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Effects of scale and scaling in predictive modelling of forest site productivity

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A B S T R A C T

Site productivity, commonly expressed by site index, is a key indicator of the potential of forested land to deliver ecosystem services like wood production and carbon sequestration. It is an important criterion for decision makers and managers of both production and multi-purpose forests. In many situations forest site index cannot be directly measured and must be estimated from site characteristics related to climate, topography and soil, using appropriate models. A major difficulty herewith is that the models must capture the spatial and temporal variability of the ecological processes, knowing that the magnitude and the variability of the driving forces and responses may show scale dependencies. Scale is therefore an important issue in successful forest site productivity modelling.

In this study, empirical forest site productivity models are evaluated for their scale dependency whereby reference is made to the threefold concept of 'scale' (extent, support, coverage) as proposed by Bierkens et al. (2000). We also addressed the applicability of models at other extents or other supports than the one they were developed at, i.e. the effect of scaling. The results show that meaningful site index models for small extents require higher resolution support to catch the short-distance variability, whereas for larger extents a coarser support is sufficient to characterize the variability. Where it regards scaling, it is found that the validity of empirical site index models is restricted to the scale level for which they are calibrated. Also the application of site index models on an extent which is adjacent and not overlapping with the extent at which they were developed proved to result in inadequate predictions. Although the structure of site index models is scale-dependent and their applicability limited to the scale of development, it is beyond doubt that such models have the potential to provide good insight into the biophysical drivers of site productivity and can result in good predictions at unsampled locations whenever the scale of model establishment is adapted to the scale of the studied processes and predictions are restricted to the extent for which the model is calibrated.

1. Introduction

Site productivity, commonly expressed by site index, is a key indicator of the potential of forested land to deliver ecosystem services like wood production and carbon sequestration. It is an important criterion for decision makers and managers of both production and multi-purpose forests. It allows foresters to forecast growth and production and hence select the most suitable tree species for a site. In many situations forest site index cannot be directly measured and must be estimated from other site characteristics related to climate, topography and soil, using appropriate models (Aertsen et al., 2011; McKenney and Pedlar, 2003). A major difficulty herewith is that the models must capture the spatial and temporal variability of the ecological processes, knowing that the magnitude and the variability of the driving forces and responses may show scale dependencies. Scale-related issues are common in environmental sciences, and the scale dependency of spatial heterogeneity has been widely recognized (Wu, 2004). Spatial heterogeneity, non-linearity of ecological processes and emerging phenomena are key features to understand biodiversity and ecological complexity, but also major hurdles for the successful transfer of ecological relations over different scales (Peterson, 2000; Wu et al., 2006). To study ecological processes in a successful way, decisions need to be made about the appropriate spatial and temporal scale.

Scale is a widely used but very broad term, with high risks of confusing or ambiguous interpretations. Traditionally, it is used in cartography as the ratio of a distance on the map and the actual distance on the earth's surface. This definition is useful for cartographic representation, but inadequate for studying the

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scale-dependent relationships between patterns and processes in ecology because of its intended rigid connotation (Wu et al., 2006). Clear definitions are therefore important when dealing with scale in ecological modelling. In an ecological context, *scale* usually refers to the spatial, temporal or hierarchical dimensions of a phenomenon, whereas *scaling* is referring to the transfer of information between different scales (Wu et al., 2006). Bierkens et al. (2000) identified three components of scale along which scaling can operate. In this article we adhere to Bierkens' definitions of these components and scaling operations, as complemented by Wu et al. (2006) and illustrated in Fig. 1. As the focus of this study is mainly on spatial scale, the term scale as used in the rest of this article does not imply the temporal dimension of scale, unless explicitly mentioned.

Bierkens et al. (2000) defined *extent* as the component of scale which specifies the magnitude of the territory which is subject to modelling. Increasing the extent is called *extrapolation*, whereas reducing the area of interest is called *singling out*. The *support* component of scale (also called 'grain' (McBratney, 1998)) is defined as the magnitude of the elementary observation or modelling units. It is the size of the areal units for which the characteristic of interest is considered homogeneous. For these support units we only know 'representative' values and not their within variation. Increasing the support (making the units larger) is termed *upscaling*, while for decreasing the support the term *downscaling* is used. The ratio of the area of the support units, for which the average value is known, to the extent of the study is the third component of scale and is called the *coverage* of the study. Increasing the coverage without additional observations is termed *interpolation*. *Sampling*, i.e. taking a subset of support units and using these for modelling, makes the coverage decrease for a given extent. In this framework, scaling in environmental modelling is mostly a combination of two or more of the mentioned operations. Moreover 'scale level' points to a specific combination of extent, support and coverage. Care should be taken using the term resolution because it can refer to both the support as the coverage (Bierkens et al., 2000).

