A Framework for Assessing the Lifecycle Greenhouse Gas Benefits of Forest Bioenergy and Biofuel Application in an Era of Forest Carbon Management

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ABSTRACT. An increase in the frequency and intensity of wildfire both empirically observed and predicted by climate change models has focused forest management on the need to actively manage forests to increase the resilience of forests to wildfire. The use of forest wastes for the production of bioenergy and liquid biofuels has potential to increase the stability of carbon in a number of forest types and to offset the use of fossil energy sources. Some studies suggest biofuel and bioenergy produced from the removal of forest waste - products considered to be uneconomical to harvest - generates significant well-to-tank greenhouse gas (GHG) emission savings than energy produced from fossil resources. However, most lifecycle analysis (LCA) studies fail to take into account the dynamics of carbon cycle between the forest management practices, forest fire behaviors, and the utilization of forest biomass. This paper outlines a framework for evaluating system-level lifecycle GHG emissions of forest biomass utilization under various forest management strategies.

KEYWORDS. Biofuels, forests, lifecycle assessment, risk assessment, wildfire, forest carbon, forest products, bioenergy, biomass, sustainability, forest policy.

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BACKGROUND

As a result of global and national efforts to manage anthropogenic emission of greenhouse gases (GHG) (Nunez 2006; United Nations 1997), policy frameworks – both in statute and under development – as well as emerging markets for emission credits have created market-based incentives aligned with GHG reduction goals. Policies regulating GHG emission are a result of broad scientific agreement that the global climate is being adversely impacted by anthropogenic emissions (IPCC 2007). The imposition of this global imperative on the political and economic milieu of forests has created new challenges as well as opportunities for forest managers and society at large. If forest management is to maximize the climate change mitigation benefits forests provide, then the energy, climate and natural resource policies that govern this management should reflect a nuanced understanding of forest ecosystems as well as the industrial ecology of energy, fuels, and wood products derived from forest biomass. Policies must be developed with a clear understanding of the range of possible forest management scenarios, metrics to evaluate performance relative to goals, and mechanisms to incentivize favorable action.

CONVERGENCE OF ENERGY, CLIMATE, AND FOREST POLICY IN CALIFORNIA

In California, several policy initiatives focusing on forest carbon offsets, transportation fuels, and renewable electricity production represent a convergence of climate and energy policy that is affecting forests and forest management. This policy convergence has challenged the capacity of traditionally disparate research and policy communities to develop analysis and tools that address tightly coupled climate and industrial wood and energy production systems.

Forests in California Climate Policy

In September, 2006 the California Climate Change bill (AB32) was signed into law outlining a broad plan to achieve an 80% reduction in the states GHG emissions from 1990 levels by 2050. The California Air Resources Board (CARB), the agency in charge of regulating GHG emissions, adopted a Scoping Plan to reduce state-wide GHG emissions levels to 1990 levels by 2020 on the way to the 2050 target established by AB32. One component of the plan is the implementation of a statewide cap and trade system for GHG emissions. Cap and trade policies set a limit on the total emission of GHGs over a period of time and allocate allowances to regulated emitters. Regulated emitters can reduce its GHG emissions or buy allowances from the cap-and-trade market. Individual projects achieving GHG emission reductions from activities not otherwise regulated, covered under an emissions cap, or resulting from government incentives can generate "offsets" credits. Emissions offsets are an important aspect of cap and trade systems particularly for forest managers. Under California's cap and trade system, carbon sequestered in forests as a result of management can be sold to emitters as emission offsets.

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The California Climate Action Registry (CCAR) was formed by the state legislature in 2000 to serve as a repository for voluntary GHG emissions reporting and to develop protocols for inventorying carbon stocks and emissions from primary industrial sources. The CCAR has since initiated the development of protocols for the inventory of carbon from forestry projects (afforestation) and from the forest products industry. These protocols are the framework through which forest owners may obtain and sell offset credits.

