |  |  | SMZ |
| 2026 |  |  | prep cut |  | CTR cut |  |  |  |  |  |
| 2028 |  |  |  | prep spraying |  |  |  |  |  |  |
| 2031 | PCTR | Final Cut |  |  |  | CTR cut | CTR cut |  | SMZ |  |
| 2036 |  |  | Final Cut |  |  |  |  | CTR cut |  | SMZ |
| 2038 |  |  |  | Final Cut |  |  |  |  |  |  |
| 2046 |  | PCTR | PCTR |  |  | prep cut/  spraying |  |  |  |  |
| 2051 | PCTR |  |  | PCTR | Final Cut |  |  |  |  |  |
| 2056 |  |  |  |  |  | Final Cut |  |  | SMZ | SMZ |
| 2061 |  | PCTR/  reserve tree cut | PCTR/  reserve tree cut |  |  |  | prep spraying |  |  |  |
| 2071 | CTR/DoC |  |  | PCTR/DoC/  reserve tree cut |  |  | Final Cut |  | SMZ |  |
| 2076 |  |  | CTR/ DoC/  reserve tree cut |  | PCTR/  reserve tree cut | PCTR/  reserve tree cut |  |  |  |  |
| 2081 |  | CRT/ DoC/  reserve tree cut |  |  |  |  |  |  |  |  |
| 2091 | CTR/DoC |  |  |  |  |  |  | Final Cut | SMZ | SMZ |
| 2096 |  | CTR/DoC | CTR/ DoC | CRT/ DoC/  reserve tree cut | CTR/  reserve tree cut | CTR | PCTR/  reserve tree cut |  |  |  |
| 2106 | Final Cut |  |  |  |  |  |  |  |  |  |
| 2111 |  | CTR/DoC |  |  |  |  |  | PCTR/  reserve tree cut | SMZ |  |

In the years following the initial regeneration harvest, the silvicultural system modeled for all stands was conceptualized to be analogous to the less frequent, higher post-harvest retention even-age scenario found by Nunery and Keeton ([2010](#_ENREF_107)) to sequester more carbon than conventional even-age forestry. Specifically, the irregular shelterwood method was employed with an overall even-age approach, in lieu of the two-aged approach as defined by Stringer ([2006](#_ENREF_134)). This system embodies the widely recognized shelterwood harvest method espoused by Loftis ([1990](#_ENREF_88)), which calls for specific basal area reductions from the understory to midstory in order to bolster oak advance-regeneration development. Simulated prescriptions generally followed the guidelines for a shelterwood cutting sequence while retaining 10-15 ft2 ac-1 of basal area (BA) in healthy sawtimber trees after overstory removals as recommended by Stringer ([2006](#_ENREF_134)). Instead of implementing the two-age system, whereby all reserve trees would be held for another full rotation, reserve trees were cut back to 10 ft2 ac-1 BA or completely removed during thinnings begun at ages 20-30.

Doing so alleviated overstocked conditions that elevated stand mortality rates, thereby enhancing subsequent growth rates. Reserve tree removals also captured revenues that helped finance cultural treatments. Note that this revenue would have otherwise not been realized (i.e. under a two-age system) since none of these stands received a second final harvest in the duration of the project. While standing, the carbon stocks in reserve trees helped buffer carbon losses from harvests and hastened the recovery of forest carbon stocks to baseline levels. Reserve trees were assumed not to be severely wounded or knocked down in logging operations and assumed healthy enough to resist damaging agents; though, some mortality occurred over time because the Sn-variant applies some amount of mortality however small to all trees in each cycle. Each final harvest was extended beyond the number of years-to-maturity (see appendix B) indicated at project inception by the Silviculture for Allegheny Hardwoods (SILVAH) decision support system’s equations, which define maturity as stands with an 18″ BA-weighted arithmetic mean DBH of merchantable trees (or MDM). According to this years-to-maturity (YTM) metric, overstory harvest deferments were approximately 10, 20, or (in one case) 50 years. In addition, pre-harvest stand-MDMs are provided for each final harvest year in appendix B, demonstrating the extent of such deferments (i.e. increments beyond the 18″ MDM defining stand maturity). One stand (ER4) was harvested just before achieving an 18″ MDM but after the YTM-implied harvest date. This circumstance is consistent with SILVAH guidance for mixed-oak stands, which suggests an MDM as low as 15″ for such fair-quality dry oak stands.

* + - 1. ***Immature Oak Management Prescriptions and Silvicultural Rationale***

Codominant saplings that regress to the intermediate canopy class have a small chance of long-term survival without regaining a competitive canopy position with the help of human or natural disturbances ([Trimble 1974](#_ENREF_138)). In the presence of shade-intolerant regeneration on intermediate to good sites, failure to release oaks early will guarantee low oak-stocking in the new stand as most non-coppice oaks cannot compete in the long-run without a head start on such competition. While intolerant species tend not to respond to crown release after partial suppression ([Trimble 1974](#_ENREF_138); [Smith and Lamson 1983](#_ENREF_126)), they along with oak saplings easily maintain their competitive positions in the codominant class if fully released ([Miller 2000](#_ENREF_96)). Moreover, the occasional ascension of Northern red oaks (*Quercus rubra*) of intermediate canopy position to a codominant position can occur nearly twice as frequently after full crown release ([Miller 2000](#_ENREF_96)).

LeDoux and Miller ([2008](#_ENREF_85)) found CTR via mechanical removal to be a sound investment at about age 30 and beyond in intermediate-site Appalachian mixed hardwood stands harvested at age 76 (optimal) or 100, demonstrating the financial limitation to maximizing crop tree abundance and somewhat corroborating the age recommendations for initial upland oak thinnings by Hilt and Dale ([1989](#_ENREF_71)). The hack and squirt herbicide injection (or chemical control) method produced even higher returns between ages 25 and 30 but could probably not be economically justified over mechanical operations or the no treatment option much beyond age 30 (assuming a 100 year rotation) under the circumstances in the study. By contrast, a hardwood stand’s canopy closes within 10 years of regeneration harvests on high quality sites and within 15 years on poorer sites. Yet, even at an age of 30, there is no pragmatic economic rationale for these treatments because the typical landowner is not likely to live as long as the payback period on such an investment. Nevertheless, the number of crop-trees ac-1 falls precipitously after canopy closure ([Miller et al. 2007](#_ENREF_101)) as does the growth potential of crop-trees ([Miller 1997](#_ENREF_95)), so there is appreciable value to be gained (in theory) by employing precommercial-CTR (PCTR), especially if carbon revenues are large enough to finance such rarely applied but promising cultural treatments early-on in the rotation.

To ensure the survival and competitive canopy positions of oaks and other desirable crop trees, PCTR via chemical control was simulated for each even-aged stand zero to ten years after canopy closure depending on site quality, as shown in Table 2. An average of 60-70 crop trees were assumed to be favored in CTR treatments in agreement with guidance by Miller et al. ([2007](#_ENREF_101)). Chemical release at initial canopy closure was simulated in relevant stands instead of treatment by chainsaw felling or girdling because the herbicide injection method is less expensive ([Groninger et al. 1998](#_ENREF_62); [Kochenderfer et al. 2001](#_ENREF_77)). Regardless of cost savings, chemical control may provide an extended period of release relative to mechanical treatment ([Wendel and Lamson 1987](#_ENREF_146)). Again, thinnings were repeated in the latter half of the simulation to maintain periodic annual growth but also to prevent the crowding out of intolerant species such as Scarlet oak (*Quercus coccinea*), Black cherry, and Black walnut by the pervasive Red and Sugar (*Acer saccharum*) maples. Of those that were commercial operations or nearly so, distribution-of-cut (DoC) recommendations for Allegheny hardwoods ([Nowak and Marquis 1997](#_ENREF_106)) were employed as proxy CTR thinnings since there is no other specific and standardized guidelines by which to carry out thinnings; DoC guidelines were found to target trees among crop tree heights just as CTR marking guidelines suggest. From a cash-flow perspective, these treatments represented both expenditures and earnings depending on stand age, as indicated by color codes in Table 2.

* 1. ***Carbon Accounting Approach and Assumptions***

CAR projects estimate the below-ground live carbon pool (course-root carbon) using the Cairns et al. ([1997](#_ENREF_33)) equation. This relationship is derived from temperate forest studies across the globe but does not differentiate between conifers and hardwoods and is a function of AGL biomass on a ac-1 basis, whereas Jenkins et al.’s([2003](#_ENREF_74)) BGL equations are derived from eastern U.S. forests and are a function of species groups and stem DBH, which is more consistent with the requisite per tree procedure for estimating AGL biomass. Consequently, BGL carbon stocks resulting from the Jenkins et al.(2003) equations are likely to be more accurate for the forests modeled here. Because they happen to be significantly larger than those given by the Cairns et al. (1997) equation and considering that CAR allows for the approval of other BGL biomass formulas better suited to a given project area, the Jenkins et al.(2003) BGL biomass equations were used instead. Standing dead carbon estimates were taken from the standard output of the FVS Carbon submodel, the methods of which are reported in Rebain et al. (2010). AGL biomass stocks are calculated from CAR-approved biomass equations coupled with the component-ratio method developed by the USFS ([Heath et al. 2009](#_ENREF_69)), which involved utilizing the database of wood density factors in Miles and Smith ([2009](#_ENREF_93)).

According to the former version of the protocol, forest areas were deemed ineligible as a single project if a secondary forest community type existing in patches of at least 20 contiguous acres constituted over ten percent of the proposed project area. In other words, CAR projects had to be comprised of forestland in which at least 90 percent of all 20ac patches within the area were classified under the same community type (or assessment area). Although the CAR northern hardwoods assessment area is still a minority forest cover type in the Southern Cumberland Mountains ([USDA Forest Service 2010a](#_ENREF_15)), it could characterize up to three of the four non-oak stands in this analysis. As a consequence, these stands (ER24,35,& 152) were originally assumed to be interspersed (in patches smaller than 20 contiguous acres) among upland oak stands, and in turn, were included in the oak-hickory assessment area for the estimation of the common practice benchmark. The remaining yellow poplar stand (ER3), representative of CAR’s cove hardwoods assessment area, was assumed to be contiguous and comprise ten percent of project area (i.e. 90% in oak-hickory and 10% in cove forest). Other configurations were tested but all yielded initial carbon stocks less than the common practice (CP) values computed. Only CP values from the CAR low productivity class were used since FIA data indicated that areas in a high site productivity class are extremely rare in the Cumberlands ([USDA Forest Service 2010a](#_ENREF_15)).

Figure 3. Above-ground live-tree carbon for project management regime and BAU regime (actual and annualized)

The procedure to determine the project’s baseline carbon stock was simplified further by assuming that either all of the forestland on the hypothetical tract was included in the project or that the AGL stocks of any excluded forestland in the relevant CAR-defined “logical management units” were within 20 percent of those in the project. While shorter DL cutting intervals are commonly assumed in hardwood silviculture studies, a conservative 40 year interval was used to elevate the averaged BAU scenario’s AGL carbon stock. Residual poletimber (PT) and defective sawtimber (ST) trees catalyzed a rapid rebound in AGL stocks (shown in orange in figure 3) within these long cutting intervals, but they did not encompass enough merchantable volume to finance stand entry for three stands in 2053 (ER3, 24, & 34-SMZ) and 1.5 stands in 2093 (ER25 & 34-SMZ). In effect, the average of BAU scenario stocks, depicted by the red line in figure 3, became higher than the initial AGL stocks (by 0.7 Mt), which is a requirement of the modeled baseline.

