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Effects of parameter and data uncertainty on long-term projections in a model of the global forest sector

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ABSTRACT

This study explored the consequences for long-term projections and impact analysis of the uncertainty in model parameters and initial conditions. Using the Global Forest Products Model, multiple replications of projections were carried out with parameters or initial condition data sampled randomly from their assumed distribution. The results showed that parameter uncertainty led to uncertainty of the projections increasing steadily with the time horizon, and more rapidly than the uncertainty stemming from initial conditions. Among the parameter uncertainties, those in the supply and demand elasticities tended to dominate the uncertainty in the other parameters describing forest growth, manufacturing activities, and trade inertia. In an application to impact analysis it was found that, due only to the uncertainty of the model parameters, and conditional on other assumptions, an assumed rise in global temperature of 2.8 °C over a century caused the forest stock in 2065 to be 2.4% to 4.0% higher in developed countries, and 2.5% to 3.9% lower in developing countries, with 68% probability, a conservative estimate of the true uncertainty given all the other factors involved in such a prediction.

1. Introduction

"How sensitive are your results to the assumptions regarding the values of the parameters?" This question, frequently and legitimately asked by reviewers of forecasting and policy papers based on forest sector models, is rarely answered in full. At best, one or two parameters subjectively deemed important for the analysis may be changed to trace their effects on the results. More extensive sensitivity analyses are rare (see Chudy et al., 2016 for a review). One notable exception for forest sector models is in Kallio (2010) who applies Monte Carlo simulation to a model for Finland to determine how the uncertainties of the parameters and world forest product prices affect projections. She finds that while the uncertainty in the parameters has a moderate impact, the unpredictability of world product prices (that are also affected by exchange rates) leads to much variation in projections. Skog (2008) also used Monte Carlo simulation to assess the uncertainty of estimates of carbon stored in harvested wood products in the United States in 2005, concluding that the uncertainty is between −23% and +19%. Heath and Smith (2000) find that uncertainty in carbon inventory in the private forests in the United States is approximately ± 9% in the year 2000, rising to 11% in projection year 2040.

A large degree of the uncertainty lies in the underlying economic data from which forest sector models are built. While it is well known that global databases like those provided by the International Monetary Fund (IMF), the Organization for Economic Cooperation and Development (OECD), the World Bank, and the Food and Agriculture Organization (FAO) of the United Nations have serious measurement errors (Van Bergeijk, 1995; Jerven, 2014), forest sector models must still rely on them for development indicators such as gross domestic product (GDP) and population, as well as for data on forest resources. Yet, any error in historical data will be retained in parameter estimates and in the initial conditions of the model, and carried forward in projections and scenario analysis.

Beyond uncertainty in the initial conditions of the forest sector and its context, there is uncertainty due to the way in which the model parameters are estimated. Quantitative models rely on parameters obtained econometrically or by other methods, such as price and income elasticities of demand, and parameters in equations of forest area change and supply shifts. Inevitably, errors in the historic data and in theoretical formulations will lead to faulty interpretations of the past (Morgenstern, 1963; Boumans, 2012), and one is left to construct proxies for the unknown relationships governing the phenomena under study (Griliches, 1986). Consequently, these uncertainties can lead to considerable variation in model projections and policy analysis (Kann and Weyant, 2000; Orrell et al., 2001). Recognizing that measurement errors are an unavoidable characteristic of historical data and that

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inaccuracy is inherent in all model parameters has led researchers to build this uncertainty explicitly into the model structure with Monte-Carlo simulation methods by sampling randomly from the distributions of the data or parameters (O'Neill et al., 1980; Abler et al., 1999).

The present study followed Kallio's (2010) suggestion to investigate the effect of parameter and data uncertainty in the case of widely applied global forest sector models. Using as a case study the Global Forest Products Model (GFPM, Buongiorno and Zhu, 2017) this paper concentrated on the issues of uncertainty in parameter values and initial conditions and their consequences for projections and impact analysis. With the goal of guiding future research, the work gave special attention to the uncertainty in different parameter types: demand and supply elasticities, forest growth parameters, manufacturing costs and input-output coefficients, and trade inertia parameters. The method consisted in making multiple replications of projections to 2065 with all parameters, or only parameters of a specific type sampled randomly from their assumed distributions.

In the GFPM the calculation of the equilibrium in each projected period is a constrained quadratic optimization, and non-linear recursive equations link one period solution to the next. The projections obtained with such a highly nonlinear system may be sensitive to the initial conditions, so that a small change in the initial state (the base year data of the GFPM) could lead to large variations in the predictions. This sensitivity of the GFPM to initial conditions was tested with replications of projections to 2065 with initial conditions randomly selected from their assumed distribution.

