Journal of Forest Economics, 2019, 34: 1–5

State of the Art Methods to Project Forest Carbon Stocks

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Forests play a considerable role in the global carbon cycle, containing around 860 Pg C (Pan *et al.*, 2011), but over the last century this carbon stock has seen considerable variation. Deforestation, one of the primary drivers of global climate change, has emitted up to 130 Pg C (Ciais *et al.*, 2014; Houghton *et al.*, 2000; Houghton, 2003; Baccini *et al.*, 2012), contributing around 10% of total emissions. Despite this deforestation, Ciais *et al.* (2014) estimate that over 150 Pg C of additional carbon was stored in forests, making them a net carbon sink during the last century. Multiple processes influence these trends, including climate change, carbon fertilization, and aging forests, but the role that forest managers play in managing the stock of carbon in forests is undoubtedly important, especially since forest management has been increasing globally in recent decades (UN FAO, 2015).

While understanding the past is important, it is equally critical to look to the future. This point came to the forefront as countries around the world started to develop their strategies for managing carbon emissions as part of the Paris Climate Accord. Of more than 175 countries that submitted an (Intended) National Determined Contribution, 100 explicitly identified mitigation strategies involving land use (Grassi *et al.*, 2017), and mitigation within the land use sector is expected to account for 20%–25% of the total emission reductions across all sectors (Forsell *et al.*, 2016). Prior studies suggested that the role of forests could be even as high as 30% of the global effort in carbon abatement at costs comparable to the energy sector (Sohngen and Mendelsohn, 2003), and recent studies have confirmed these earlier findings (Griscom *et al.*, 2017). Although most countries have opportunities to manage forests as carbon sinks, they do not always have the tools available to conduct analysis that will help them evaluate their options. This special issue illustrates several analytical approaches that could be used by individual countries to help fill this need.

The task of projecting carbon stocks in forests is, of course, complicated by several factors. First, there is a question of data. Projections of future forest carbon stocks, and hence the annual change in carbon stocks, depends in large

ISSN 1104-6899; DOI 10.1561/112.00000440

measure on having estimates of current carbon stocks. Not only do policy analysts need a starting point, but they also need observations to validate important elements of projections, such as forest growth and yield functions for different systems, and monitor efficacy of current mitigation programs.

Second, there is a question of methods: How should forest carbon stocks be projected into the future? Forests are biological stocks that are changing each year, and this rate of change shifts over the growing cycle with younger stands actively increasing net biomass annually, and older stands holding potentially large stocks of carbon that are susceptible to disturbance and dieback. While it is tempting to assume that the primary drivers of forest stocks will be natural drivers, including aging, climate change, carbon fertilization, natural disturbance, etc., the human dimensions cannot be discounted. If policy makers hope to use forests to improve upon national level greenhouse gas emissions levels, human management components could play a critical role in reducing emissions and enhancing the forest carbon sink. Thus, developing methods that appropriately account for human management, including the responsiveness of management to policy or market stimuli, will be critical for carbon flux management.

Third, the issue of uncertainty looms large over the role of forests in climate mitigation, ranging from the concerns about measurement of forest carbon stocks, to economic parameters related to the supply or forest land or the demand for products, to the handling of future risk and uncertainty in projections. Uncertainty is recognized as important, and included in many estimates of carbon pools, and it has been incorporated in economic analysis in various ways, ranging from simulation approaches to stochastic dynamic programming. Despite these advances, uncertainty remains a critical issue for developing projections of future carbon.

Fourth, the bottom-up approach of the Paris Climate Accord places significant emphasis on individual countries to make their own analyses of what levels of C storage are possible from their forest land base. Such an approach requires a robust assessment of current carbon stocks and projections of baseline forest carbon fluxes in the absence of any policy or program designed to increase carbon storage. Some countries are well-equipped to develop scientifically rigorous baseline projections, but a vast majority of countries around the world have not developed models to make projections of carbon stocks. This special issue fills a critical research gap by offering a toolbox of economic approaches that those countries could consider using for baseline projections and subsequent analysis of climate mitigation and resilience pathways.

This special issue provides a broad range of potential methodologies, based in economics, for projecting forest carbon stocks. Papers included highlight new analyses from various economists that have projected carbon fluxes nationally and globally. Through carefully designed research, these authors have provided deep insights into methods that can be applied broadly.

The article by Daigneault *et al.* addresses the critical issue of developing a common set of input assumptions for forestry modeling. Substantial work has gone into developing common input assumptions for other sectors like energy and agriculture, but little effort has been expended to develop common assumptions in the forestry sector. This paper provides analysis and insights that will help forestry modelers link their models directly to the underlying drivers in the Shared Socio-economic Pathways (SSPs) presented by the Intergovernmental Panel on Climate Change (IPCC).

Johnston *et al.* explore the use of spatial equilibrium and trade modeling to project future carbon fluxes in forests for 180 individual countries. Their analysis has adapted carbon modeling into the well-established Global Forest Products Model (GFPM; Buongiorno *et al.*, 2003) in order to track fluctuations in carbon stocks in response to market perturbations. Their approach relies on data from the UN Food and Agricultural Organization (e.g., FAOSTAT, 2019) to develop econometric estimates of demand and supply functions, which can be used to project future equilibrium outcomes. They have supplemented their projections with a unique assessment of historical trends in carbon fluxes from 1960 to the present.

Wear and Coulston similarly have a data-intensive approach for modeling carbon, but they focus on the supply-side, developing methods to model and project forest structure based on detailed US Forest Inventory and Analysis data. They incorporate several innovations to handle forest growth and disturbance and make projections in forest stocks. Because their data is tied explicitly to forest inventory data that can be generalized across a region, they are able to project forest stocks across large geographical spaces.

The next several articles in this special issue focus on the role of uncertainty. The paper by Yousepour and Augustynczik contributes to this important discussion about how uncertainty affects carbon projections. They explicitly point out that there are important uncertainties associated with projecting forest growth that will affect forest management decisions. Their study is conducted with a single site Faustmann model, which is carefully linked to an ecological model that projects forest growth, and they make a compelling case that it is critical to account for the role uncertainty plays in forest growth when projecting carbon because it affects future carbon both directly (through growth) and indirectly (through management).

Sohngen *et al.* use the Global Timber Model (GTM; e.g., Kim *et al.*, 2018) to assess the role of parametric uncertainty in dynamic forestry models. They consider uncertainty in forest growth and land rental function elasticity parameters, and use Monte Carlo techniques to assess how uncertainty in these parameters influences projected carbon fluxes in the 16 regions in their model. The results suggest that uncertainty in forest growth has large effects on future carbon flux, while uncertainty in the land rental functions that account for shifts between forestry and agriculture has a smaller impact. This result, conducted across hundreds of forest types globally, and with a price endogenous model, is consistent with the assessment in Yousepour and Augustynczik that uncertainty in forest growth is critical for assessing carbon.

Van Kooten *et al.* directly tackle the issue of uncertainty by developing stochastic methods to model management of forest stocks and carbon in the interior region of the British Columbia, Canada. Rather than focusing on parametric uncertainty, as in Sohngen *et al.*, or changes in net growth as in Yousefpour and Augustynczik, they consider how management adapts to shifts in disturbance regimes and carbon prices. They find that increasing disturbance, which could occur with climate change, would lead to less carbon, but that proactive management through planting could limit some of the losses.

The papers in this first volume of our special issue provide a range of tools that can be used to model forest carbon. These approaches focus on demand and supply side elements that are important for forest projections, but also on developing a better understanding of uncertainty. The papers in the next volume focus more explicitly on tools and the application of those tools.

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