Forests in California Energy Policy

In 2002, California adopted the Renewable Portfolio Standard (RPS) which requires utilities to generate or purchase 20% of their electricity from renewable sources by 2010. In addition, Executive Order S-06-06 (Schwarzenegger 2006) established a goal of the use of biomass to produce 20% of the renewable electricity component of the RPS. California has had a strong focus on biomass energy beginning in the early 1980s and growing to a net output of 800MW at its peak in 1994 (approximately 2 percent of California electricity consumption). Currently, as a result of the deregulation of the California energy markets that lowered the electricity price, only approximately half of those plants operating in 1994 are in operation. The California Energy Commission estimates the technology potential of biomass energy may reach 4.7–10.7 GWe, of which 3.6 GWe may come from forestry biomass (ref).

The passage of AB32 and subsequent Executive Order S-01-07 established a statutory framework for the implementation of a Low-Carbon fuel standard (LCFS) in California. The LCFS measures all transportation fuels by their lifecycle carbon intensity based on their global warming potential measured in grams of CO_2 equivalent per mega joule of energy produced (gCO_2e/MJ) (CARB, 2009). Carbon intensity (CI) is measured using a well-to-wheels life cycle analysis, capturing emission from production, harvest, transport, conversion, distribution and ultimately combustion. The effect of the LCFS will be that the regulated parties in California (gasoline and diesel fuel providers) will need to ensure that the average fuel carbon intensity (AFCI), which is the weighted CI average of all fuels sold by a regulated party, will be 10% below the baseline gasoline and diesel CIs by 2020. CARB has identified at least nineteen low-carbon fuels pathways that can contribute to the low carbon transportation fuel mix in California. These pathways include cellulosic ethanol from forest waste through fermentation and gasification. Blending low-GHG biofuels in the gasoline mix has been identified as an important compliance strategy for meeting the LCFS goals (CARB 2009a).

CURRENT GHG ACCOUNTING AND LIFE CYCLE ANALYSIS OF FOREST-BASED BIOFUEL AND BIOENERGY

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In California, forests store over 2 billion tons of carbon and accumulate approximately 1.5 million tons annually (Christensen, Campbell, and Fried 2008). Average annual GHG emissions from wildfires in California during the 1990's were estimated at 1.55 million metric tons (MMT) CO_2e/yr and annual GHG flux from forestlands in California for the same period was + 7.35 MMTCO2e/yr (Brown et al. 2004). Westerling *et al* (2006) find that the incidence of large (>400ha) fires in the western US has increased significantly since 1987. Though forests in California and the Western US serve as net carbon sinks, there is reason to be concerned that forest carbon pools are increasingly at risk of catastrophic phase change from wildfire and other disturbances (Covington and Moore 1994; David D. Breshears 2002). It has not been demonstrated conclusively that increasing wildfire frequency and intensity is causally linked to climate change (Westerling et al. 2006). However, national (Westerling and Bryant 2008) and regional (Northern California) (Fried, Torn, and Mills 2004) modeling studies as well as anecdotal evidence suggest that wildfire frequency and intensity will increase as a result of predicted climate change. If prescribed carefully, silvicultural treatments can increase the rate of sequestration, and reduce the risk of stand replacing wildfire (Hurteau and North 2008; North, Hurteau, and Innes 2009; Schmidt, Taylor, and Skinner 2008; Schoennagel, Veblen, and Romme 2004). Treatments also effect the balances and the dynamics of four carbon pools (trees, debris, soil, and products) with each other and with the atmosphere (Dore, Kolb, and Montes-Helu 2008; Ritchie, Skinner, and Hamilton 2007; Safford et al. 2008; Schmidt, Taylor, and Skinner 2008).

Current LCA accounting for biofuels and bioenergy

A typical forest biomass to biofuel LCA accounting framework is illustrated in **Error! Reference source not found.**. CARB used a modified version of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and followed the linear approach illustrated in **Error! Reference source not found.** estimating a lifecycle emission of 21.4gCO_2e/MJ for ethanol produced via gasification of forest residues harvested in the US Midwest for use in California (CARB 2009c). For comparison, the lifecycle emissions from the production of gasoline for sale in California is 96gCO_2e/MJ (CARB 2009b) and the production of biofuel from this particular forest residue pathway resulted in 78% GHG emissions savings compared with gasoline. The methodology applies a linear view of the benefits of using forest biomass for biofuel: treating the residue as a waste product that does not interact with the rest of the forest system (Figure 1). The limited scope of the linear LCA approach is due to a lack of understanding of the complex dynamics within the forest systems.