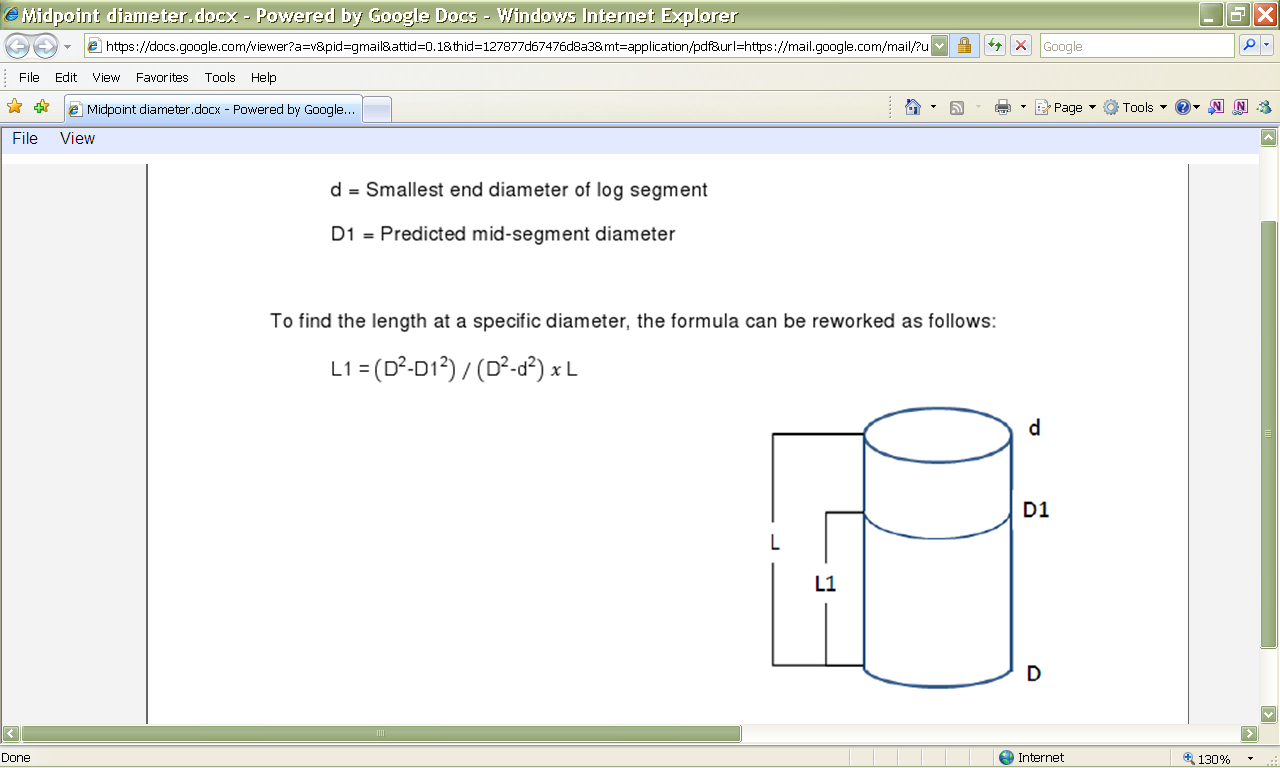
Baseline HWP carbon is accounted for separately in CAR projects. The default method for HWP forecasts is to sum the carbon in all harvested tree boles (excluding tops), multiply the total carbon weight by the relevant mill efficiency factor, partition the result into HWP classes based on each class’s relative share of the region’s wood production (regardless of each tree’s species and commercial value), and multiply the value of each by its respective 100 year average storage factor ([see CAR 2010, Appendix C](#_ENREF_2)). For actual harvests, HWP carbon can be calculated directly from mill receipts. As the intention of this analysis was to build a simulation model reflecting actual IFM implementation, this latter approach was taken by making merchantability assumptions (as seen in Table 3) based on advice from professionals[[26]](#footnote-26) and consistent with BF timber calculations described earlier.

Harvested ST up to a 12″DIB contributed to the hardwood (hwd) and softwood (swd) lumber categories for trees with grades of one and two only. The hwd lumber percentage of the actual HWP distribution was less than half that of the default HWP distribution, whereas the actual swd lumber percentage was less than one-eighth of its default percentage, as shown in table 3. Each respective HWP class in the table was populated by the residual parts of tree boles remaining after accounting for contributions to preceding classes. For Yellow poplar, Cucumber (*Magnolia acuminata*), Basswood (*Tilia* sp.), and Red maple trees, the remainders of tree boles above ST-tops, or entire tree boles (if no grade 1 or 2 butt log), up to 8″DIBs were accounted for in the non- structural panel category.

|  |  |  |  |
| --- | --- | --- | --- |
| **Table 3. HWP Estimation using CAR default method and applied method based on assumed merchantability** | | | |
| **HWP class** | **100yr Average Storage Factor** | **Default HWP distribution** | **Merchantability-based HWP Distribution** |
| Hardwood Lumber | 25.0% | 69% | 28.2% -Grade 1 & 2 ST-stump →ST-top or 12″DIB |
| Non-Structural | 38.0% | 5% | 4.2% -YP,CT,BW,RM residual bole→8″DIB |
| Miscellaneous | 17.6% | 3% | 10.9% -Residual bole→ST-top (if any) |
| Softwood Lumber | 46.3% | 4% | 0.5% -Grade 1 & 2 ST-stump →ST-top or 12″DIB |
| Softwood Plywood | 48.4% | 4% | 0.9% -Residual bole to 8″DIB |
| OSB | 58.2% | 12% | 26.1% -Residual bole →5″DIB x 0.5 |
| Paper | 5.8% | 7% | 29.2% -Residual bole →4″DIB top |

For all other low grade hwd ST-trees, merchantable portions up to ST-tops were lumped into the miscellaneous category. Residual portions of harvested tree boles up to 5″DIBs were split evenly between the OSB and paper classes, and any residual portions over 8′ long were allocated to the paper class. As seen in Table 3, these classes’ shares of the HWP distribution were multiples of their default percentages. Paper and OSB were accounted for under the project management regime because, unlike the BAU case, project management called for the occasional removal of low value stems. HWP carbon in-use was the only eligible source of HWP carbon in the project scenario, owing to CAR rules requiring the project’s harvested carbon in a given year to be lower than that in the baseline in order to qualify for the accounting of HWP carbon in-landfills (for both the project’s and baseline’s HWP stocks). Conversely, the HWP carbon stock of the baseline accounted for both HWP carbon sources in each non-harvest year in adherence to CAR rules, which marginally reduced the carbon removals credited to the project.

The HWP estimation procedure relied on National Volume Equation Library (NVEL) Microsoft-Excel functions ([USDA Forest Service 2010b](#_ENREF_16)), merchantable stem heights (including a 1′ stump), predicted inside diameter at breast height (DiBH) ([Clark III et al. 1991](#_ENREF_38) ), average DIB top diameters for standard ST and PT top diameters (by species) ([Clark III et al. 1991](#_ENREF_37)), and wood density parameters in Miles and Smith ([2009](#_ENREF_93)) as follows. While the NVEL functions allow for the use of ST heights to compute ST volume inside bark, they require standard hwd and swd ST heights measured at 9″ and 7″ DIBs respectively in addition to the ST height of interest. Because the Sn-variant instead computes merchantable heights to standard DOB tops and since the ST heights used to estimate harvested BF volume had unknown diameters, there was no easy way to estimate biomass volume in different portions of a bole. A solution to this dilemma was found[[27]](#footnote-27) in exploiting Smailian’s log volume formula to interpolate between stem heights in order to find the stem height at a given mid-section diameter as shown in equation 3 and figure 4.



Where: *D1* = Mid-section diameter

*D* = Large end diameter

*d* = small end diameter

*L1* = Length to mid-section diameter

*L* = Length of stem segment **Figure 4. Log taper diagram**

Since average DIBs and associated heights for all commercial species were known or could be predicted for DBHs, 4″DOB PT-tops, and 9″ and 7″ DOB ST-tops for hwds and swds respectively, any merchantable height to a given mid-stem diameter could also be found with the Smailian formula. This in turn enabled the calculation of volumes to various DIBs, the primary determinant of merchantability, because the Clark III et al. (1991) volume equations have the capability of using a given mid-stem height to compute volume as long as a greater height to a standard top diameter is known. An example of how this procedure was utilized to determine the height to the minimum 12″ scaling diameter for lumber is shown below equation 3 (assuming an 8″DIB for a 9″DOB top). However, there is a caveat to these Excel volume equations in that all height inputs are interpreted as heights associated with DOB measurementsxxvii. As a consequence, volumes were really estimated to a lower DIB than desired, yielding conservative volume estimates.

|  |  |
| --- | --- |
| **Table 4. Reversal Risk Assumptions** | |
| Risk Category | Risk Factor |
| Financial Failure | 1% |
| Illegal Forest Biomass Removal | 0% |
| Conversion | 0% |
| Over-Harvesting | 2% |
| Social | 2% |
| Wildfire | 4% |
| Disease or Insect Outbreak | 3% |
| Other Catastrophic Events | 3% |
| **Reversal Risk Rating** | **15%** |

A reversal occurs any time project carbon stocks decline. In order to minimize the reversal risk rating and the corresponding reduction in creditable carbon, it was assumed that a conservation easement was instituted along with the requisite 100 year project implementation agreement; there was no compensation assumed for the easement. Although owners are able to reduce the risk profile of their project through fuel treatments and other relevant activities, the same risk rating shown in table 4 was applied in every verification year. Thus, relative creditable carbon contributions to the forest carbon buffer account were constant over time.

It was also assumed that the aggregate associated with the project included 24 or more other projects In order to assume away the moderate level of uncertainty (8 percent) in carbon stocks and reduce the exorbitant costs of monitoring and verification in accordance with CAR aggregation rules. Specifically, this assumption legitimized the monitoring-cost minimizing assumption that the costs of each site-verification following the initial verification were shared with another project in the aggregate. Applying the CAR aggregation rules to a 25 project aggregate also meant that the cost of desk-audits would be shared by 5 projects at a time. Therefore, the $10,000 initial verification cost was assumed to be brought down to $6,000 for repeat site-verifications, while desk-verifications were assumed to cost $2,000. Because the monitoring schedule of a 25 member aggregate would be highly dynamic, desk-audits were not simulated randomly (as would happen in reality) but were assumed to occur at the request of the owner up to 5 year intervals. However these costs were incurred more often during most of the projection owing to the frequency of reversals.

|  |  |  |
| --- | --- | --- |
| Table 5. IFM Project Cost Assumptions | |  |
| Implementation Activity | Costs | Source |
| Project development | $20 ac-1 | Galik et al. ([2009b](#_ENREF_56)) |
| Inventory conversion to initial carbon stocks | $6.50 ac-1 | Ibid |
| Year-one growth modeling | $1.75 ac-1 | Ibid |
| Annual growth modeling[[28]](#footnote-28) | $1.50 ac-1 | Ibid |
| HWP carbon estimation[[29]](#footnote-29) | $0.75 ac-1 | Ibid |
| Periodic inventory | $8 ac-1 | Gunn et al. ([2008](#_ENREF_63)) |
| Initial/Subsequent  site-verification | $25/$15 ac-1 | Expert Verifiers |
| Desk-verification | $5 ac-1 | Expert Verifiers |
| Year-one registration fee | $2.50 ac-1 | Climate Action Reserve |
| CRT issuance + seller fee | $0.23 CRT-1 | Climate Action Reserve |
| Aggregator commission | 12% of CRT sales | Galik et al. ([2009b](#_ENREF_56)) |
| Opportunity cost | 4% | LeDoux and Miller ([2008](#_ENREF_85)) |
| Sustainability certification | $1.25 ac-1 | NA |

The verification costs ac-1 (shown in Table 5) derived from these assumptions were suggested as reasonable preliminary estimates by expert carbon offset verifiers but could not be confirmed given that such CAR aggregates have just begun to form. Although measurement and monitoring activities are required for 100 years following each issuance of Carbon Reduction Tonnes (CRTs) by CAR, their costs after the 100 year project term were ignored because the time-discounted values were negligible. Moreover, even though simulated project management could be considered compliant with the FSC-US standard, FSC certification was not assumed. Sustainable forestry certification costs could be negligible or prohibitively expensive depending on the forestry standard and characteristics of the aggregate, so they were ignored in the first tier of assessment cases (see appendix B). Certification costs were however added as a variable in secondary tier cases in the form of annual aggregator fees of $500 beginning in year 2. All first tier cases in appendix B shared the same 4 percent discount rate and price growth assumptions.

## RESULTS

* 1. ***Timber Production Economics: BAU vs. Oak-sustaining Silviculture***

As expected, the sustainable oak management regime generated relatively high operational costs and relatively less timber value than BAU, valuing timber only. Management costs were roughly $250ac-1 more in present value while sawlog production over the 100 year projection was 3,670 BF ac-1 more than in the BAU scenario. Despite the focus on high grade sawtimber production, the present worth of stumpage from the project scenario was $1,008-$1,430ac-1 less than that of the BAU case depending on stumpage rate, owing to the effect of time-discounting. This was the primary reason that the BAU scenario had an overall net present value (NPV) about 73 percent ($2,323-$3,355ac-1) higher than the oak-silviculture scenario ($1,342-$1,938ac-1); in other words, it was $981-$1,417ac-1 more cost effective, which clearly proves the economic feasibility of the modeled BAU scenario, which is one of the options the protocol affords for the justification of the BAU regime claimed. As such, the oak-management regime was demonstrably unappealing by comparison without substantial incentives that lend support to sustainable hardwood management. Some incentives are available to FFOs (depending on the county) through the Environmental Quality Incentives Program but were ignored here due to the variability of the program’s implementation and funding. In addition, the marginal net value to the landowner of BAU harvests may in reality fall short of that found here given that the aforementioned accounting of felling costs was arbitrary. This exaggeration was also due in part to the conservative assumption ignoring sawtimber merchantable height growth before year 40 of the project, primarily affecting the value of project scenario’s second, third, and fourth harvests in the third decade**.**  While the BAU scenario’s economic advantage over the project scenario may be overstated, the amount of such bias is not likely to be consequential considering the size of the disparity in NPV. Other augmented benefits not evaluated here but that could be potential sources of increased project revenues include more valuable hunting leases, biomass energy markets, and transactions for water pollution credits in high conservation value watersheds.

* 1. ***IFM financial feasibility under CAR***

Despite early expectations, the project management regime did not result in any carbon-related net benefits under the CAR protocol. Improved management practices included: an appreciable reduction in harvesting on 20 percent of project area (two SMZ stands); 10+ ft2 ac-1 of BA retained for decades after regeneration harvests (except one); thinnings to maintain vigor and minimize susceptibility to natural mortality; and overstory harvest delays of 8, 18, 23, 25, 28, 48, and 68 years compared to the BAU management regime. Regardless, the accrual of creditable-carbon was almost negligible as shown in figure 5.The amount of carbon

Figure 5. Cumulative creditable carbon and credit liabilities ac-1 in verification years

removals credited to the project can be perceived in figure 5 by the increments in cumulative creditable-carbon values, whereas reversals or credit-liabilities are characterized by decrements. These increments and decrements signify the Carbon Reduction Tonnes (CRTs) ac-1 that can be sold or that must be surrendered, respectively, as portrayed in figure 6 in yellow. However, those in red signify the true carbon credits/debits resulting from the project (i.e. ignoring the resale of credits that were purchased to compensate for reversals).

