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Spatio-temporal prediction of tree mortality based on long-term sample plots, climate change scenarios and parametric frailty modeling

Arne Nothdurft

Forest Research Institute Baden-Württemberg, Department of Biometrics and Informatics, Germany

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ABSTRACT

An approach is presented to predict the effects climate change may have on mortality of forest trees. Mortality is modeled using long-term observations from the Pan-European Programme for Intensive and Continuous Monitoring of Forest Ecosystems plots, retrospective climate data and frailty models having a parametric baseline hazard function. The linear predictor is modeled by B-spline regression techniques to allow for nonlinear cause-and-effect curves. Spatio-temporal predictions of mortality of four major tree species in the German state of Baden-Württemberg were derived in terms of unconditional hazard ratios and based on climate projection data.

According to the model, marginal risk of tree death for 100 year old Norway spruce trees will be doubled until 2100. Hazard rates of common beech will be halved in low elevation areas and will be reduced by 25% in higher elevations until 2100. Hazard rates of silver fir will be less affected by a changing climate and will increase by at least 25% and by a maximum of 100% in mountainous regions. Scots pines hazard rates will be halved on higher elevation sites and will increase on lower elevation sites.

1. Introduction

Developing climate change adaptation strategies for managed forests requires understanding of how forests may react under perturbed climate conditions. Altered tree species composition (Iverson and Prasad, 2010), treeline shifts (Dullinger et al., 2004), changes in site productivity (Albert and Schmidt, 2010) as well as in tree mortality (Breshears et al., 2008) are presumably the major effects of a changing climate. For the German state of Baden-Württemberg (Fig. 1) models exist so far for site index prediction based on climate change scenarios (Nothdurft et al., 2012) as well as for predictions of tree species shifts from Norway spruce to common beech (Hanewinkel et al., 2010). In addition to these recent results on climate change effects, a new method is presented in the following chapters which can be used to predict lifetime of forest tree species under a changing climate.

Death of forest trees often follows complex ecological processes with multiple contributors (Franklin et al., 1987). Climate may initially act as predisposing factor for biotic agents, such as bark beetles or fungi, who then attack the stressed trees and may finally cause death of a tree. The present work does not aim at reproducing the complex causal mechanisms behind tree mortality, it rather intends to model the relationship between tree death and climatic variables in a sound statistical framework.

In gap models mortality occurs if a tree's growth rate falls below a critical threshold driven by other factors (see Keane et al. (2001) for an overview). The individual risk of death is thereby often modeled as a constant rate over the total life span using exponential functions. However, that assumption seems not realistic when predicting major diebacks following warming (Loehle and LeBlanc, 1996).

The principles of the approach presented in this paper are related to the basic idea shown in Staupendahl and Zucchini (2011) and in Staupendahl and Möhring (2011), who applied more flexible techniques of survival analysis to parametrically model the risk of tree death. My model is based on annual tree measurements on permanent sample plots, which have been incorporated into the "Pan-European Programme for Intensive and Continuous Monitoring of Forest Ecosystems" (de Vries et al., 2003; Eichhorn, 2007), also called the Level-II Program. The Level-II data set has a clustered structure meaning that several trees are measured on each sample plot and thus leading to correlated failure times. Therefore, the new approach to model lifetime is directly inspired by the methods shown in Wienke (2011), who outlines the theory of frailty models, which allow to adopt survival modeling to clustered data.

Concluding from the findings in Dullinger et al. (2004) about a nonlinear relationship between temperature and mortality of Pinus mugo and from analogous experience made in previous work on modeling the effects of climate change on site index (Nothdurft et al., 2012), it was claimed prior to the present study that the