Alternatively, more comprehensive LCA taking into account the impacts of biomass extraction on forestry resource cycle (Cowie 2004) and on fire behavior (Nechodom et al. 2008) have been proposed,

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but so far the applications have been limited to conceptual models or case studies. None has applied the system approach to a landscape level.

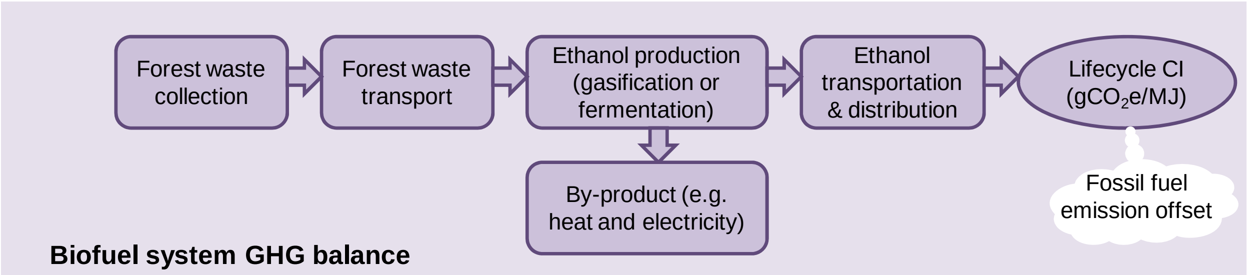

Figure 1. Flows and system boundary of a linear view of biofuel LCA accounting.

PROPOSED MODELING FRAMEWORK

The examination of GHG impacts of utilizing forest biomass resources cannot be separated from the important role forests play in sequestering carbon and maintaining important biological function. A comprehensive framework for modeling the lifecycle emissions from managed forests is needed (Birdsey, Pregitzer, and Lucier 2006). This model framework must account for stand level dynamics (growth, decay, harvest, and disturbance) as well as emissions and displacement from the range of industrial processes for converting forest biomass into the range of products for which it may be used, including energy and biofuels. The objective in the development of this framework is to more clearly understand the tradeoffs inherent in management decisions with regard to GHGs, and assist policy makers in establishing more rigorous performance criteria for electricity, heat, and transportation fuel produced from forest biomass. It will also help to establish consistent goals between GHG programs with different objectives: programs aiming to reduce total GHG emissions and conserve overall GHG stocks, versus programs aiming to maximize GHG savings from displacing fossil fuels. Examples include the AB32 program vs. the LCFS in California; and the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD Programme) vs. the European Union’s Renewable Energy Directive (RED) in promoting biofuels offsetting GHG emissions from fossil fuels.

Figure 2 shows a conceptual biofuel LCA model that includes forest carbon balances. Unlike the linear model in Figure 1, the utilization of forest waste for biofuel production interact with the highly integrated forest system, and affect the overall GHG fluxes and stocks balances.