The Jenkins et al. (2003) BGL-carbon deviation generally had a marginal effect on issued/surrendered CRTs as shown in figure 6 (blue and yellow) but increased the NPV of CAR engagement by $113ac-1 to $1,177-$1,822ac-1, assuming $10 per metric ton CO2 equivalent (Mt-1). Again, valuing timber only, the NPV of the project scenario amounted to $1,342-$1,938ac-1. So notwithstanding the rise in economic value rendered by the deviation in BGL-carbon accounting, this CAR participation base case was $165ac-1 less cost effective than the timber-only project scenario under the low stumpage case but only $116 ac-1 less under the high stumpage case. This higher margin for the pessimistic stumpage case may be due to a shift in the pricing relationship between species that occurred between the stumpage report publishing dates. The Solver add-in for Microsoft Excel was used to try to find the carbon price required for CAR involvement to merely break even with the timber-only project scenario but a NPV asymptote prevented a solution; this asymptote was revealed as carbon price approached zero. NPV actually exhibited a negative relationship with carbon price, peaking at near zero dollars Mt-1 and equaled $0 ac-1 at $344 Mt-1. Figure 5 depicts why this is the case; shortly after final harvests commence, CRT liabilities dominate the projection.

Figure 6. Carbon Reduction Tonnes ac-1 issued/surrendered in verification years

It should be noted that the quantity of CRTs ac-1 reported herein is specific to the management regime simulated so it does not vary with acreage. Yet, project size strongly influences the financial prospects of a project as planning, measurement, and monitoring costs ac-1 are contingent on project acreage ([e.g. Mooney et al. 2004](#_ENREF_102)). Such costs were difficult to obtain for more than one hypothetical project size, so project sizes smaller than 400ac were not evaluated. Unless noted otherwise, the price of $10 Mt-1 is the basis of all NPV calculations reported herein. This price is considered high in today’s nascent U.S. offset market; on the other hand, it is assumed not to change throughout the 100 year projection. Moreover, the high level of additionality assumed here and the value brought from sustaining the level of biodiversity in southern Appalachian forests lends support to the use of a relatively high price; though it may not be considered so for long, as the first reported forward contract for California carbon emissions allowances was set at $11.50 Mt-1 ([Carbon Positive 2010](#_ENREF_3)).

New CAR aggregation rules will now render cost-effective IFM projects that would not otherwise be viable. Many IFM project developers assume the up-front costs of project development, measurement and monitoring in exchange for a percentage of carbon credit sales. As aggregators are likely to be the most generous in this regard, an extreme case of such an arrangement was tested in which all of these costs throughout the 100 year period were ignored except CAR fees and the aggregator’s percentage of sales of issued CRTs. The resulting NPVs still fell short of the timber-only project; though, at a price of zero Mt-1, they were roughly equal. Thus, CAR participation would provide no additional value to the oak-management scenario even when assuming away implementation costs. In this case, results reflect the findings of Galik et al. (2009b) in that protocol accounting methods are more consequential to project feasibility than implementation costs.

* 1. ***Results from Potential Protocol Refinements***

If the CAR protocol is to be workable for IFM projects that continue management for timber products after project registration, it must not inflate the tradeoff between timber and carbon values as it appears to do. Thus, in pursuit of the principal factors determining IFM feasibility under the circumstances herein, reasoned adjustments to the baseline methodology and rules governing how reversals are resolved were tested to reveal the relative influence each adjustment had on the project’s economic performance. The first hypothetical modification was made to the rules governing compensation of reversals because they were hypothesized to be the cause of the negative relationship found between NPV and carbon price. Note that projects under 1,000ac are permitted to reduce AGL carbon stocks to 20 percent below the minimum baseline level (MBL) of AGL carbon as part of normal silvicultural activities, but as previously mentioned, the reversals must be fully compensated for. The NPV of the unadjusted[[30]](#footnote-30) baseline case grew by about $49ac-1 ($19,600 total) to $1,225.7-$1,822.2ac-1under the assumption that, in years in which reversals occurred, project owners were only responsible for paying back CRTs issued prior to that time, in lieu of the current rule that stipulates compensating for the entire reversal. The effect of this modification on the quantity of CRTs traded is demonstrated in figure 6 (in red) by the reduced amount of CRTs purchased for reversals and the subsequent disappearance of CRT trades. This change was examined because necessitating compensation for negative carbon stock-changes beyond the CRTs issued prior to the reversal seems to unnecessarily penalize owners that do not choose to sacrifice timber value for carbon value.

In fact, eliminating this punitive measure corrected the negative relationship between NPV and carbon price and allowed an initial break-even carbon price to be found. A price of at least $52.9 Mt-1 was necessary to render CAR participation favorable over the timber-only project scenario but assuming away implementation costs brought this down to $0.45 Mt-1 under the one percent growth rate in carbon price[[31]](#footnote-31). Although this adjustment to reversal compensation is economically desirable and is justified by these results, the consequent economic improvement of the IFM project case under realistic carbon prices was not enough to justify CAR engagement compared to the timber-only project case unless all implementation costs were assumed by the aggregator. It should be noted that even under a minimal rate of increase, high initial carbon prices grow to unrealistic quantities in the latter part of the simulation, so the break-even prices assumed to grow are only realistic at relatively low initial prices. Moreover, a growing carbon price yields higher year-one break-even prices than those assumed to be constant, owing to the fact that the number of CRTs sold are eventually repurchased at a higher price in reversal-years. Given that carbon offset prices are likely to increase in the future and that aggregators probably will not be able to cover costs as generously as the extreme example tested, results generated under the 1 percent price growth and full cost assumptions deserve the most attention (see appendix B).

In a second variation of the protocol, the method to quantify annual changes in baseline-HWP carbon stocks (after discounting by averaged 100-year decay factors) was adapted to account for changes as harvests occurred on an annual basis (depicted at the bottom of figure 7). The current method calls for HWP stock-changes over the project to be annualized (averaged over the 100 years) so that annual changes in HWP stocks are constant and applied in each year in the baseline (seen in black). Although the project scenario renders a HWP pool more than double the size of the baseline-HWP pool over the project term, baseline-HWP stock changes under the adjusted accounting method disproportionately affect the project in early years. This adjustment allowed the project’s creditable carbon to be drawn down by the simulated amount of baseline-HWP stock-changes (shown in light orange in figure 7, before the requisite 20 percent market leakage discount),

Figure 7. HWP carbon pool accumulation and annual changes from project and BAU scenarios

which were not completely offset by actual project-HWP stock changes for 25 years (as displayed in figure 7 in sky blue). Because the benefits of project-HWP stock changes were delayed in comparison, they were substantially reduced by time-discounting (not illustrated in figure). The resulting NPVs ($986-$1,582.40ac-1) were much less than the unadjusted cases and swelled the NPV shortfall of CAR engagement. The difference in verified removals and reversals between this alternative HWP accounting case and the unadjusted case can be seen in figure 8, which is almost entirely manifested in the first verification year. The negative impact of baseline-HWP carbon on creditable carbon early in the project term is significantly lessened by the default HWP carbon accounting method. These findings support the rationale of reducing the baseline’s sensitivity to speculative harvests by annualizing baseline HWP-carbon changes.

Figure 8. CRTs acre-1 issued/surrendered in verification years resulting from adjustment to HWP carbon accounting

In light of the unfavorable findings heretofore, an alternative baseline scenario was constructed that expresses a nexus with the BAU management scenario modeled and counteracts the evident disadvantage of starting with AGL stocks near but below the CP statistic. Instead of a static baseline AGL carbon stock based on a 100 year average[[32]](#footnote-32), this alternative baseline determination method relied on computing a ten year moving average of AGL stocks across the projection period. A 5 year basis for the moving average was not used because a ten year moving average was found to be more conservative. However, the moving average was only applied during and after the year that the BAU scenario’s AGL stocks first decreased. Hence, the initial AGL stocks were set as the baseline AGL stocks in keeping with the unadjusted baseline methodology until the first simulated harvest occurred. Afterward, the product of the CP statistic and the ratio of the ten year moving average to the initial AGL carbon stock was treated as the AGL baseline except for years in which this exceeded CP, which in such cases the CP statistic was made the AGL baseline, as expressed in equation 4.

*Equation 4*: Aboveground live carbon baseline = Max

Linking the AGL stock’s moving average (nominator in equation 4) to the CP statistic in this way made the AGL baseline higher than would be the case if it was set directly to the moving average, which rendered more conservative amounts of creditable carbon. Because the AGL baseline is based on the size of the moving average AGL carbon stock in relation to initial AGL stocks, projects with less mature initial forest conditions (i.e. further from the relevant CP statistic) are benefited less from this accounting technique, owing to the fact that this ratio is likely to be greater for IFM projects largely made up of stands at younger stages of forest development. As a result, a higher percentage of the CP statistic becomes the AGL baseline in such cases. This function therefore would increasingly disfavor project proponents that would try to game this system by simulating harvests prematurely in the BAU management scenario as a means of dampening the baseline. Furthermore, the standardized ceiling of the AGL baseline as illustrated in figure 9 would grow more conservative over the course of a project rising from the initial AGL carbon stock to the CP statistic, and in effect decreasing (somewhat) the likelihood of non-additional CRTs being issued. As shown in figure 9, this hybrid alternative baseline more closely reflects the simulated BAU regime while also encompassing the CP benchmark, a standardized benchmark common to all projects in a given ecoregion. Consequently, carbon removals in early years of this projection are significantly larger than those generated from other baseline variations but come with similarly sized reversals (see figure 10). Figure 9 also depicts the irony of DL harvesting with regard to BAU AGL-carbon stocks, in that BAU stocks rise over time despite the magnitude of AGL-carbon diminutions while residual timber quality and biodiversity deteriorate.

Figure 9. Modeled AGL carbon stocks ac-1 for BAU management, the hypothetical CAR baseline, and the project scenario

Incorporating this hybrid alternative baseline produced a NPV of $1,322.20-$1,918.70ac-1. Although it still fell short, this was the only protocol modification to come close to generating value from CAR registration at a year-one price of $10 Mt-1. Aside from the baseline modification, this case also ignored the obligation to undergo a site-verification every year a reversal occurs, since reversals in this case are sporadic and depend on movements in both project and baseline AGL carbon stocks; this is why the verification years between assessment cases do not match in figure 10. Nevertheless, desk-reviews scheduled in between site-verifications were changed to site-audits if a harvest was undertaken during the relevant verification period. Under the carbon price growth assumption, a year-one price of at least $49.8 Mt-1 was necessary to achieve NPVs that met or exceeded those of the timber-only project scenario. The outcome improved after assuming adjusted reversal compensation, which rendered $1,326.5-$1,922.9ac-1 in NPV. The year-one price needed to add carbon value to the project dropped to $11.1 Mt-1, whereas the year-one price needed to totally compensate for abandoning BAU management (i.e. opportunity costs) was $85.7-$118.7 Mt-1. Hence, only with the adjustment to reversal compensation does even this hybrid baseline case provide an acceptable break-even price relative to the timber-only case. The primary reason for this was the fact that enough carbon value was realized early in the project (as indicated in figure 10) to offset all management and project implementation costs incurred throughout the project term. However, these hypothetical adjustments to the protocol did not generate enough carbon value at foreseeable prices to also offset the opportunity costs of harvesting delays relative to BAU. Incidentally, the same was true for the case-study involving version 2.1 of the protocol by Galik et al. (2009b). Still, this hybrid baseline case with limited reversal liability was the only case in which CAR involvement could pay for itself and the oak-sustaining management regime at foreseeable prices.

Figure 10. CRTs acre-1 issued/surrendered resulting from a major revision of the current CAR baseline methodology

For this adjusted baseline and reversal rules case, the $10.40 Mt-1 difference found between the break-even price resulting from inclusion of all implementation costs and that based on no implementation costs is markedly smaller than that ($52.45 Mt-1) found in the earlier assessment. This constitutes a 94 percent difference and can be interpreted as the percentage of the project’s earnings that is spent on implementation costs at this break-even point. This relative difference indicates a greater potential for profitability but shows that these costs continue to strongly influence economic viability under the alternative baseline scenario, as is generally expected for smaller projects. Indeed, the additional certification cost assessment case further increased the influence of these costs (by $1.90 Mt-1), rendering implementation costs even more consequential in project feasibility under this hypothetical protocol revision. Yet, treating this variable instead as annual property taxes, assuming as before that certification costs were covered by other aggregator fees, gives a sense of what carbon price is required to generate enough of a return to pay for property taxes. Raising the discount rate also gave results that were expected in that the detrimental impact of doing so had a greater effect on the optimistic stumpage price scenario in which the opportunity costs were already inflated (see appendix B).

It should be noted that all variations of the protocol could be even less cost-effective if a considerable amount of road/landing construction (additional to that assumed in the BMP costs and low stumpage rates) was necessary. Depending on the assumed accessibility of each stand, the opposite could also be true given that such costs could be more heavily discounted with regard to the time value of money under the project scenario in comparison to the BAU scenario. At the same time, these results are likely conservative considering the conservative approach undertaken in the modeling. The profitability of the project scenario would further improve if the area converted to roads and landings during harvests could be significantly and cost-effectively reduced. Wang et al. ([2005](#_ENREF_144)) imply that a benefit of about $90 ac-1 could be realized from decreasing the area in primary skid roads and landings from 10 percent to 6 percent for a 383ac harvest; though it remains to be seen if such a scenario would be cost-effective in practice and at a smaller scale. Such scenarios were not evaluated because they would have made results less interpretable.

