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Modelling the nutrient cost of biomass harvesting under different silvicultural and climate scenarios in production forests

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ABSTRACT

Intensifying the use of forest biomass to produce fuelwood, through the removal of harvest residues or reductions in rotation length, increases nutrient outputs and can ultimately lead to reduced soil fertility. We developed a modelling approach for the evaluation of different forest management options under future climate scenarios. This approach allows management systems to be evaluated in terms of their nutrient costs by quantifying several variables: nutrient outputs (N, P, K, Ca and Mg) resulting from harvesting, ecosystem N and P balances, and changes in organic C, N and P stocks in the soil. In addition, we calculated a "nutrient cost index" (in kg-harvested-biomass g-exported-nutrients^{-1}). As part of this study, we looked at the effects of harvesting branches, foliage and stumps in addition to tree stems, as well as the effects of changing rotation length in *Pinus pinaster*, *Pseudotsuga menziesii* and *Fagus sylvatica* forest stands, under contrasting Representative Concentration Pathway climate scenarios (RCPs). Comparably to previous studies, our simulations showed that removing harvest residues and, to a lesser extent, reducing rotation length have high nutrient costs. Climate was also found to have an impact, mainly caused by larger amounts of standing tree biomass, and therefore larger biomass harvests and increased nutrient outputs in the scenario which involved elevated atmospheric CO_2. Using contrasting forest management systems and climates, we showed that our modelling approach can be used to guide forest managers in their choice of future silvicultural practices (rotation length, conventional stem-only harvest versus intensive harvest, thinning regime) based on future climate scenarios. Finally, our approach can be used to determine, more accurately than simple allometric relationships, the amounts of nutrients that would need to be applied in order to compensate for losses.

1. Introduction

Silvicultural options are primarily oriented towards driving tree growth and providing quality wood products. An emerging issue in the field of forest management is how to maximize ecosystem services, and in particular the carbon (C) balance of the forest-wood chain in order to mitigate global warming (Fortin et al., 2012). However, while forest soils and biomass may currently act as a C sink (e.g. in Europe; Luyssaert et al., 2010), the short- and long-term effects of management practices have not been clearly established and are conflicting (Lindner and Karjalainen, 2007; Valade et al., 2017). For instance, the benefits of intensifying biomass harvesting to produce fuelwood, and hence reduce the use of fossil fuels, are still up for debate, since removing tree components that were conventionally left in the forest (i.e. the so-called "harvest residues"; Nunez-Regueira et al., 2005; Diaz-Yanez et al., 2013) decreases soil organic carbon (SOC) stocks, partly offsetting the soil C sink (Achat et al., 2015a). In addition, the removal of harvest residues increases the nutrient outputs (or losses; Rodriguez-Soalleiro et al., 2007; Augusto et al., 2015) from managed forest ecosystems, with negative feedbacks on the soil's chemical fertility, nutrient status and tree growth, and therefore the capacity of production forests to accumulate C in forest biomass (see the reviews written by Thiffault et al. (2011); Wall (2012) and Achat et al. (2015b)). Alternative cropping systems, such as short rotation coppices (Aylott et al., 2008), can also be used to provide fuelwood. Reducing rotation length and harvesting younger trees leads, however, to an increase in nutrient outputs, since young trees have higher nutrient concentrations than adult trees (Ranger and Nys, 1986, 1996; Augusto et al., 2000). There is thus an

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increasing amount of evidence to suggest that nutrient outputs have to be considered in addition to the C balance when evaluating silvicultural systems (Achat et al., 2015b).

The effects of management practices (e.g. rotation length, thinning regime, harvest intensity) on C sequestration in the soil and biomass of production forests have previously been studied using simulations and soil or forest growth models (Peng et al., 2002; Bravo et al., 2008; Johnson et al., 2010). However, a more thorough evaluation of management scenarios, aiming at maximizing C balance and sequestration, should also include the lifecycle of wood products, and therefore chains of models representing forest growth, wood production and wood product decay have also been developed (Liski et al., 2001; Perez-Garcia et al., 2005; Fortin et al., 2012). The first link in this kind of chain should be process-based forest growth models, since they allow the effects of temporal changes in climatic variables – such as air temperature and humidity, precipitation, and atmospheric CO_2 – to be taken into account (Kimmins et al., 2008; Augustynczik et al., 2017). Unfortunately, process-based models are generally poorly designed to simulate management practices. At the same time, silvicultural alternatives and innovations need to be evaluated in terms of their benefits under future climate scenarios (Augustynczik et al., 2017). The GO+ forest model has been specifically developed beginning in 2011 to evaluate the response of forest ecosystems to both forest management and climate scenarios (Loustau et al., 2018). It has been coupled with a model simulating wood production and wood product lifecycles (Fortin et al., 2012; Fortin and Ningre, 2012) in order to evaluate C budgets, and used to help forest managers and policy makers in their choice of future management strategies.