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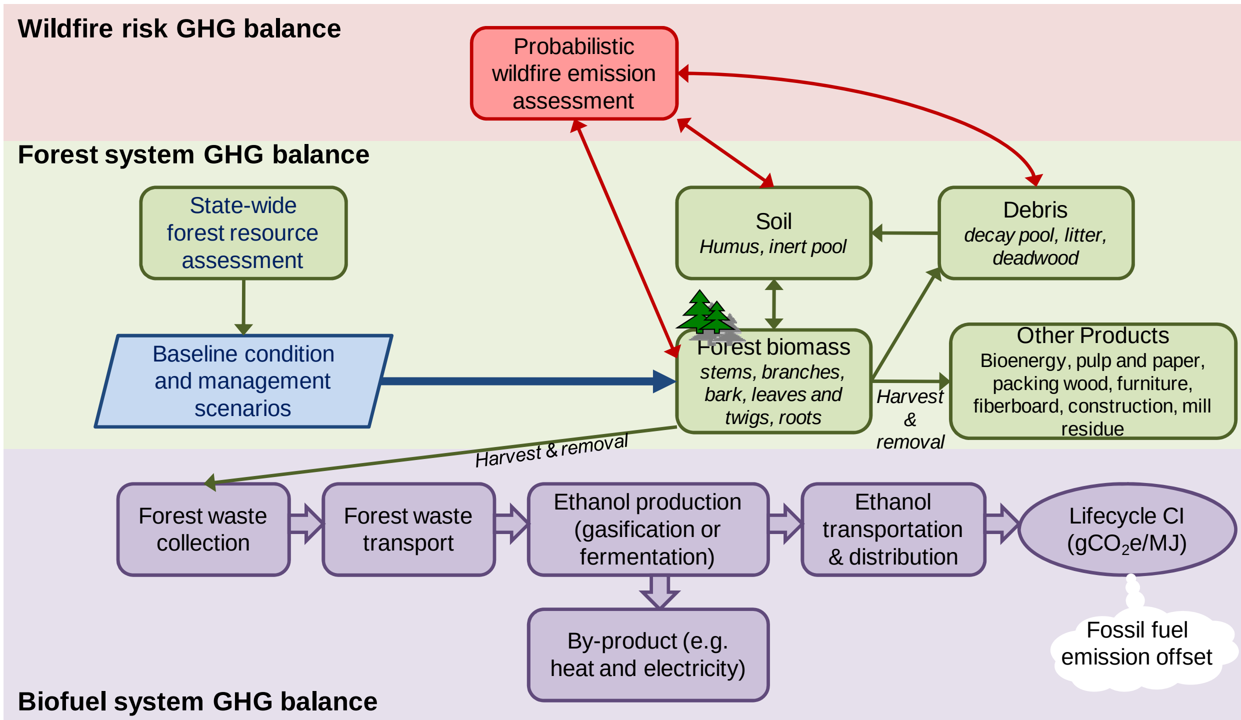

Figure 2. Proposed modeling framework for the dynamic resource-based biofuel LCA GHG accounting.

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Forest stand GHG balance

The geographic variability in growing conditions, forest types, climate, and use pattern, as well as a range of other variables, greatly affect the rate of sequestration, stability of the carbon pool, and management strategies. A system-wide LCA accounting begins with a spatially explicit inventory of biomass in managed forest landscapes. The stand – an area defined by similar fire, use, and biomass volume characteristics – may serve as the primary analysis unit. The resource assessment data can then be used to simulate growth under a range of management scenarios over an analysis period. Using spatially explicit resource data as a foundation for modeling enables predictive modeling for a unique set of conditions in an individual stand or for a region comprised of many stands.

Disturbance can have a profound effect upon GHG balance. Disturbances that fundamentally alter the forest structure and succession characteristics such as crown fire result in a one-time release of GHG from oxidization of biomass. Stand-replacing wildfires can fundamentally alter GHG dynamics in the area affected over time, replacing forest cover with grasslands or scrublands. Management activities directly impact the risk and effects of disturbance in forests. For example, selective harvesting of dominant canopy trees reduces the crown bulk density and therefore the likelihood of crown fire (Agee and Skinner 2005). Activity fuels produced from the same harvest and left on the surface, however, can result in surface fires of increased intensity (Stephens and Moghaddas 2005) and adverse GHG impacts.

Integrating risk assessment (RA) with spatially explicit LCA provides an opportunity to analyze management scenarios and establish best practices based upon site specific conditions and to address temporal impacts of management activities. Systems which pose risks of extremely adverse and often acute impacts (nuclear power, petroleum refining, chemical production) are generally evaluated using a RA framework. In contrast, LCA has been more widely used to assess the incremental and cumulative impacts of a production system (Cowell, Fairman, and Lofstedt 2002). Forests should be viewed both as potentially catastrophic sources of atmospheric GHG as well as systems capable of incrementally sequestering and emitting GHG's as a part of an industrial production system. Wildfire risk in a forest stand is an uncertain variable. This uncertainty can be classified into two general categories: *incidence* and *impact*. The likelihood of each, though uncertain, can be estimated using data describing causative factors. Incidence is correlated with use patterns, lightening frequency, etc., while intensity is affected by dominant climate patterns and fuel characteristics among other factors. An example analysis of wildfire RA challenges is presented by Finney (2005). A system-level LCA can be evaluated by including the effect of stand-level management activities on the risk of wildfire incidence and the likelihood of severe wildfire impact. Integrating probabilistic risk assessment into lifecycle GHG analysis for wood based bioenergy can significantly improve the full carbon accounting of forest management and utilization.