## DISCUSSION

In summary, the timber-only oak-management scenario was much less profitable than the BAU scenario due in large part to the stumpage values that were realized very early in the BAU simulation, and in effect, were not significantly diminished by time-discounting. Another contributor to this outcome and potential source of bias might be the static stumpage rates used, which are based on a sample of sawtimber sales that is likely made up of lower amounts of the highest grade sawtimber than that produced from the project scenario and possibly higher amounts of the high grade sawtimber than that from the baseline scenario. The economic disparity between these scenarios presented a daunting challenge for IFM project feasibility, so it was not surprising to find that CAR participation would not add enough carbon value to the timber-only project scenario to favor it over BAU management. However, the discovery that CAR engagement as written and under all tested-variations of the protocol would worsen the financial prospects of adopting the oak-management scenario at reasonable carbon prices was surprising.

Comparing the age-classes inferred from the inventory and regional FIA data reveals that initial conditions implied from the inventory data represent the median age-class (61-70) of the even-aged timberland in the region, or about one-fifth of even-aged timberland acreage; nearly two-fifths are younger and another two-fifths are older ([USDA Forest Service 2010a](#_ENREF_15)). In addition to being relatively mature upland hardwood forests, the applicability of this analysis must also be interpreted in the context of unthinned stands comprised of one or two consecutive age-classes. As most of the difference in present worth between the two management regimes can be attributed to the deferment of harvests required to balance age-classes, it is important to point out that the cost-effectiveness of a CAR project in upland hardwood forests would presumably be more favorable than suggested here if the project initially consisted of a variety of age-classes. Such projects would incur opportunity costs far lower than those brought to bear in this case study. However, it is less common for smaller size tracts to have this age-class diversity compared to large tracts.

* 1. ***Problematic CAR implementation***

Apart from much needed guidance brought by recent changes made to the initial nationwide CAR protocol, the revised standard (version 3.2) still presents implementation problems for IFM projects and seems not to be “inclusive of many landowners who manage their forestland for the sustainable production of wood products” as claimed ([CAR 2009](#_ENREF_1)). Even though the project scenario was designed to significantly attenuate the reductions to AGL carbon stocks projected in the BAU scenario (as shown in figure 9) and forgo lucrative timber harvests in the short-term, the CAR protocol gave little credit for doing so under the conditions modeled. The results from this assessment imply that IFM projects largely consisting of stands nearing financial maturity that undertake sustainable management following guidance in the hardwood silviculture literature and the even-age management limitations dictated by CAR cannot accrue enough creditable carbon under the CAR protocol to justify CAR registration, unless a far more significant curtailment of near-term timber production than was simulated is compatible with owner objectives. These findings suggest that relatively mature upland hardwood IFM projects such as this with stocking levels below the CP statistic are inherently at a disadvantage, since they cannot earn the automatic credits awarded for stocking levels above CP but must still adopt a relatively high baseline, providing little incentive to forestall lucrative harvests. The extent of this drawback is a function of multiple factors but is largely contingent on the silvicultural regime adopted and its objectives.

Moreover, CAR rules in the context of this study present an obvious paradox, as they clearly prohibit the long-term diminishment of species diversity but appear to afford quite limited prospects for silviculturally sound and sustainable timber production (in adherence to CAR criteria), which in Southern Appalachia is essential to the maintenance of current biodiversity levels. These results also revealed that limitations on even-aged opening size and project age-class distribution have no influence on even-age harvest levels possible in eastern hardwood IFM projects, as barely complying with them in the first half of the simulation (in the interest of upland oak sustainability and economies of scale) produced more liabilities than credits. Given that project viability necessitates low harvest levels to begin with, sustainable forestry certification will not be needed to ensure sustainable harvesting levels and may otherwise offer little value relative to its cost.

Furthermore, the requirement that any decrease in carbon stocks be compensated for in its entirety (i.e. not limited to the number of CRTs issued prior to the stock reversal) was found to effectively discourage active management and in turn CAR participation by reversing the relationship between project value and carbon price in this case. This had the most devastating effect on project economics of all elements of the existing protocol that were evaluated. Even after ignoring this additional liability, no minor adjustment to the protocoladded economic value to the timber-only project scenario at realistic starting carbon prices and costs. Only under the assumption that all implementation costs were covered by the aggregator in exchange for a 12 percent commission on CRT sales, a very unlikely possibility, did the adjustment to reversal compensation create the conditions for financial feasibility in comparison to the timber-only case. Apart from reversal compensation, an exception to the verification protocol also seems warranted for smaller projects with regard to reversals, since planned reversals involving silviculturally appropriate treatments are already allowed for projects under 1,000ac. In particular, it looks as if appreciable savings could be achieved over a project’s lifetime from permitting desk-verifications in place of site-audits for such anticipated reversals with the stipulation that a site-verification occur in the next scheduled verification year. Discouraging active management makes even less sense in light of recent revelations that increases in harvest intensity (exclusive of clearcutting) lessen carbon accrual rates ([Nunery and Keeton 2010](#_ENREF_107)). Although clearcutting was found to have the highest rate of carbon sequestration, clearcutting is not likely to be commonly employed in IFM projects because it leaves no reserve trees to buffer the drop in carbon stocks. Thus, the enhancement of carbon accrual rates and total sequestration from reduced management intensity provides enough of an incentive on its own for adoption of less intensive management in IFM projects.

* 1. ***Additionality Considerations***

Every market invariably attracts actors that will try to game the system. When this occurs in carbon offset markets, “non-additional” offsets may enter the system, as opposed to additional offsets resulting from actions that would not have occurred without the anticipation of added value from carbon revenues. When “non-additional” offsets are credited, the real emissions from the buyers of those offsets then exceed emission goals or quotas, which cumulatively amplifies climate change beyond what would have otherwise resulted. These pseudo-mitigation projects in turn actually mitigate the GHG reduction program that enables them.

Additionality testing is a critical component of a carbon offset system because the chosen standard controls the larger mitigation system’s level of environmental integrity. Since additionality standards are the gatekeepers of mitigation project credibility, they must strike a delicate, quantitatively derived balance between policy objectives of cost-effectiveness, environmental integrity and getting a market established sooner than later ([Trexler et al. 2006](#_ENREF_137)). They must be adaptable and relatively easy to implement and understand in the interest of reducing the uncertainty that impedes investment in offset projects and providing the optimal supply of offset credits with respect to the size of the market. A common practice test designed for a carefully selected group of activities allowed to initially participate that targets low cost, highly additional offset projects would be ideal, because it could ensure that the supply of credits from fake offsets are minimized while also minimizing lost opportunities ([Trexler et al. 2006](#_ENREF_137)). CAR appears to be designed in such a way, but its IFM methodology clearly did not yield carbon value from the highly additional activities modeled in this study.

Conversely, in the context of small to medium size ownerships, it seems most suited for non-timber focused owners that would most likely let their forestland grow unmanaged anyway. Not only is this counterintuitive for a forest management methodology but it also has implications on the amount of non-additional IFM-generated CRTs making it to the market. Concerns about additionality focus attention on what BAU practices and management are assumed to occur. Yet regardless of whether a given FFO has discernable intentions regarding timber production, it is impossible to ascertain if and when he, she, or they (and heir(s) to the land) would institute harvests over a 100 year BAU period. Consequently, it is impossible to know the true amount of non-additional credits that will be issued to a given IFM project.

The current baseline determination approach sets a MBL towards which modeled carbon stocks are induced to gravitate. Hypothetically, a project owner originally with no intention of harvesting timber would be incentivized to characterize the BAU simulation with timber harvesting in order to ensure the annualized AGL value for BAU was very close to the MBL. Whether a given CAR-IFM project undertakes sustainable timber production or none at all, the CAR protocol contains no measure that would preclude project proponents from making fallacious timber harvesting characterizations of BAU management for carbon benefit, which would generate more non-additional credits than what might have otherwise resulted, depending on the past intentions of the owner and the project management employed.  If the economic feasibility of small to medium sized CAR-IFM projects that undertake sustainable timber harvesting is generally as bleak as this study indicates, most of these projects are likely to be passively managed if at all. Proponents of such projects would not be able to justifiably characterize BAU management with immediate, frequent and/or heavy cutting activities if held to a financial additionality standard requiring positive marginal NPVs at foreseeable carbon prices. Such a scenario would fail such an additionality test because one would have to claim to forgo activities that would yield much higher financial returns than what CAR participation could provide, which a rational individual would not be expected to do. Consequently, the potential for non-additional crediting and for emission reductions lost to leakage[[33]](#footnote-33) is higher with these projects that produce little to no timber. As a result, the market supply of IFM-generated CRTs is likely to have a higher proportion of illegitimate CRTs than would be the case if the viability of sustainable timber production was less daunting as an IFM project, which could affect the protocol’s credibility.

One could argue that FFOs with a predisposition to let their forests grow unmanaged would be concentrated in small ownerships that cannot economically manage their timberland for forest products or afford IFM project development and implementation costs; hence, most would not be expected to participate as an IFM project. On the other hand, aggregation reduces the costs of CAR participation and facilitates the involvement of such smaller ownerships more likely to let nature take its course in the absence of an offset crediting mechanism. Thus, ratcheting up the rigor of the current set of additionality-tests for IFM projects (in an aggregate) below a certain acreage and/or without sufficient records of past forest management would perhaps serve as an adequate deterrent to the enrollment of lands unlikely to be managed in the absence of carbon value, without imposing undue burdens on projects more likely to be additional.

In response to public comments, CAR staff and the protocol workgroup asserted that they “operated under a principle of designing standards that would ‘do no harm’ to background ‘natural’ forest conditions” ([CAR 2009](#_ENREF_1)). In pursuit of this goal, it appears that the CAR protocol was designed too broadly in some ways and too restrictive in others, for which CAR has been both lauded and criticized. The reversal compensation issue is a key example of how the CAR protocol was structured too broadly. The rule as written seems appropriate for avoided deforestation projects that by definition are meant to permanently protect forest carbon stocks; yet it makes no sense for IFM projects that may involve temporary but significant reductions in carbon stocks at one or more instances in the 100 year project. Moreover, the diversity of forest ownership and management intentions in the U.S. does not seem to lend support to the notion of an all-encompassing standardized IFM protocol that is largely independent of owner characteristics and regional differences in applied management.

While natural forest development sequesters more carbon than any form of active management ([Nunery and Keeton 2010](#_ENREF_107)), the carbon benefits of IFM have principally been investigated in the context of managed forests only (e.g.[Gutrich and Howarth 2007](#_ENREF_64); [Sohngen and Brown 2008](#_ENREF_131); [Galik et al. 2009b](#_ENREF_56)), that is, under the assumption that management practices are altered not ceased. Thus, “natural” forest conditions have never before been as pertinent to the discussion on IFM as they are in the CAR protocol. This “natural” forest consideration may explain why CAR appears to essentially discourage engagement from those with interests in sustainable timber production as opposed to those that would not pursue overstory removals to maximize carbon revenues. It should be noted that the 100 year agreement to maintain carbon gains made by CAR participants minimizes the probability of conversion to developed use on project area. However, the chances of development are also reduced if a tract remains a productive asset, in terms of the commercial sale of forest products, rather than an expendable asset. Indeed, it seems that the added value from an IFM protocol should ultimately come from its ability to dovetail with sustainable forestry to enhance the permanence of IFM project activity in both ways as opposed to working primarily for forest preservation efforts.

* 1. ***Hybrid Baseline Approach***

Many entities following the evolution of IFM methodologies advocate for measures that are practical and less expensive to implement. Yet, it is hard to envision how a process employing sufficient additionality-tests could reduce the complexity of IFM project development without substantially limiting participation in the hope of averting a flood of credits entering the market that would dampen both market price and confidence. As all IFM methodologies rely on growth and yield models for baseline quantification, forest modeling is one complicated element of IFM project development that seems to be a necessary evil in determining either a standardized baseline stocking level or a dynamic baseline linked to anticipated conventional management.

Determining the baseline from which to measure progress is the most important step in offset quantification because forest offsets in theory represent additions to a baseline level of carbon stocks. Realistically simulating 100 year management regimes is a difficult and time consuming task, even for forest modeling experts. The expense of such complex modeling is not well understood either, especially in the context of aggregator-developed projects. It is even unclear what context the modeling cost assumed in this analysis was calculated under. What is clear is that projections of diverse hardwood forests and dynamic management regimes are likely to be relatively expensive. Yet, there does not appear to be any tacit advantages in the CAR protocol to building such complex and expensive modeling efforts, as perhaps there should be. The hybrid baseline determination approach that was tested represents a fundamental revision to the CAR baseline methodology in this regard as it produces creditable carbon somewhat proportional to the actual difference in carbon stocks between the BAU and project scenarios. In other words, the investment in modeling is rewarded with more creditable carbon earnings.