The main objective of this study was to develop a modelling approach that would allow for an assessment of management practices in terms of the nutrient cost of harvesting biomass when future climate changes are taken into account. To this end, we developed a “nutrient” package for the process-based GO+ model and evaluated a range of standard, intensive and extensive systems under contrasting climate scenarios. We studied three tree species that are abundant in Europe or highly productive (Thivolle-Cazat & Najar 2001; Thurm and Pretzsch, 2016; Augustynczik et al., 2017): *Pinus pinaster*, *Pseudotsuga menziesi* and *Fagus sylvatica*. Ecosystem productivity and hence harvestable biomass increase with increasing atmospheric CO_2 (e.g. Goll et al. 2012). We thus hypothesised that nutrient outputs (or losses) with biomass harvests are highest under elevated atmospheric CO_2 scenarios.

Since no explicit representation of the biogeochemical cycles of nutrients is currently included in the GO+ model, our second objective was to verify the accuracy of model simulations in terms of the amounts of nutrients required in the predicted biomass and soil organic matter (SOM) (Hungate et al., 2003; Penuelas et al., 2013; Wieder et al., 2015), focusing on the main nutrients that can limit ecosystem productivity, namely nitrogen and phosphorus (N and P; Elser et al., 2007; Augusto et al., 2017). The nutrient package was thus used to calculate changes in organic N and P in the ecosystem (vegetation plus SOM compartments). Changes in organic N and P in the ecosystem were subsequently compared to available data documenting the input-output balances of managed forests.

2. Materials and methods

2.1. Description of the GO+ model

A full description of the GO+ model is provided in Loustau et al. (2018), and it will therefore be presented here only briefly. The GO+ model describes the radiative and energy balances and biogeochemical cycles of C and water. It also describes the development, growth and mortality of the vegetation in two layers: the tree canopy and the ground vegetation. The tree canopy layer represents a collection of individual trees, in which biomass is distributed through the foliage, branches, stems and roots. The ground vegetation layer is composed of understorey species and includes three parts (foliage, roots, and perennial parts). The soil is partitioned into three horizontal layers according to its water content (unsaturated upper and middle layers, and a saturated bottom layer) in order to simulate water transfers, and the Roth-C model (v. 6.3) is incorporated with only a small number of modifications (Coleman and Jenkinson, 1999; Jenkinson and Coleman, 2008) in order to simulate four active SOM compartments (decomposable plant material, or DPM; resistant plant material, or RPM; microbial biomass, or BIO; and humified organic matter, or HUM) as well as an inert SOM compartment (IOM).

The model includes a “forest management” package, which simulates silvicultural systems by specifying soil preparation techniques, ground vegetation removal, initial tree density, rotation length, and tree compartments harvested, as well as the frequency, selection method and intensity of thinnings. As the model is forced by climatic variables (air temperature and humidity, wind speed, precipitation, long- and short-wave incoming radiation, atmospheric CO_2 concentration), climate scenarios such as the Representative Concentration Pathway scenarios (RCPs; IPCC, 2014) are used to simulate forest growth while taking into account future climate conditions.

2.2. Nutrient package

GO+’s nutrient package was developed for one broadleaf deciduous tree species (*Fagus sylvatica*) and two evergreen conifers, one with a sparse canopy (*Pinus pinaster*) and the other with a dense canopy (*Pseudotsuga menziesii*). Due to its sparse canopy, *Pinus pinaster* stands have an abundant understorey (Gonzalez et al., 2013), which is simulated in GO+ (no simulated understorey in *Fagus sylvatica* stands; limited understorey biomass simulated in *Pseudotsuga menziesii* stands, with the exception of young stands).

The nutrient package allows for evaluation of the nutrient stocks (N, P, K, Ca and Mg) in standing tree biomass. From these, the nutrient outputs from the ecosystem resulting from biomass harvesting can be calculated. Nutrient concentrations in foliage vary with needle age (Ranger et al., 1995; Augusto et al., 2008), and those in stems, branches and roots decrease as the diameter of these compartments increases (Santantonio et al., 1977; Augusto et al., 2008; Hellsten et al., 2013; Wernsdörfer et al., 2014). Thus, fixed values for nutrient concentrations cannot be used to estimate nutrient stocks in tree biomass. As demonstrated by Augusto et al. (2008), using fixed nutrient concentrations in tree stems could result in values in small trees being underestimated (−40% to −60%) and/or values in old trees being overestimated (+70% to +110%). Consequently, coupling biomass production models with mean nutrient concentrations (calculated, for example, for the tree stem in Rodriguez-Soalleiro et al. (2007)) could lead to an erroneous evaluation of nutrient outputs (e.g. underestimation of values for young stands; Augusto et al., 2008). In order to accurately estimate nutrient stocks and outputs, two approaches can be used. The first approach consists of distributing the biomass of a given tree compartment over different age or diameter classes and using specific nutrient concentration values for each class. A second approach would involve using variable nutrient concentration values for a given tree compartment depending on its size. Both approaches were combined in the present study. The nutrient package accounts for variations in nutrient concentration depending on tree age and the size of tree compartments, as follows:

(i). The GO+ model annually simulates the diameter at breast height (DBH in cm) and dry mass of the stem, roots, branches and foliage (in kg-dw $tree^{-1}$) for each individual tree.
(ii). The relative proportions of two classes of needle (one-year-old needles and those older than one year), three classes of branch diameter and four classes of roots (fine roots, small roots, coarse roots and stump plus taproot) are computed as a function of tree age or DBH using allometric relationships.