There has been some work being done to assess the impact of management strategies on carbon dynamics within the forest (Hurteau and North 2008; Hurteau, North, and Innes in press). Hurteau and North (2009) compares the effects of different fuel treatments on *tree-based* C storage and release and forest stand structure over a century, with and without a wildfire in midcentury. Historical fire return intervals varied by forest type, but for the largest forest community, mixed conifer, averaged 10-17 years before European settlement (McKelevey et al. 1996). The study concludes that, with wildfire, the control (no treatment) had the largest wildfire C emission and the largest reduction in live-tree-based C stocks. In wildfire-prone forests such as California, tree-based C stocks would be best protected by fuel treatments that produced a low-density stand structure dominated by large, fire resistant pines.

Forest product system GHG balance

The treatment of stands for wildfire risk reduction is becoming more common. The federal government tripled the funding for hazardous fuel reduction to $546 million between 2000 and 2003 (Winter, Vogt, and McCaffrey 2004). The material produced from these activities is rarely utilized due to treatment regimes which restrict cutting trees of merchantable (i.e millable) size and the prohibitive cost of processing and transport of small diameter slash shrubs and thinnings. The cost of these types of treatments are often justified by projected reduction in future fire suppression costs and property damage

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(Kline 2004; Mason et al. 2006; Snider, Daugherty, and Wood 2006) so that the treated biomass is considered to be a waste product with little or no value.

The residues produced from harvesting, such as limbs, tops, and smaller trees from thinning operations, are often piled and burned at log landings or left in the stand. These residues are currently vastly under-utilized due to the cost of processing and transport. They represent a significant (Perlack et al. 2005) and generally short-lived biomass (Barber and Van Lear 1984; Palviainen et al. 2004; Wagener and Offord 1972; Wihersaari 2005) pool and may in some cases increase the risk of GHG loss from catastrophic wildfire when left in the stand. Biomass from forests used in the production of fiber, building materials, energy, and fuel displaces competing products derived from fossil energy sources. The fate of biomass produced from forestry activities can play an important role in determining the lifecycle impacts of forest management decisions. For example, in 2002 the wood products industry produced 55% of its energy demand from residues and the paper industry produced 48% of its demand. Total net energy usage in these sectors combined was 2.9 quads (EIA 2002).

Much work is needed to assess the impact of management strategies on carbon dynamics within the forest. Biomass from fire risk reduction activities, if utilized to displace fossil based energy and products, has the potential to reduce the lifecycle GHG emissions from those industries, and lower the cost of hazardous fuel reduction treatments. Some studies suggest that the use of forest biomass residue for energy and liquid fuel has potential to increase the stability of carbon in forests and to offset the use of fossil energy sources (Cowie 2004; Nechodom et al. 2008). A recent study disagrees and suggests that utilizing carbon harvested in fuel reduction treatments as biofuels cannot offset the reductions in total ecosystem C storage resulting from fuel reduction (Mitchell, Harmon, and O'Connell 2009). The relevant issue here, however, is not whether forest thinning *and* biofuel utilization will improve the total carbon stock. Rather, it is whether biomass from fire risk reduction activities, if utilized to displace fossil-based energy and products, has the potential to reduce the lifecycle GHG emissions from those industries, provided that the utilization of these waste streams will not undermine the ecological and environmental values of these irreplaceable forest resources.

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An example of expanded LCA

We re-examined the Hurteau and North study (2009) by expanding the boundary of the carbon accounting and systematically comparing the total net carbon balances in different treatment scenarios examined in the original paper (Table 1). We include the carbon savings from utilizing biomass for biofuel/energy production and the resulting net carbon emissions and credits. This initial analysis is consistent with, albeit much simpler, than what we reference in Figure 2. Our emission accounting

captures the carbon sources and sinks and compares the net carbon balance by the end of the 100-yr modeling period. Emissions associated with utilizing forest biomass for ethanol production are based on the lifecycle GHG emission calculated from the CA-GREET model (CARB 2009c). Table 1 describes the range of forest management scenarios examined here.

Table 1. Forest treatment scenarios examined in the Hurteau and North study (2009).