* + 1. ***Implications of Alterntive Hybrid Baseline Methodology***

The hybrid baseline alternative was found to counteract the apparent disadvantage of starting with AGL stocks near but below CAR’s CP threshold. Despite multiple attempts at adjusting CAR’s baseline methodology, the hybrid baseline alternative was the only variation found to make CAR participation more economically attractive than the timber-only project scenario at foreseeable carbon prices. This alternative baseline methodology implicitly assumes a more onerous review of the BAU management simulations than is presently dictated in the CAR protocol. Because BAU simulation specifics are only speculative guesses of what might happen in the future, not much confidence can be placed in them. If IFM baselines become more dependent on forest growth and yield modeling, oversight of the justification given for parameters and assumptions used in baseline simulations must in turn become more rigorous and methodical. Even if this were the case, proponents of projects similar to this hypothetical project would be incentivized to simulate low DL cuts that occur frequently or otherwise lie about their management intentions, since heavier cutting results in the lowest baseline AGL carbon stocks. In practice, DL cutting occurs at a variety of DBHs, scales, and time intervals, as do virtually all cutting practices. Similarly, project proponents would be incentivized to simulate heavy and long lasting damage to the residual stand caused by imprudent logging crews.

Requiring BAU management justification to be drawn from historical timber sale records and/or management plans would probably disqualify most FFOs that are likely to engage in unsustainable harvesting. Thus, oversight of IFM baseline modeling could not be so rigid that it would preclude relatively large numbers of FFOs from financially feasible CAR involvement. Current and projected timber prices and the financial feasibility of various operations at different scales and locales play would play an important role in the justification of baseline harvests under this alternative approach. Because the alternative baseline methodology would increase the reliance on speculative assumptions, CAR would probably need to require periodic revisions of the assumptions affecting the baseline simulation in future years. Although doing so could inject more uncertainty into projects than many potential proponents might tolerate, baseline assumption revisions could benefit project owners by allowing them to adjust the baseline down to account for better than expected timber markets and significant natural disturbances in qualifying circumstances.

While the justification of speculated BAU management is currently required, a financial analysis is merely one of the two options a CAR project proponent can use to do so. Even if CAR were to necessitate this financial analysis of the BAU regime, such a rule would be of little value if not assessed in comparison with the anticipated project management regime’s profitability (valuing timber and carbon value); this would constitute a financial additionality test. Although the CAR protocol employs a standardized performance benchmark and requires proof of regulatory additionality, a financial additionality test similar to the cost-benefit analysis undertaken for this study also seems warranted given the need to substantiate BAU management claims. However, it is important to note that if the simulation of forest management is to be commonly used to define IFM baselines and to forecast the viability of project management regimes, the area required for skid roads, haul roads, and landings corresponding with different harvest techniques on various slopes needs to be understood far better given how little current information exists on the expense and environmental impact of steep terrain logging equipment and roads. Further research is also needed on finding acceptable bounds for many other assumptions in IFM project assessments and particularly on elucidating the effect of specific silvicultural applications on the establishment, composition, and growth of natural regeneration if simulation models are to serve such a meaningful role.

The addition of a financial additionality test to the CAR protocol —requiring the positive marginal value of carbon sequestration be demonstrated— would effectively reverse the incentive to embellish management intensity in BAU simulations and would thereby minimize the issuance of non-additional CRTs. Note that the low DL cutting regime simulated herein could be considered a “worst case scenario” in the sense that purely exploitative[[34]](#footnote-34) practices were simulated early in the projection and because the return interval was quite long, allowing enough time for residual trees to grow large. As such, the BAU regime nearly produced the highest timber revenues possible and ironically induced an impressive increase in carbon stocks over time, thereby raising the bar for IFM relative profitability under all tested-cases. Not even the alternative baseline case could produce results that favored the IFM oak-management scenario over BAU. While adding a financial additionality-test to current requirements (that the commonality and legality of BAU management be demonstrated) would increase project development costs, it would benefit project owners by ensuring that they are fully informed about the financial prospects of IFM adoption.

On the other hand, applying this financial additionality test could lead to many missed opportunities with FFOs that would engage in practices approaching a “worst case scenario” similar to the circumstances modeled herein. Yet, considering that it is unknown whether a less intensive BAU harvesting regime would render this hypothetical project scenario profitable, the potential for missed opportunities may be much greater than implied by this case-study. Projects proposing relatively unprofitable IFM scenarios in comparison to BAU can be considered missed opportunities because some FFOs intending to harvest timber in a short-term profit maximizing way could presumably be convinced to avoid such practices and accept lower short-term timber revenues if made aware of the long-term implications. That is, the relevant break-even price would fall from $86-$119 Mt-1 to $11 Mt-1. Only under this assumption and the alternative baseline scenario would the hypothetical FFO in this case-study look favorably on CAR involvement.

Arguing a counterfactual such as this may seem like an exceedingly tall order, but it is quite plausible for an FFO to be convinced to abandon lucrative harvesting plans in favor of sustainable forestry given that far more FFOs in the South consider passing on their property to their heirs and aesthetic values important reasons for owning forestland than do those that find timber production a central reason ([Butler 2008b](#_ENREF_32)). Although many FFOs care about leaving their forests in good condition so that their heirs can benefit from future timber sales, property taxes are also a prominent concern, second to the importance of land bequeathal. Property taxes are actually of equal concern for those without written management plans ([Butler 2008b](#_ENREF_32)). This is probably due to the fact that FFOs without a written plan are usually not eligible for present-use valuation (i.e. timberland appraisal), which markedly reduces assessed property taxes. Therefore, many FFOs could presumably be persuaded by a qualified forester to revise unsustainable harvesting plans for property tax, sustainability, and legacy purposes. This presents a dilemma, as projects in similar circumstances as those modeled herein would not be conceivable under the alternative baseline approach if financial additionality was strictly required despite the obvious additionality of oak sustaining silviculture. However, perhaps this potential for missed opportunities could be minimized with a “back door” provision, whereby projects that sacrifice economic value (relative to BAU) by adopting unconventional management practices, such as those that regenerate and sustain oaks, would still be eligible for participation.

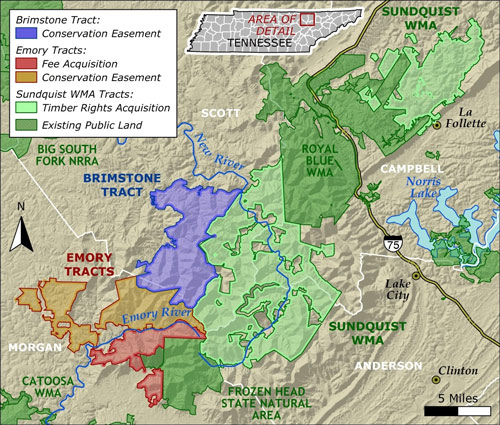
* 1. ***Alternative Strategies and Niche Opportunities***

Group selection may be a more compatible harvesting strategy for IFM projects, especially those that are relatively small, since patch cuts of adequate size can successfully regenerate monetarily valuable intolerant species ([Dale et al. 1995](#_ENREF_43)), perhaps even oaks if coupled with requisite treatments. In fact, hardwood management can become more efficient in this way by targeting mixed-oak forest patches in most need of management. Apart from species diversity considerations, the establishment of even age cohorts in this way (as opposed to single-tree selection) facilitates good stem form development ([Smith 1981](#_ENREF_124)), which is essential in hardwood timber production. Group selection complicates management planning and lowers financial yields, but harvesting small patches in lieu of entire stands lends itself to maintaining overall carbon stocks and a potentially rapid return to creditable carbon gains, whose value could offset increased management costs. Patch cuts in some cases can actually be as financially attractive as diameter limit cuts without carbon compensation ([Baumgras and Ledoux 1995](#_ENREF_24)). Furthermore, this uneven-aged approach would make the project owner exempt from the costly sustainable forestry certification requirement of the protocol. Because modeling patch cuts is more involved than the stand-based approach, this harvesting method was not evaluated. However, LeDoux et al. ([2003](#_ENREF_84)) have developed a method for estimating production rates and costs for hardwood group selection harvests in Appalachia employing THIN-PC software, which could prove useful in future examinations of such IFM opportunities.

Group selection also diversifies forest habitat and is better suited to meeting the needs of endangered species such as the cerulean warbler, a neotropical migratory bird that requires contiguous mature hardwood forest. As Cerulean warblers in the northern part of their breeding range show a preference for upland oak forests ([Hamel 2006](#_ENREF_66)), sustaining oaks as a dominant component in Appalachian forests will be important to the stabilization and recovery of the Cerulean warbler population, which has declined 70 percent in recent decades and whose core breeding range includes the Cumberland Mountains ([Sauer et al. 2005](#_ENREF_116)). Although the U.S. Fish and Wildlife Service in 2006 denied a petition to give the cerulean warbler protection under the Endangered Species Act (ESA), the presence of existing ESA-protected species in the Cumberland Mountains such as the Indiana bat (*Myotis sodalis*) and Gray bat (*Myotis grisecens*) may provide alternative funding mechanisms for oak restoration efforts. Conservation easements established for this reason or for watershed protection may very well facilitate subsequent entry into carbon markets since voluntary participation in these areas of opportunity are eligible as CAR projects.

* 1. ***Applicability of Results***

Approximately two-fifths of the region’s forests are more mature than those modeled here. Thus, there may still be considerable potential for CAR participation in this area since mature stands can earn a handful (or better) of stocking retention credits at project inception due to better than average intial AGL stocks. Yet, as management options for southern upland hardwood forests diminish with stand age, more mature forests do not necessarily stand a better chance at IFM success unless timber extraction becomes a far less important management objective. Silvicultural guides and optimal rotation studies for these forests suggest rotation lengths of up to 100 years ([Pearson 2008](#_ENREF_110); [Ledoux and Miller 2008](#_ENREF_85)), but recommended rotation can vary considerably depending on site quality, geography, species mix, timing of intermediate treatments (if any), timberland accessibility, distance to mills, stumpage rates, and management aims. Ignoring road construction costs, long rotations are appropriate when coupled with intermediate treatments that maintain forest health ([Clatterbuck and Kauffman 2006](#_ENREF_40)) and productivity ([Hilt and Dale 1989](#_ENREF_71); [Ledoux 2007](#_ENREF_83)), but the time value of money and stumpage value ultimately govern harvest decisions and limits the delay of regeneration harvests. Other constraints such as sawlog merchantability limits and natural mortality and defect do not warrant long harvest deferments in southern hardwood stands. Therefore, the prevalence of mature forests in the region and the results from this assessment suggest that the opportunity costs of harvest deferments may be too great for carbon values to overcome for many FFOs that sustain their interest in timber production. This may still be the case for some FFO projects that would halt timber production for increased carbon revenues, because in some states, doing so would make the FFO ineligible for timberland appraisal, substantially increasing assessed property taxes. If long harvest deferments in mature southern hardwood stands are legitimately undertaken for CAR-IFM projects, it follows that offset prices must be relatively high or increase rapidly to compensate for decreasing quality sawtimber volume or potentially increasing market stumpage rates. On the other hand, the CAR protocol looks as if it could favor projects with younger forests, so CAR may still prove useful in facilitating much needed management in immature hardwood stands that contain larger numbers of crop trees and respond more vigorously to thinning than stands near maturity.

A landmark conservation project of the Nature Conservancy and State of Tennessee was finalized in 2007 that purchased land and negotiated conservation easements on about 53,000 acres of timberland (see non-green areas in Figure 11), including the land where the data used in this analysis was collected ([Kingsbury 2008](#_ENREF_76)). According to figures from Druckenbrod et al. ([2006](#_ENREF_47)) and those from above, about half of the Southern Cumberland Mountains in Tennessee is now apparently owned by the state or under conservation easement while the remaining half is about evenly split between large and smaller landowners. The size of the corresponding TN Division of Forestry district reported in Evans et al. ([2002](#_ENREF_48)) suggests that this unprotected area could amount to 500,000ac. Therefore, results from this paper may provide enough useful insight into this **Figure 11. Connecting the Cumberlands Campaign conservation achievements. Source: Kingsbury (**[**2008**](#_ENREF_76)**)**

type of IFM project to compel many landowners in this area and perhaps others further away to engage with IFM project developers and/or aggregators or otherwise seek more knowledge about IFM opportunity and protocol evolution. The sustainable management of a large majority of this area would be a momentous achievement given its historical importance to regional biodiversity ([Muller 1982](#_ENREF_103)), which is conveyed best by Braun’s ([1942](#_ENREF_28)) description of it: “In number of tree species, in size of individuals, in variety of forest types it ranks as one of the finest deciduous forest areas of North America. The mixed mesophytic forest association is here at its best; nowhere else is it as well developed.”

## CONCLUSIONS

It is clear that there is a host of coinciding burdens that upland hardwood forest owners and managers are facing. Most FFOs do not obtain professional guidance on the appropriate preparation for and execution of harvests in the context of long-term ecological and/or timber production considerations. The implications of this trend continuing are troubling to say the least. Schuler ([2004](#_ENREF_118)) asserts that “the regional decline of oak species suggests that only intensive and specific forest management focused on maintaining oak species can maintain historical levels of diversity.” Considering that immediate financial concerns tend to override those not mandated by environmental laws and regulations, it is hard to imagine how this threat could be confronted under the status quo.

IFM programs are certainly being seen as a potential way of averting more than just climatic changes, but implementing them cost-effectively at meaningful scales continues to be a challenge. CAR certainly deserves credit for establishing an unprecedented level of rigor in its IFM protocol while maintaining its commitment to additional refinements that increase functionality and ease of implementation. However, the findings in this assessment show that further adjustments to the CAR protocol are critical to its applicability to managed Appalachian hardwood forests and perhaps sustained yield hardwood forestry in general. Indeed, the specific refinements analyzed herein deserve consideration in future protocol revisions.