The last part of the paper reports on the consequences of model parameter uncertainty for impact and policy analysis. Here, impact analysis referred to the effect of an environmental or policy change on a projection, other things equal. As an example we used the potential effect of a rise in global temperature on the forest sector. In this context the main concern was not the future level of a particular variable such as the forest stock of a country, but the difference in future forest stock with or without the temperature increase. How this difference varied due to uncertain model parameters was the object of study.

2. Methods and data

The GFPM calculates every year a global market equilibrium across countries and products, linked to past equilibria. The current model deals with 180 countries, forest area and stock, and 14 wood product groups ranging from fuelwood to paper and paperboard. More details concerning the formulation and the computer implementation are available in Buongiorno and Zhu (2017).[1]

The spatial global economic equilibrium of the forest sector in a given year is obtained by quadratic programming. The objective function is the social surplus in the sector, which is maximized by competitive markets (Samuelson, 1952; Takayama and Judge, 1971). This surplus is equal to the value of the products to consumers (area under all the inverse demand curves), minus the cost of supplying the raw materials (area under their inverse supply curves), minus the transformation cost at each stage of manufacturing, and minus the transport cost between countries. The constraints express the equilibrium conditions: for each country and product, the quantity imported plus the domestic supply and the manufactured quantity must equal the domestic demand plus the quantity used in manufacturing other products, plus exports.

In view of the objective of this study, concerning the impact of parameter and data uncertainty on projections, twenty replicated runs of the current GFPM (Buongiorno and Zhu, 2017) were carried out from the base year 2014 up to 2065. In each run, all or specific parameters were drawn randomly from their assumed distribution. The coefficients of variation of the 2065 projections were used to assess the variability of the projections and to compare them with the projection obtained with the model with average parameters.

Specifically, twenty replications were carried out with random selections of each of the following parameter categories, other parameters being held constant at their average value:

(i) demand elasticities,
(ii) supply elasticities,
(iii) forest parameters,
(iv) manufacturing parameters,
(v) trade inertia parameters.
(vi) all of the above.

In addition, twenty replications were carried out to determine the effect of uncertainty in the initial conditions, i.e. the production, consumption, trade, and price data in the base year, with the model parameters held at their average value. Last, twenty replications were done to assess the consequences of uncertainty in all the GFPM parameters when the model was applied for impact analysis such as the long-term effect of climate change on the forest sector.

2.1. Effect of uncertainty in demand elasticities

In each year and country, the demand of each end product (fuelwood, sawnwood, panels, paper and paperboard) shifts over time according to GDP growth and the attendant GDP elasticity, α_y. The current demand curve is defined by the consumption at last year's price after the demand shift, and by the price elasticity, δ. The values of the demand parameters and their standard errors are in Table 1. To judge the impact of this source of uncertainty on the projections, other things being equal, the GFPM was run twenty times, each time with a different set of randomly drawn elasticities, holding all other parameters at their average value. For example, the price elasticity of demand for a product in a country was obtained from:

$$\delta = F^{-1}(r \mid \bar{\delta}, s_\delta) \tag{1}$$

Where F^{-1} was the inverse of the normal cumulative density function, r was a uniformly distributed random number in the [0,1] interval, $\bar{\delta}$ was the mean elasticity and s_δ was its standard error (Table 1). The GDP elasticities were randomized in similar fashion.

2.2. Effect of uncertainty in supply elasticities

The wood supply (fuelwood and industrial roundwood) in a country and year is defined by the current production at last year's price, and the price elasticity of supply, λ. The supply shifts with changes in forest stock, according to elasticities, β_I. For other fiber and waste paper the supply depends on price and GDP. The supply elasticities and their standard errors are in Table 2.

To assess the partial effect of the uncertain supply elasticities on projections twenty replications were carried out, each with a new set of elasticities obtained with the analog of Eq. (1) and the expected values and standard errors of the elasticities in Table 2.

2.3. Effect of uncertainty in forest parameters

The rate of change of forest area, g_a in a country and year is defined by the following equation, based on the “environmental Kuznets” theory (Buongiorno, 2014):

$$g_a = (\alpha_0 + \alpha_1 y')e^{\alpha_2 y'} \tag{2}$$

Where y' is the income per capita in a country and year. With $\alpha_1 > 0$, and $\alpha_2 < 0$ Eq. (1) yields negative growth rates at low

[1] The software, documentation, and data for the GFPM version 2017 are available free of charge for academic research at: http://labs.russell.wisc.edu/buongiorno/welcome/gfpm/