To track the fate of carbon in logs and slash removed during thinning operations we partitioned the material based on its likely fate. In the thinning scenarios, we assumed that 20% of the standing volume to be treated would not be recovered and would remain as scattered slash in the stand. Of the material recovered during treatment operations we estimated the volume of material available for energy or fuels production to be 48% of the total harvested material (Fight and Hartsough 2005). In the analysis, milling waste and recovered slash is used to produce biofuel and offset credits for gasoline consumption. Based on a tree carbon content of 51.7% and ethanol yields for woody biomass of 90 gal/dry ton (CA-GREET default), we estimate 60.3 dry tons/ha and 44.4 dry tons/ha of forest biomass will available to produce 5,430 gallons/ha and 3,990 gallons/ha of ethanol in the understory and restoration thinning scenarios, respectively. Our analysis shows that if all carbon sinks and sources are taken into account, 1865 restoration, burn, and 1865 restoration and burn have the highest cumulative carbon balances at the end of 2100 (Figure 3). Understory thin and burn have the least carbon balance in 2100.

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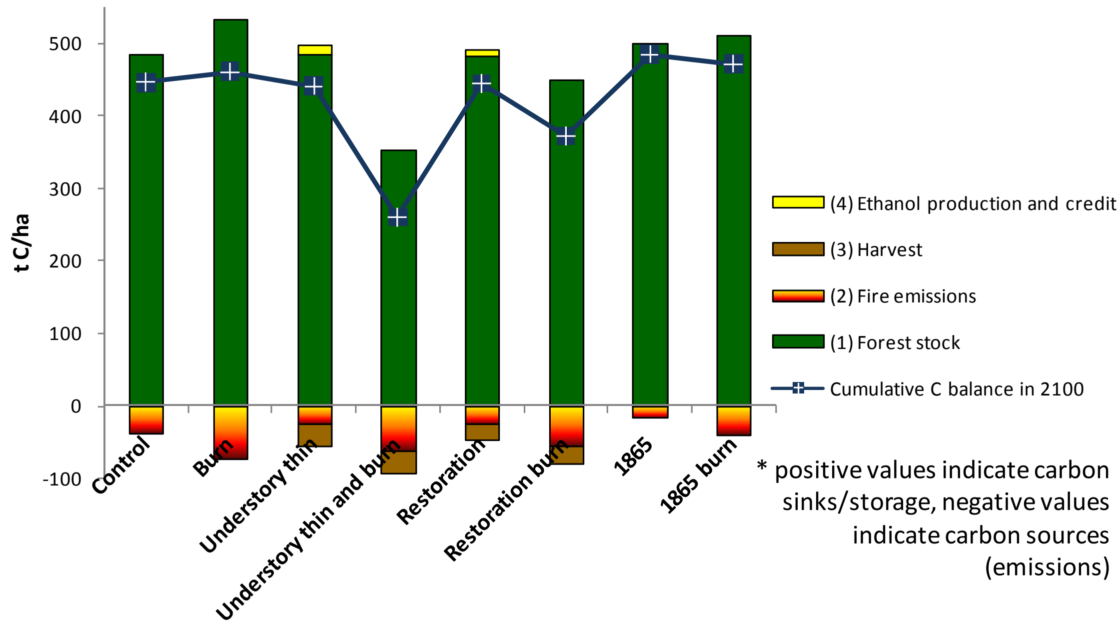

Figure 3. Cumulative carbon balances in 2100 by sources and sinks in eight forest management scenarios. "Ethanol production and credits" includes GHG emissions from transport and collection, production, and fossil fuel offset credits.

Since the initial carbon stocks vary among the scenarios, we show in Figure 4 the beginning carbon stock (in live and dead trees, soil and roots), cumulative carbon balance in 2100, and the net changes in carbon balance between 2000 and 2100. The net carbon balance between 2000 and 2100 in the control case is relatively unchanged (Figure 4, line). The highest increase in net carbon balance between 2000-2100 is understory thin (77 t C/ha), followed by restoration, burn, 1865 burn and 1865. Significant net carbon losses are observed for understory thin and burn (-64 t C/ha). The results suggest that compared with control, understory thin and restoration treatments with no burns can significantly increase the overall net carbon balance (increase storage) over the long term, both with and without biofuel credits.