Baring modifications to the CAR protocol’s rules and procedures, the results of this study cast doubt on the utility of the protocol as a catalyst for popularizing sustainable even-age forestry in medium to small size tracts of relatively mature upland hardwood forests, and in turn, call into question the pragmatism of different protocol elements. However, it should be noted that tracts largely consisting of immature stands younger than those modeled here would likely present more favorable conditions for CAR-IFM participation. And there is certainly a great need for management in immature mixed hardwood stands still containing competitive oaks, as intermediate treatments would afford them the site resources needed to persist in the overstory. Hence, it would be interesting to see similar research examining the CAR-IFM project feasibility of largely immature hardwood tracts in the South. The findings in this study also imply that it may be unlikely for any strictly financial additionality focused IFM accounting scheme to offer a compelling alternative to Appalachian FFOs with the intention of harvesting relatively mature timber in the near-term with a profit maximizing objective.

In summary, the potential for the monetization of forest carbon sequestration to facilitate widespread sustainable forest management in the South ultimately hinges on whether an IFM methodology can be constructed/revised that harmonizes notions of additionality and baseline characterization in a systematic and results-driven way. Such a methodology is suggested in the previous section but this conceptual approach needs further testing, since the potential level of participation resultant from any offset mechanism’s additionality standards has serious implications on offset market price ([Trexler et al. 2006](#_ENREF_137)). Indeed, further analyses similarly exploring the financial feasibility of scenarios meaningful to large groups of FFOs are needed to test the practicality of all prominent IFM standards including those of the Voluntary Carbon Standard, American Carbon Registry, and CAR. FFOs are not likely to engage in IFM opportunities without reliable information that gives them a sense of the benefits that can be expected from doing so. By minimizing the barriers to forest carbon monetization through further protocol testing and revision, IFM programs will render more cost-effective mitigation activities on smaller tracts than would otherwise be possible, which will yield a more equitable distribution of IFM program benefits given that the vast majority of FFOs characterize the smaller ownership size-classes. IFM protocol development must seek the realization of win-win outcomes in balancing the tradeoff between accounting, environmental, and monitoring rules and the cost of application on relatively small projects, but not to the extent that protocols merely facilitate higher returns for modest changes to conventional management regimes. IFM protocols would clearly do the most good if constructed in ways that concurrently ensure additionality and incentivize silvicultural practices proven to sustain biodiversity in a given area.

## Literature Cited:

Abt, R.C., F.W. Cubbage and K.L. Abt 2009. "Projecting southern timber supply for multiple products by subregion." Forest Products Journal **59**(7-8): 7-16.

Adams, D., J. Mills, R. Alig and R. Haynes 2005. "SOFRA and RPA: Two Views of the Future of Southern Timber Supply." Southern Journal of Applied Forestry **29**(3): 123-134.

Alig, R.J., S. Stewart, D.N. Wear, S.M. Stein and D. Nowak 2008. "Forest Parcelization." Encyclepedia of Southern Bioenergy. Retrieved August 4, 2010, from <http://biomass.forestencyclopedia.net/p/p3121>.

Armsworth, P.R., B.E. Kendall and F.W. Davis 2004. "An introduction to biodiversity concepts for environmental economists." Resource and energy economics **26**: 115-136.

Arthur, M., D.L. Loftis and P. Brose 2009. Fire returns to southern Appalachian forests. Fire Science Brief. Boise, ID, Joint Fire Science Program. **35:** 6.

Barlow, R.J., M.F. Smidt, J.Z. Morse and M.R. Dubois 2009. "Cost and cost trends for forestry practices in the South." Forest Landowner **68**(5): 5-12.

Batteson, A.R. and H.C. Hitchcock 1976. Tennessee Valley Authority Continuous Forest Inventory Field Manual for County-Units in the Tennessee Valley. Division of Forestry, Fisheries, and Wildlife Development, TVA, Norris, TN. 77p.

Baumgras, J.E. and C.B. LeDoux 1995. Hardwood silviculture and skyline yarding on steep slopes: economic and environmental impacts. In: Gottschalk, Kurt W.; Fosbroke, Sandra L. C., ed. Proceedings, 10th Central Hardwood Forest Conference; 1995 March 5-8; Morgantown, WV.: Gen. Tech. Rep. NE-197. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 463-473.

Beck, D.E. and L. Della-Bianca 1981. Yellow-poplar: Characteristics and management. U.S. Dept. of Agriculture, Agriculture Handbook No. 583, 92 p.

Birdsey, R.A. 1996. Carbon storage for major forest types and regions in the conterminous United States. Forests and Global Change, Vol 2: Forest Management Opportunities for Mitigating Carbon Emissions. R. N. Sampson and D. Hair, eds. Washington, DC: American Forests, Chapter 1.

Birdsey, R.A. and G.M. Lewis 2003. Carbon in U.S. forests and wood products, 1987-1997: state-by-state estimates, Gen. Tech. Rep. NE-310. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 42p.

Braun, E.L. 1942. "Forests of the Cumberland Mountains." Ecological Monographs **12**(4): 413-447.

Brose, P.H., K.W. Gottschalk, S.B. Horsley, P.D. Knopp, J.N. Kochenderfer, B.J. McGuinness, . . . S.L. Stout 2008. Prescribing regeneration treatments for mixed-oak forests in the Mid-Atlantic region, Gen. Tech. Rep. NRS-33. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 100 p.

Buehler, D.A., M.J. Welton and T.A. Beachy 2006. "Predicting cerulean warbler habitat use in the Cumberland Mountains of Tennessee." Journal of Wildlife Management **70**(6): 1763-1769.

Butler, B.J. 2008a. National Woodland Owner Survey Table Maker Version 1.01, Amherst, MA: USDA Forest Service, Forest Inventory and Analysis Program.

Butler, B.J. 2008b. Family Forest Owners of the United States, 2006, Gen. Tech. Rep. NRS-27. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.72p.

Cairns, M.A., S. Brown, E.H. Helmer and G.A. Baumgardner 1997. "Root biomass allocation in the world's upland forests. Biomedical and Life Sciences." Oecologia **111**(1): 1-11.

CAR 2009. Summary of comments & responses on the draft forest project protocol, Version 3.0. Los Angelas, CA, Climate Action Reserve**:** 132.

CAR 2010. Forest Project Protocol Version 3.2. Climate Action Reserve. Los Angelas, CA**:** 134.

Carbon Positive, November 25, 2010. "First California carbon trade at $11.50." Retrieved December 2, 2010, from <http://www.carbonpositive.net/viewarticle.aspx?articleID=2197>.

Carmean, W.H. and S.G. Boyce 1974. "Hardwood log quality in relation to site quality. Research Paper NC-103. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. 7p."

Cascio, A.J. and M.L. Clutter 2008. "Risk and required return assessments of equity timberland investments in the United States." Forest Products Journal **58**(10): 61-70.

Cassens, D. 2001. Log and Tree Scaling Techniques. Publication FNR-191. West Lafayette, Indiana: Purdue University Cooperative Extension Service. 16 p.

Clark III, A., R.A. Souter and B.E. Schlaegel 1991. Stem profile equations for southern tree species. Res. Pap. SE-282. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 113p.

Clark, S.L., S.J. Torreano, D.L. Loftis and L.D. Dimov 2007. Twenty-two year changes in regeneration potential in an old-growth Quercus forest in the Mid-Cumberland plateau, Tennessee. In: Buckley, D.S.; Clatterbuck, W.K., eds. Proceedings, 15th central hardwood forest conference. E-Gen. Tech. Rep. SRS-101. U.S. Department of Agriculture, Forest Service, Southern Research Station: 286-294. [CDROM].

Clatterbuck, W.K. and B.W. Kauffman 2006. Managing Oak Decline. Professional Hardwood Notes. J. W. Stringer and W. K. Clatterbuck, University of Kentucky, Cooperative Extension Service, Lexington. **FOR-099:** 6.

Connor, R.C. and A.J. Hartsell 2002. Forest area and conditions. In: David N. Wear and John G. Greis, eds. Southern Forest Resource Assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: USDA Forest Service: 357-401.

Crookston, N.L. and G.E. Dixon 2005. "The forest vegetation simulator: A review of its structure, content, and applications." Comput. Electron. Agric. **49**(1): 60-80.

Dale, M.E., H.C. Smith and J.N. Pearcy 1995. Size of clearcut opening affects species composition, growth rate, and stand characteristics. Res. Pap. NE-698. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 21 p.

Davis, H.C. and J.R. Yaeger 2007. Soil Survey of Morgan County, Tennessee. United States Department of Agriculture, Natural Resources Conservation Service.

Davis, S.C., A.E. Hessl, C.J. Scott, M.B. Adams and R.B. Thomas 2009. "Forest carbon sequestration changes in response to timber harvest." Forest Ecology and Management **258**(9): 2101-2109.

Delcourt, P.A. and H.R. Delcourt 1987. Long-term forest dynamics of the temperate zone, Springer-Verlag, New York.

Doolittle, W. T. 1958. Site Index Comparisons for Several Forest Species in the Southern Appalachians. Soil Sci Soc Am J **22**(5): 455-458.

Druckenbrod, D.L., V.H. Dale and L.M. Olsen 2006. "Comparing current and desired ecological conditions at a landscape scale in the Cumberland Plateau and Mountains, USA." Journal of Land Use Science **1**: 169-189.

Evans, J., N. Pelkey and D. Haskell 2002. An assessment of forest change on the Cumberland Plateau in southern Tennessee: small area assessment forestry demonstration project for the Southern Forest Resource Assessment. University of the South, Landscape Analysis Laboratory, Sewanee, TN. 193p.

Fajvan, M.A. 2006. Research on Diameter-Limit Cutting in Central Appalachian Forests. In: Kenefic, Laura S.; Nyland, Ralph D. eds. Proceedings of the conference on diameter-limit cutting in northeastern forests; 2005 May 23-24; Amherst, MA. Gen. Tech. Rep. NE-342. Newtown Square, PA: U.S. Forest Service: 32-38.

Fajvan, M.A., S.T. Grushecky and C.C. Hassler 1998. "The effect of harvesting practices on West Virginia's wood supply. ." Journal of Forestry **96**(5): 33-39.

Fajvan, M.A., K.E. Knipling and B.D. Tift 2002. "Damage to Appalachian hardwoods from diameter-limit harvesting and shelterwood establishment cutting." Northern Journal of Applied Forestry **19**(2): 80-87.

Fajvan, M.A. and J.M. Wood 1996. "Stand structure and development after gypsy moth defoliation in the Appalachian Plateau." Forest Ecology and Management **89**(1-3): 79-88.

Fenneman, N.M. 1938. Physiography of eastern United States. NYC, NY, McGraw-Hill Co.

Foley, T.G., D.d. Richter and C.S. Galik 2009. "Extending rotation age for carbon sequestration: A cross-protocol comparison of North American forest offsets." Forest Ecology and Management **259**(2): 201-209.

Finite Carbon, July 13, 2009. "Forestry and Finance Experts Establish Finite Carbon to Facilitate U.S. Landowners’ Participation in Carbon Offset Markets." Retrieved July 29, 2009, from <http://www.finitecarbon.com/news/7_13_2009.html>.

Forest-Climate Working Group 2009. Policy platform. Washington D.C., American Forest Foundation.

Forest Stewardship Council 2010. FSC-US Forest Management Standard (v1.0). 122p.

Franklin, J.F., D.A. Perry, T.D. Schowalter, M.E. Harmon, A. McKee and T.A. Spies 1989. "Importance of ecological diversity in maintaining long-term site productivity. In: Perry, D.A., Miller, R., Boyle, J., Perry, C.R., Powers, R.F. (Eds.), Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. Timber Press, Portland, OR, pp. 82-97."

Galik, C.S., J.S. Baker and J.L. Grinnell 2009b. Transaction costs and forest management carbon offset potential, Working Paper, Climate Change Policy Partnership, Duke University**:** 15.

Galik, C.S., M.L. Mobley and D. Richter 2009a. "A virtual “field test” of forest management carbon offset protocols: the influence of accounting." Mitigation and Adaptation Strategies for Global Change **14**(7): 677-690.

Gass, R., M. Rickenbach, L. Schulte and K. Zeuli 2009. "Cross-Boundary Coordination on Forested Landscapes: Investigating Alternatives for Implementation." Environmental Management **43**(1): 107-117.

Germain, R.H. and J.F. Munsell 2005. "How Much Land is Needed for the Harvest Access System on Non-Industrial Private Forestlands Dominated by Northern Hardwoods?" Northern Journal of Applied Forestry **22**(4): 243-247.

Gingrich, S.F. 1971. Management of Young and Intermediate Stands of Upland Hardwoods, Res. Pap. NE-195. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 26 p.

Greenstone, M. and A. Looney 2010. An Economic Strategy to Renew American Communities, Strategy Paper. The Hamilton Project. Washington D.C., The Brookings Institute**:** 22.

Groninger, J.W., H.D. Stein, S.M. Zedaker and D.W. Smith 1998. "Growth Response and Cost Comparisons for Precommercial Thinning Methods of Appalachian Oak Stump Sprout Clumps." Southern Journal of Applied Forestry **22**: 19-23.