Changing the extent of analysis might not only affect the variability in forest site productivity, it might also alter the relative importance of environmental variables explaining the variability. At continental extent site productivity is mainly determined by climatological and geological gradients, whereas at the forest complex extent these determinants have little explanatory power whereas micro-topographical and soil factors do (Mummery et al., 1999). As a consequence of this type of scale dependency, models calibrated at a certain extent cannot be expected to perform well at extents characterised by different environmental gradients and limiting factors. Although general tree growth variability at large extent can often be captured by models, their accuracy is found to be lower than those developed for smaller extents (Chen et al., 2002; Ung et al., 2001). For the prediction of forest soil carbon stocks Zirlewagen and von Wilpert (2010) observed at large extent (i.e. federal state) no negative upscaling effect, whereas at smaller extent (i.e. growth region) a decreased model performance was observed when using a coarser support. Moreover, switching from the large extent to the smaller extent resulted in models with completely different sets of predictor variables.

Changes in support (and related coverage) can also introduce serious implications on the structure and performance of site productivity models. Management planning and control should often be conducted at the landscape level, whereas the existing observations at plot scale level are often not appropriate as a basis for decision making (Araujo et al., 2005; Zirlewagen and von Wilpert, 2010). Upscaling is the enlargement of the support units prior to model calibration, typically by aggregation of observations or model output available for smaller units, and can provide a solution in these situations. A variant is to substitute plot-level observations by information retrieved from thematic maps. Pinno et al. (2009) could however not develop reasonable models for the site productivity of trembling aspen based on map unit information because the coarse support provided by the map did not correspond to the site specific predictors. The site specific predictors could however explain the variability in site productivity properly.

The concept 'scale' in spatial statistical analysis can however still further be refined for each of the scale components of Bierkens's framework in observation scales, scales of ecological phenomena and statistical analysis scale, all of them also having a possible impact on the performance of empirical models (Dungan et al., 2002).

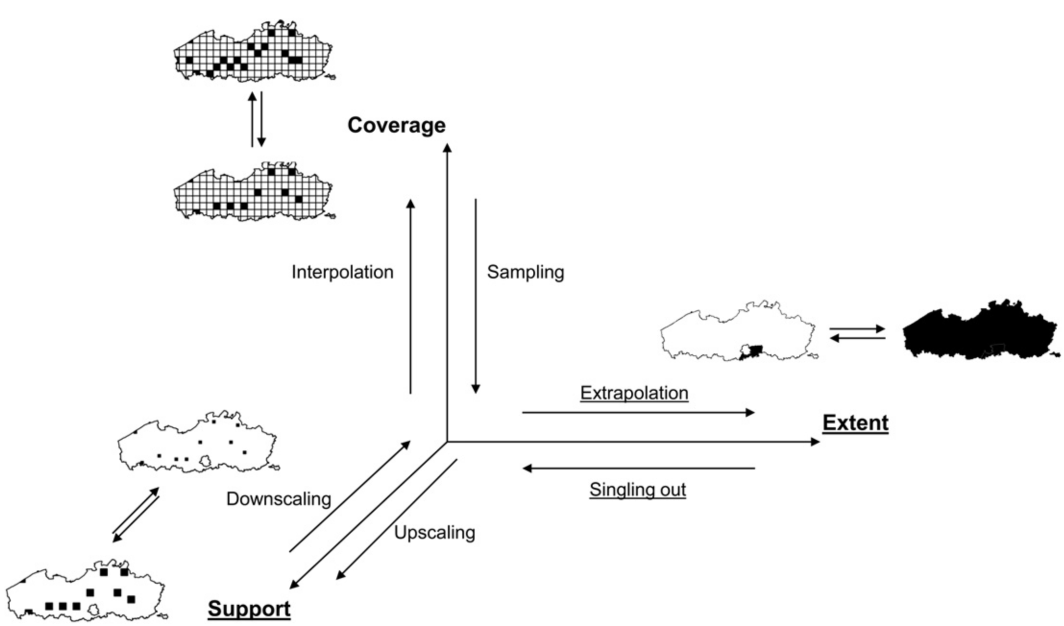

Fig. 1. Framework for defining scale and scaling based on Bierkens et al. (2000). The scale components and scaling operations of which the effects were investigated in this study are underlined.