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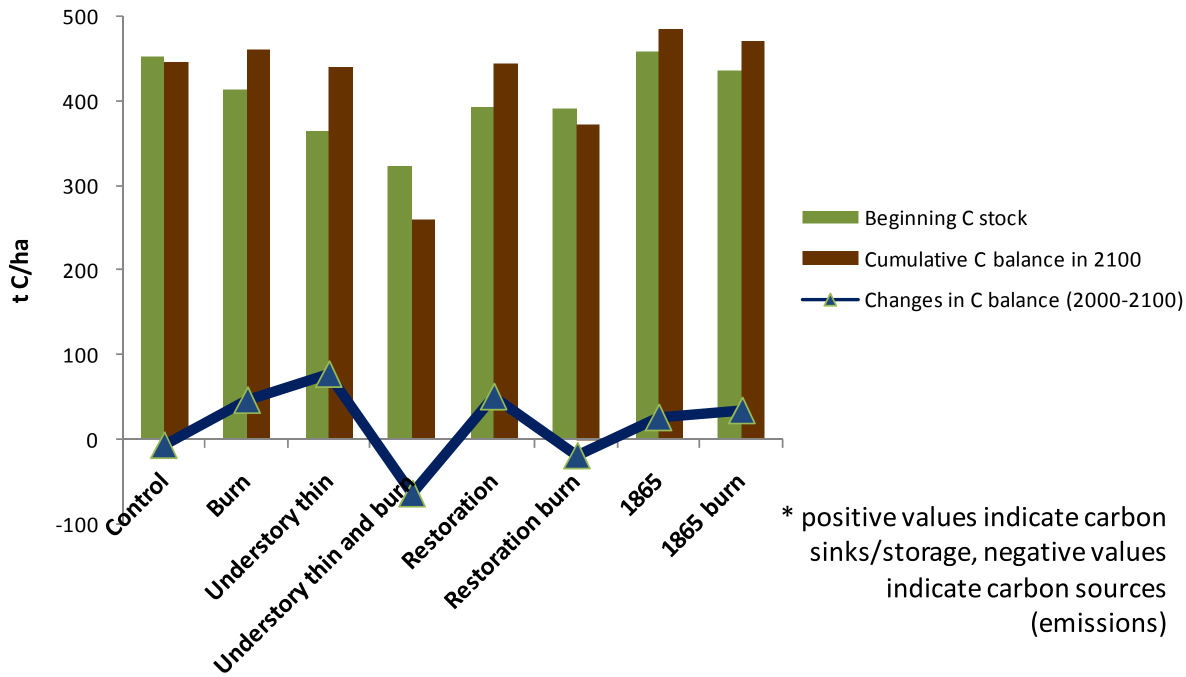

Figure 4. Beginning carbon stock, cumulative carbon balance in 2100 and the net changes in carbon balances over a century (2000-2100).

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This initial analysis points to the need for more comprehensive state-wide and regional modeling of risk-based forest management in order to maximize the long-term net lifecycle carbon balance inclusive of all biomass fates. Even though soil carbon fluxes are not included in this analysis, soil carbon fluxes are a function of live trees. Thus, the inclusion of soil carbon fluxes is likely to favor most of the treatment scenarios. The Hurteau and North (2009) study only includes immediate direct carbon emission from a wildfire. Studies show that high-intensity burns generate substantially higher sustained post-wildfire carbon emissions than from unburned sites for decades after the high-intensity fire events (Dore et al. 2008). Other research has shown that the combination of wildfire and climate change effects may result in shifting large portions of US forests into other, less carbon rich plant communities with potentially more frequent and complete carbon cycling (Dale et al. 2001; Flannigan, Stocks, and Wotton 2000; McKenzie et al. 2004).

DISCUSSION

This article outlines a modeling framework to help understand the implications of a range of forest management scenarios driven by climate and energy policy on GHG production from forests and forest products. To address this we propose a life-cycle analysis incorporating spatial variation in forest types, the dynamics of the effects of forest management on net GHG exchange from forests systems, wildfire risk assessment, and GHG savings from displacing fossil fuels with forest residues. We consider

emissions from wildfire, decomposition, forest products, bioenergy production, and biofuels production and consumption and how these factors are dynamically modified by forest management practices.