Gunn, J., W. Price, J. Battles, D. Saah and K. Siegel 2008. The Development of an Ecosystem Services Trading Program for Family Forest Landowners to Promote the Protection of Atmospheric, Water, and Soil Resources in Maine, New Gloucester, ME: Trust to Conserve Northeast Forestlands. Final Report Submitted to the USDA Natural Resources Conservation Service Conservation Innovation Grants Program. 61p.

Gutrich, J. and R.B. Howarth 2007. "Carbon sequestration and the optimal management of New Hampshire timber stands." Ecological Economics **62**(3-4): 441-450.

Hall, R.C. 1910. Preliminary study of the forest conditions of Tennessee. Geological Survey Service, 10A, 56p.

Hamel, P.B. 2006. Adaptive forest management for Cerulean Warbler Proceedings of Society of American Foresters National Convention. 25-29 Oct. 2006, Pittsburgh, PA. [CD-rom].

Hart, J.L. and H.D. Grissino-Mayer 2008. "Vegetation patterns and dendroecology of a mixed hardwood forest on the Cumberland Plateau: Implications for stand development." Forest Ecology and Management **255**(5-6): 1960-1975.

Haynes, R.W., D.M. Adams, R.J. Alig, P.J. Ince, J.R. Mills and X. Zhou 2007. The 2005 RPA timber assessment update. Gen. Tech. Rep. PNW-GTR-699. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 212 p.

Heath, L.S., M. Hansen, J.E. Smith, P.D. Miles and B.W. Smith 2009. Investigation into calculating tree biomass and carbon in the FIADB using a biomass expansion factor approach. In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. Forest Inventory and Analysis (FIA) Symposium 2008; October 21-23, 2008; Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 26 p.

Hersey, C. and D. Kittredge 2005. "The Expense of Private Forestry: Survey Results of Private Practicing Foresters in Massachusetts." Northern Journal of Applied Forestry **22**: 211-212.

Hilt, D.E. and M.E. Dale 1989. Thinning Even-aged Upland Oak Stands. In: Clark, F. Bryan, tech. ed.; Hutchinson, Jay G., ed. Central Hardwood Notes. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: Note 6.06.

Hinkle, C.R., W.C. McComb, J.M. Safely Jr. and P.A. Schmalzer 1993. Mixed mesophytic forests. Biodiversity of the Southeastern United States: Upland Terrestrial Communities. W. H. Martin, S. G. Boyce and A. C. Echternacht. New York, John Wiley and Sons**:** 203-253.

Hoover, C. and S. Stout 2007. "The carbon consequences of thinning techniques: stand structure makes a difference." Journal of Forestry **105**(5): 266-270.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath and R.A. Birdsey 2003. "National scale biomass estimators for United States tree species " Forest Science **49**: 12-35.

Kauffman, B.W. and W.K. Clatterbuck 2006. Forest management strategies to minimize the impact of gypsy moth. Professional Hardwood Notes. J. W. Stringer and W. K. Clatterbuck, University of Kentucky, Cooperative Extension Service, Lexington. **FOR-102:** 8.

Kingsbury, P. 2008. Connecting the Cumberlands: Tennessee’s Big Conservation Success for People and Nature. Tennessee Conservationist**:** 18-23.

Kochenderfer, J.D., S.M. Zedaker, J.E. Johnson, D.W. Smith and G.W. Miller 2001. "Herbicide Hardwood Crop Tree Release in Central West Virginia." Northern Journal of Applied Forestry **18**: 46-54.

Kochenderfer, J.N. 1977. "Area in skidroads, truck roads, and landings in the central Appalachians." Journal of Forestry **75**: 507-508.

Kochenderfer, J.N. and G.W. Wendel 1978. Skyline Harvesting in Appalachia. Res. Pap. NE-400. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 9p.

Lamson, N.I., H.C. Smith and G.W. Miller 1984. Residual stocking not seriously reduced by logging damage from thinning of West Virginia cherry-maple stands. Res. Pap. NE-541. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiement Station. 7p.

Lamson, N.I., H.C. Smith, A.W. Perkey and S.M. Brock 1990. Crown release increases growth of crop trees. NE-RP-635. Radnor, PA: US. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p.

LeDoux, C.B. 2000. "Matching Skidder Size to Wood Harvested to Increase Hardwood Fiber Availability: A Case Study." Forest Products Journal **50**(10): 86-90.

LeDoux, C.B. 2007. Impact of Alternative Harvesting Technologies on Thinning Entry and Optimal Rotation Age for Eastern Hardwoods. In: Buckley, David S.; Clatterbuck, Wayne K. eds. 2007. Proceedings, 15th central hardwood forest conference. e-Gen. Tech. Rep. SRSÂ–101. U.S. Department of Agriculture, Forest Service, Southern Research Station: 122-128.

LeDoux, C.B., B. Gopalakrishnan and R.S. Pabba 2003. An expert system for estimating production rates and costs for hardwood group-selection harvests. In: Van Sambeek, J. W.; Dawson, Jeffery O.; Ponder Jr., Felix; Loewenstein, Edward F.; Fralish, James S., eds. Proceedings of the 13th Central Hardwood Forest Conference; Gen. Tech. Rep. NC-234. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 390-396.

LeDoux, C.B. and G.W. Miller 2008. Exploring the optimal economic timing for crop tree release treatments in hardwoods: results from simulation. In: Jacobs, Douglass F.; Michler, Charles H., eds. 2008. Proceedings, 16th Central Hardwood Forest Conference; 2008 April 8-9; West Lafayette, IN. Gen. Tech. Rep. NRS-P-24. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 265-274.

Lemoine, D., J.P. Evans and C. Ken Smith 2006. "A Landscape-Level Geographic Information System (GIS) Analysis of Streamside Management Zones on the Cumberland Plateau." Journal of Forestry **104**: 125-131.

Li, Y., J. Wang, G.W. Miller and J. McNeel 2006. "Production economics of harvesting small-diameter hardwood stands in central Appalachia." Forest Products Journal **56**(3): 81-86.

Loftis, D.L. 1990. "A Shelterwood Method for Regenerating Red Oak in the Southern Appalachians." Forest Science **36**: 917-929.

McGrath, D.A., J.P. Evans, C.K. Smith, D.G. Haskell, N.W. Pelkey, R.R. Gottfried, . . . E.D. Williams 2004. "Mapping Land-Use Change and Monitoring the Impacts of Hardwood-to-Pine Conversion on the Southern Cumberland Plateau in Tennessee." Earth Interactions **8**(9): 1-24.

McShea, W. and W.M. Healy, Eds. (2002). Oak forest ecosystems: ecology and management for wildlife. Johns Hopkins University Press, Baltimore, Maryland, USA.

McShea, W., W.M. Healy, P. Devers, T. Fearer, F.H. Koch, D. Stauffer and J. Waldon 2007. "Forestry matters: decline of oaks will impact wildlife in hardwood forests." Journal of Wildlife Management **71**(5): 1717-1728.

McWilliams, W.H., R.A. O’Brien and G.C.R. L.Waddell 2002. Distribution and abundance of oaks in North America. Oak forest ecosystems: ecology and management for wildlife. W. J. McShea and W. M. Healy, Johns Hopkins University Press, Baltimore, Maryland, USA**:** 13-33.

Miles, P.W. and W.B. Smith 2009. "Specific gravity and other properties of wood and bark for 156 tree species found in North America. Res. Note NRS-38. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 35 p."

Miller, G.W. 1993. "Financial aspects of partial cutting practices in central Appalachian hardwoods. Res. Pap. NE-673. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 9 p."

Miller, G.W. 1997. Effect of crown growing space and age on the growth of northern red oak. In: Spiecker, H.; Rogers, R.; Somogyi, Z., comps. IUFRO Proceedings: advances in research in intermediate oak stands; 1997 July 27-30; Freiburg, Germany. Freiburg, Germany: University of Freiburg: 140-159.

Miller, G.W. 2000. "Effect of Crown Growing Space on the Development of Young Hardwood Crop Trees." Northern Journal of Applied Forestry **17**: 25-35.

Miller, G.W. and J.N. Kochenderfer 1998. "Maintaining species diversity in the central Appalachians." Journal of Forestry **96**(7): 28-33.

Miller, G.W., N.I. Lamson and S.M. Brock 1984. Logging damage associated with thinning central Appalachian hardwood stands with a wheeled skidder. In: Peters, Penn A.; Luchok, John., eds.; Proceedings, mountain logging symposium; 1984 June 5-7; Morgantown, WV: West Virginia University: 125-131.

Miller, G.W. and H.C. Smith 1991. "Comparing partial cutttng practices in central Appalachian hardwoods. In: McCormick, Larry H.; Gottschalk, Kurt W., eds. Proceedings, 8th Central Hardwood Forest Conference; 1991 March 4-6; University Park, PA. Gen. Tech. Rep. NE-148. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 105-119.".

Miller, G.W. and J.W. Stringer 2004. Effect of Crown Release on Tree Grade and DBH Growth of White Oak Sawtimber in Eastern Kentucky. In: Yaussy, Daniel A.; Hix, David M.; Long, Robert P.; Goebel, P. Charles, eds. Proceedings, 14th Central Hardwood Forest Conference; 2004 March 16 19; Wooster, OH. Gen. Tech. Rep. NE-316. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 37-44.

Miller, G.W., J.W. Stringer and D.C. Mercker 2007. Technical Guide to Crop Tree Release in Hardwood Forests, Publication PB1774. Knoxville, TN: University of Tennessee Extension. 24 p. [Published with the University of Kentucky Cooperative Extension and Southern Regional Extension Forestry].

Montréal Process Working Group 2009. Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests, 4th Edition. 29p.

Mooney, S., S. Brown and D. Shoch 2004. Measurement and monitoring costs: Influence of parcel contiguity, carbon variability, project size and timing of measurement events. Arlington, VA, Winrock International, Ecosystem Services Unit**:** 20.

Muller, R.N. 1982. "Vegetation patterns in the mixed mesophytic forest of eastern Kentucky." Ecology **63**: 1901-1917.

Murray, B.C., B.L. Sohngen, A.J. Sommer, B.M. Depro, K.M. Jones, B.A. McCarl, . . . K. Andrasko 2005. Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture, EPA-R-05-006. Washington, D.C: U.S. Environmental Protection Agency, Office of Atmospheric Programs. 154p.

NatureServe 2010a. "Cumberlands and Southern Ridge and Valley Ecoregion." Retrieved April 23, 2010, from <http://www.landscope.org/explore/natural_geographies/ecoregions/Cumberlands%20and%20Southern%20Ridge%20and%20Valley/>.

NC Division of Forest Resources 2010. "Forest Development Program Prevailing Rates." Retrieved April 4, 2010, from <http://www.dfr.state.nc.us/Managing_your_forest/fdp_rates.htm>.

Nowak, C.A. and D.A. Marquis 1997. Distribution-of-cut guides for thinning in Allegheny hardwoods: a review. Res. Notes NE-362. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 7 p.

Nunery, J.S. and W.S. Keeton 2010. "Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products." Forest Ecology and Management **259**: 1363-1375.

Oak, S.W., J.R. Steinman, D.A. Starkey and D.K. Yockey 2004. Assessing oak decline incidence and distribution in the southern U.S. using forest inventory and analysis data. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. pp. 236-242.

Oliver, C.D. 1980. "Forest development in North America following major disturbances." Forest Ecology and Management **3**: 153-168.

Pearson, S.M. 2008. "Environmental Gradients." Encyclopedia of Southern Appalachian Forest Ecosystems. Retrieved January 5, 2010, from <http://www.forestencyclopedia.net/p/p1585>.

Rauscher, H.M., M.J. Young, C.D. Webb and D.J. Robison 2000. "Testing the accuracy of growth and yield models for southern hardwood forests." Southern Journal of Applied Forestry **24**(3): 176-185.

Rebain, S.A. comp. 2010 (revised January 20, 2011). The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 379p.

Ricketts, T.H., E. Dinerstein, D.M. Olson, C.J. Loucks, W. Wichbaum, D. DellaSalla, . . . S. Walters 1999. Terrestrial ecoregions of North America: A conservation assessment. Washington, D.C., Island Press.

Rummer, B. and C. Erwin 2008. "Mechanical Felling." Encyclopedia of Southern Appalachian Forest Ecosystems. Retrieved November 3, 2010, from <http://www.forestencyclopedia.net/p/p2276>.

Runkle, J.R. 1985. Disturbance regimes in temperate forests. The ecology of natural disturbance and patch dynamics. S. T. A. P. a. P. S. White. Orlando, FL, Academic Press**:** 17-33.

Sauer, J.R., J.E. Hines and J. Fallon 2005. The North American Breeding Bird Survey, results and analysis 1966-2004. Version 2005.2. U. S. Geological Survey Patuxent Wildlife Research Center, Laurel, MD.

Schnur, G.L. 1937. Yield, Stand, and Volume Tables for Even-Aged Upland Oak Forests. U.S. Department of Agriculture, Technical Bulletin No. 560. 87p.

Schuler, T.M. 2004. "Fifty years of partial harvesting in a mixed mesophytic forest: composition and productivity." Canadian Journal of Forest Research **34**: 985-997.

Schulte, L.A., M. Rickenbach and L.C. Merrick 2008. "Ecological and economic benefits of cross-boundary coordination among private forest landowners." Landscape Ecology **23**(4): 481-496.