Performance basis

The use of GHG flux for environmental performance in forestry establishes a quantifiable metric against which performance of a particular practice can be measured. A performance standard differs in important ways from many regulations familiar to forest managers. It differs from technology standards in that it penalizes undesirable outcomes and rewards practices that achieve better results without requiring or restricting any specific technology or activity. In this way the means of compliance are left to the manager and compliance is enforced through a system of financial or legal penalties and incentives for performance relative to a standard. Many forestry BMPs refer to specific technological or operational requirements for forest activities such as the construction of water bars on forest roads, stream buffers, or operational windows for harvesting designed to avoid soil compaction. These types of guidelines are designed to address an environmental performance need through the application of specific technologies. Generally, performance based policies imply the identification of a quantifiable damage such as pollution level (e.g. water quality, sulfur dioxide emissions, and greenhouse gas emissions) as a means of monitoring performance, and an enforcement framework that ensures compliance.

There are two primary challenges in applying a GHG performance basis to forests. First, GHG performance can be in direct conflict with other forest values (aesthetic, social, ecological). Second, models providing quantitative and robust stand-to-fate life-cycle emission factors for forest-origin biomass that deal directly with wildfire risk as well as the range of products, co-products, and market-mediated displacement of alternative products have not been fully developed.

Defining performance

Environmental regulation of forestry activities in North America has evolved to recognize a broad range of values. Water quality, habitat, soil as well as broader social values such as ecosystem function, recreation, rural economic development and wilderness have been codified in statute or thorough management guidelines. Using GHG as a performance measure under the new climate and energy policies may create synergies or conflicts with the existing forest practices, BMPs, and regulations. As our paper describes a framework for modeling the GHG implications of various forest management strategies, we have not discussed other impacts that we mentioned above. There may be instances where other issues, such as biodiversity and water quality, are given greater social value than GHG policies. These values may not always align well. Many governments have created sustainability standards/guidelines to guide their biofuel GHG policies. For example, in the US's federal Renewable

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Fuel Standards, the definition of "renewable biomass" excludes forest biomass from federal lands (US EPA 2009) for fear that allowing biomass from slash and pre-commercial thinning operations on federal lands for biofuel and bioenergy production may create economic incentives for "residues" and induce irreversible environmental and ecological damages on sensitive areas. To address the complex issues across forest fire management, resource use, carbon management, and sustainability concerns, an Interagency Forest Work Group (IFWG) composed of the CARB, the California Natural Resources Agency, the California Energy Commission, the California Department of Forestry and Fire Protection, the United States Forest Service, the US EPA, environmental advocates, regulated parties, and other stakeholders will "consider the specific effects of incentivizing the use of forest biomass from public and private lands; the greenhouse gas emissions from different fuel pathways on public and private lands; and the additional protections, if any, necessary to ensure the sustainable and environmentally beneficial use of such forest biomass, with the goal of certifying pathways for the use of forest biomass" (CARB 2009b).

The concept of sustainability has become a significant driver for forest policy. Jack Ward Thomas and James Burchfield (Thomas and Burchfield 2008) claim that sustainability has always been an important concept in the development of forest policy. Sustainability has certainly been a prominent concept in the science of forestry from as early as the 16th century (Glacken 1976). It has been, perhaps, more narrowly interpreted to mean something akin to the concept of sustained yield (Wiersum 1995). It is possible to look at past policies and see them in a broad context of sustainability. It is, however, only recently that GHG sustainability as an explicit goal has made its way into the policy discourse (Brundtland and World Commission on Environment and Development 1987). In practice sustainability can mean a wide range of often conflicting things (Dixon and Fallon 1989). The challenge in the implementation of sustainable resource use is in the definition and prioritization of resource values. Do we focus on the effect of a policy on a particular species? If so which species? An ecosystem? A regional economy? A global climate system? The definition of forest resource values as well as the temporal and geographic scale of sustainability is an ongoing and important discourse. Performance-based GHG policies based on the LCA approach are challenging due to rapidly increasing scientific capacity to obtain, understand and model data complex global systems as well as a perceived need to develop policies which leverage the strengths of markets to meet environmental goals. Our capacity to understand the sustainability implications of policies on forests is, however, still limited. Thus we are challenged with the need to define sustainability in terms that we can measure, monitor, evaluate, and agree upon; and at the same time acknowledge the limitations of existing knowledge and provide for flexibility as our capacity to rigorously define the concept of sustainability evolves.

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