Shaffer, R.M., H.L. Haney, Jr., E.G. Worrell and W.M. Aust 1998. "Forestry BMP Implementation Costs for Virginia." Forest Products Journal **48**(9): 27-29.

Shifley, S.R., Z. Fan, J.M. Kabrick and R.G. Jensen 2006. "Oak mortality risk factors and mortality estimation." Forest Ecology and Management **229**: 16-26.

Siry, J.P. 2002. Chapter 14: Intensive timber management practices. Southern forest resource assessment. W. D.N. and G. J.G. Asheville, North Carolina, U.S. Department of Agriculture, Forest Service, Southern Research Station. Gen. Tech. Rep. SRS- 53: 327-340.

Smalley, G.W. 1984. Classification and evaluation for forest sites in the Cumberland Mountains. Gen. Tech. Rep. SO-50. New Orleans, LA: U.S. Dept of Agriculture, Forest Service, Southern Forest Experiment Station. 89 p.

Smith, H.C. 1981. Diameters of clearcut openings influence central Appalachian hardwood stem development -A 10-year study. Res. Pap. NE-476. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p.

Smith, H.C. and N.I. Lamson 1977. Stand Development 25 Years after a 9.0-inch Diameter-Limit First Cutting In Appalachian Hardwoods. Res. Pap. NE-379. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 4p.

Smith, H.C. and N.I. Lamson 1983. Precommercial crop-tree release increases diameter growth of Appalachian hardwood saplings. Res. Pap. NE-534. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiement Station. 7p.

Smith, H.C. and G.W. Miller 1987. "Managing Appalachian hardwood stands using four regeneration practices -34 year results." Northern Journal of Applied Forestry **4**(4): 180-185.

Smith, H.C. and G.W. Miller 1991. Releasing 75- to 80-year-old Appalachian hardwood sawtimber trees-5-year d.b.h. response. In: McCormick, Larry H.; Gottschalk, Kurt W., eds. Proceedings, 8th Central Hardwood Forest Conference; 1991 March 4-6; University Park, PA. Gen. Tech. Rep. NE-148. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 402-413.

Smith, J.E., L.S. Heath, K.E. Skog and R.A. Birdsey 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. USDA, Forest Service, Northeastern Research Station, Newtown Square, PA. 216 p.

Smith, W.B., tech. coord.; Miles, Patrick D., data coord.; Perry, Charles H., map coord.; Pugh, Scott A., Data CD coord. 2009. Forest Resources of the United States, 2007. Gen. Tech. Rep. WO-78. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 336 p.

Sohngen, B. and S. Brown 2008. "Extending Timber Rotations: Carbon and Cost Implications." Climate Policy **8**: 435-451.

Southern Appalachian Man and the Biosphere 1996. The Southern Appalachian Assessment Social/Cultural/Economic Technical Report. Report 4 of 5. Atlanta: U.S. Department of Agriculture, Forest Service, Southern Region.

Southern Appalachian Man and the Biosphere 1996. The Southern Appalachian Assessment Terrestrial Technical Report. Report 5 of 5. Atlanta: U.S. Department of Agriculture, Forest Service, Southern Region.

Spelter, H. 2004. "Converting among log scaling methods: Scriber, International, and Doyle versus cubic." Journal of forestry **102**(4): 33-39.

Stein, S.M., R.E. McRoberts, M.D. Nelson, L. Mahal, C.H. Flather, R.J. Alig and S. Comas 2010. "Private Forest Habitat for At-Risk Species: Where Is It and Where Might It Be Changing? ." Journal of Forestry **108**(2): 61-70.

Stringer, J.W. 2006. Two-age system and deferment harvests. Professional Hardwood Notes. J. W. Stringer and W. K. Clatterbuck, University of Kentucky, Cooperative Extension Service, Lexington. **FOR-103:** 12.

Stringer, J.W., G.W. Miller and H.C. Smith 1988. Residual stand damage from crop tree release felling operations in white oak stands, Kentucky Dept. of For. Tech. Rep. No. 8801. Lexington, KY: University of Kentucky. 15 p.

Thornthwaite, C.W. 1948. "An approach toward rational classification of climate." Geographical Review **38**: 55-94.

TN Dept. of Agriculture 2003. Guide to Forestry Best Management Practices in Tennessee. 50p.

Trexler, M.C., D.J. Broekhoff and L.H. Kosloff 2006. "A Statistically-driven Approach to Offset-based GHG Additionality Determinations: What Can We Learn?" Sustainable Development Law & Policy **6**(2): 30-40.

Trimble, G.R., Jr. 1974. Response to crop-tree release by 7-year-old stems of red maple stump sprouts and northern red oak advance reproduction. Res. Pap. NE-303. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 6p.

Trimble Jr., G.R. 1973. The regeneration of central Appalachian hardwoods with emphasis on the effects of site quality and harvesting practice. USDA Forest Service, Research Paper NE-282. Northeastern Forest Experiment Station, Broomall, PA. 14 p.

Tryon, E.H., M. Lanasa and E.C. Townsend 1992. "Radial growth response of understory sugar maple (*Acer saccharum*) surrounding openings." Forest Ecology and Management **55**: 249-257.

USDA Forest Service 2007. "Distribution of Upland Hardwood Forests." Compass Issue 9: The mighty oak in upland hardwood forests of the south. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Retrieved January 5, 2010, from <http://www.srs.fs.usda.gov/compass/issue9/03distro.htm>.

USDA Forest Service 2010a. National Forest Inventory and Analysis, FIA Database version 4.0. Washington, DC: U.S. Department of Agriculture, Forest Service. Available at <http://199.128.173.17/fiadb4-downloads/datamart.html> Retrieved January 4, 2010.

USDA Forest Service 2010b. National Volume Estimator Library. In: Excel volume functions. Fort Collins, CO, Forest Management Service Center, USDA Forest Service.

U.S. EPA 2008. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006, U.S. Environmental Protection Agency, Washington, D.C. 473p.

U.S. EPA 2009. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007, U.S. Environmental Protection Agency, Washington, DC.

Van Deusen, P. and L.S. Heath. 2007. COLE web applications suite. NCASI and USDA Forest Service, Northern Research Station. Available only on internet: <http://www.ncasi2.org/COLE/>

Vandendriesche, D. 2010. "An empirical approach for estimating natural regeneration for the Forest Vegetation Simulator. In: Jain, Theresa B.; Graham, Russell T.; and Sandquist, Jonathan, tech. eds. 2010. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate: Proceedings of the 2009 National Silviculture Workshop; 2009 June 15-18; Boise, ID. Proceedings RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 307-320p."

Vandendriesche, D. and L. Haugen 2006. Comparison of Measured Growth and Mortality Trends to Modeled FVS Projections Relative to Oak Decline Impacts as Observed Over Three FIA Inventory Cycles on the Mark Twain National Forest. USDA Forest Service. Forest Management Service Center. Fort Collins, Colorado. 42p.

Wang, J., S.T. Grushecky and J. McNeel 2005. "Production analysis of helicopter logging in West Virginia: a preliminary case study." Forest Products Journal **55**(12): 71-76.

Wear, D., J. Pye and K. Riitters 2004. "Defining conservation priorities using fragmentation forecasts." Ecology and Society **9**(5): 4. [online] URL: <http://www.ecologyandsociety.org/vol9/iss5/art4/>

Wendel, G.W. and N.I. Lamson 1987. Effects of herbicide release on the growth of 8- to 12-year-old hardwood trees. NE-RP-598. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 4 p.

Yaussy, D.A. 2000. "Comparison of an empirical forest growth and yield simulator and a forest gap simulator using actual 30-year growth from two even-aged forests in Kentucky." Forest Ecology and Management **126**(3): 385-398.

1. To be classified as forestland, an area must generally have at least ten percent live tree cover and be at least 120 ft. wide and one acre in size, including land that formerly had such tree cover and will be naturally or artificially regenerated (W.B. Smith et al. 2009). [↑](#footnote-ref-1)
2. As defined by Region 8 of the U.S. Dept. of Agriculture, Forest Service [↑](#footnote-ref-2)
3. Data from forests in the central portions of Oklahoma and Texas were not yet available for this period. [↑](#footnote-ref-3)
4. Timberlands are defined as forestland that is capable of producing in excess of 20 cubic ft. of industrial wood per acre per year in natural stands and is not precluded from timber extractions by statute or regulation (Smith 2009). [↑](#footnote-ref-4)
5. This area includes the area assessed in this analysis, the Cumberland Mountains of TN. [↑](#footnote-ref-5)
6. These statistics were computed from all southern states including Texas and Oklahoma at the 95 percent confidence level using the National Woodland Owner Survey Table Maker. [↑](#footnote-ref-6)
7. Recorded in the period 1961-90 at Oneida, Tennessee [↑](#footnote-ref-7)
8. This relative density measure is already a FVS variable; though at the present time, it must be manually calculated for simulations in southern states because it can only be used in concert with the northeast variant. [↑](#footnote-ref-8)
9. Converting FIA database fields to FVS input fields is explained in: Shaw, John D. 2009.  Using FIA data in the Forest Vegetation Simulator.   In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. Forest Inventory and Analysis (FIA) Symposium 2008; October 21-23, 2008; Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 p. <http://www.treesearch.fs.fed.us/pubs/33330> [↑](#footnote-ref-9)
10. Utilizing the Repute program involved such an exhaustive exercise because the online FIA database tool (Mapmaker 2.1) that transfigured FIA data into FVS-ready input files was lost in a server crash. [↑](#footnote-ref-10)
11. Diameter increments given by trees measured in more than one inventory (including those from FIA plots from the TN Cumberland Mountains) were basis of this calibration. [↑](#footnote-ref-11)
12. This refers to management judgments based on tree health and quality. In addition to the exception made for percent rot measurements mentioned previously, other exceptions to this rule are disclosed hereafter. [↑](#footnote-ref-12)
13. While this is most likely an unrealistic assumption for the BAU management case, it was necessary to avoid overcomplicating the scenario comparisons. [↑](#footnote-ref-13)
14. Crop trees were not grown larger than the maximum diameters that the relevant mill or steep-terrain harvester is capable of handling. [↑](#footnote-ref-14)
15. Stumpage rates were derived from delivered volumes not cruise estimates. [↑](#footnote-ref-15)
16. Pers. comm., Chad Keyser, USFS Forest Management Service Center, May 14, 2009 [↑](#footnote-ref-16)
17. Pers. comm., Richard Taylor, Columbia Forest Products, October 20, 2009 [↑](#footnote-ref-17)
18. Some trees did not have 16′ butt logs but did contain one 12′ of 14′ log. [↑](#footnote-ref-18)
19. Pers. comm., Greg Bailey, American Forest Management, January 26, 2010 [↑](#footnote-ref-19)
20. The same cost was not applied in the CAR-involvement case due to its incorporation into a project development fee. [↑](#footnote-ref-20)
21. This was the approximate age of stands simulated here. [↑](#footnote-ref-21)
22. Found in both studies for Appalachian mixed hardwood stands cut from below ~12″DBH with no prior discounting and for Appalachian oak stands cut from below ~8″DBH with time-discounting from an initial stand age of 40. [↑](#footnote-ref-22)
23. Found in Appalachian oak stand cut from below ~8″DBH with time-discounting from initial stand age of 40. [↑](#footnote-ref-23)
24. Including only wood products and above-ground living and dead pools [↑](#footnote-ref-24)
25. Percentage increases in growth were inferred from the increased-growth observations of CTR studies. These percentage increases were applied to FVS-determined stand growth obtained from unthinned model runs. The resulting augmented growth estimates were used to determine the appropriate growth multipliers to incorporate into the thinned model. [↑](#footnote-ref-25)
26. Pers. comm. Jim Sitts, Columbia Forest Products, December 15, 2009; Greg Bailey, American Forest Management, February 3, 2010 [↑](#footnote-ref-26)
27. Pers. comm., Ken Cormier, Forest Management Service Center, USFS, March 22, 2010 [↑](#footnote-ref-27)
28. Only applied at end of harvest years and in verification years if resampling occurred in the verification period [↑](#footnote-ref-28)
29. Only applied at end of harvest years [↑](#footnote-ref-29)
30. Hereafter, ‘unadjusted’ refers to the protocol as written but assumes the use of the Jenkins et al.(2003) BGL biomass equations. [↑](#footnote-ref-30)
31. While some carbon market studies take the approach of Herzog et al. (2003) whereby carbon prices are grown at the discount rate to achieve price parity over time in present value terms (i.e. the Hotelling rule), a more (continued on next page)

    conservative growth rate seems appropriate considering that CAR is a voluntary program and given that it is unfortunately very uncertain whether the world will cooperatively set a global cap on GHG emissions, making emissions a finite resource subject to the Hotelling rule. [↑](#footnote-ref-31)
32. This alternative baseline methodology was conceptualized only in the context of projects whose minimum baseline level AGL stocks are near initial stocks and did not consider the implications of applying this option to projects whose “high stocking reference” as defined by CAR exceeds initial stocks. [↑](#footnote-ref-32)
33. Leakage, which refers to the amount of carbon sequestration compromised by market feedback to changes in timber supply, is accounted for in the CAR protocol with a 20% discount of the annual change in HWP carbon. [↑](#footnote-ref-33)
34. A more retrograding scenario could be envisioned with regard to harvest frequency, residual tree damage, and logging road considerations. [↑](#footnote-ref-34)