E-mail address: arne.nothdurft@online.de

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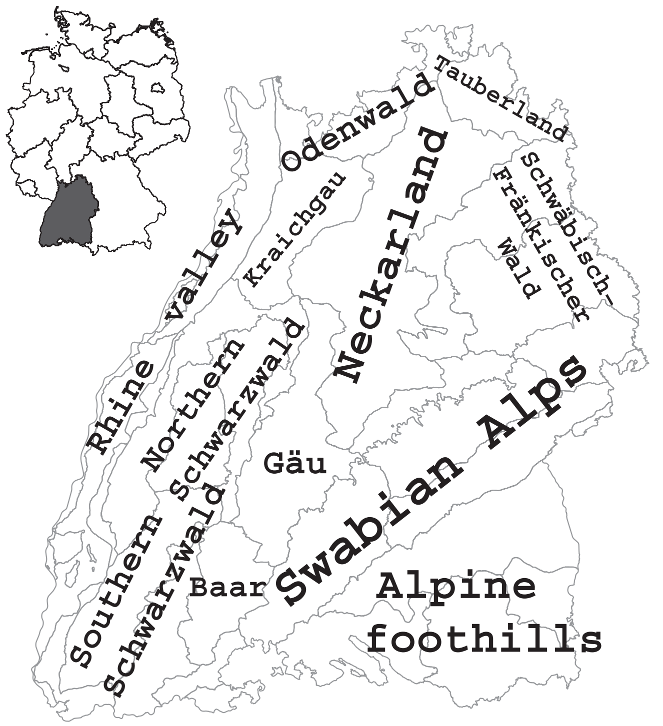

Fig. 1. Geographical regions of Baden-Württemberg located in Southwest Germany.

approach to model tree mortality dependent on climate variables should be likewise flexible enough to allow the cause-and-effect regression curves to have a nonlinear shape. It is shown in this paper how to model such nonlinear cause-and-effect relationships by incorporating B-spline regression techniques into the parametric frailty model approach.

The aim of this study is to provide predictions of tree mortality for different climate scenarios in Baden-Württemberg using a statistically sound approach to model the effects of climate change on survival of forest trees based on long-term sample plots and climate scenario projections.

2. Material

2.1. Climate and site data

The retrospective climate data were derived from gridded data files containing daily values of meteorological variables in a 50 m × 50 m spatial resolution. The gridded data were produced by a hierarchical model chain incorporating dynamical and statistical downscaling steps. The large-scale atmospheric processes were represented by NCAR/NCEP reanalysis series (Kalnay et al., 1996), which were downscaled by the non-hydrostatic regional climate model Weather Research and Forecasting (WRF) (Skamarock et al., 2005; Langkamp and Böhner, 2011). The dynamical downscaling yielded gridded data of 5 km × 5 km resolution. A statistical downscaling was consecutively applied to derive gridded data having the final 50 m × 50 m resolution. The statistical downscaling was based on multivariate transfer functions applied to topographic surface parameters, building a link between meteorological observations from the met-station network of the German National Meteorological Service (Deutscher Wetterdienst, DWD) and the WRF circulation variables (Böhner and Antonić, 2008).

In contrast to the climate sensitive site-index model shown in Nothdurft et al. (2012) where long-term means of climate variables were applied, annual climate values were used in the present study corresponding to the annual cycle of follow-up surveys on Level-II sample plots. Tree mortality was then predicted under future climate conditions using existing simulations of the regional climate model REMO (Majewski, 1991; Roeckner et al., 1996; Jacob, 2001; Jacob et al., 2001) for scenarios A1B, A2 and B1 from the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) of the Intergovernmental Panel on Climate Change (IPCC).

Before starting regression modeling the main drivers of tree mortality had to be determined. Rebetez and Dobbertin (2004) observed that mortality of Scots pine trees in the Swiss Alps was highest following the dry and hot year 1998, and they also found strong correlation between the precipitation of the previous year and tree defoliation as major predisposition factor. Van Mantgem and Stephenson (2007) found that a temperature-driven increase in water deficit leads to increasing mortality rates of Abies and Pinus in Sierra Nevada of California. Adams et al. (2009) have experimentally shown that temperature alone may increase mortality of Pinus edulis for two reasons, (i) carbon-starvation through photosynthesis inactivity and excessive respiration due to stomata closure and (ii) hydraulic failures if photosynthesis is maintained during periods of high soil moisture tension. Based on the findings of these authors, the total of average daily temperatures during the current growing season as well as the average total annual precipitation during the previous and the current growing season were identified as main explanatory climate variables to model tree mortality in Baden-Württemberg.

According to Pastor and Post (1988), who assume that differing abilities of soils to hold water are an important factor in modeling the effects of CO_2-induced climate change on northern forests, soil water-holding capacity was likewise applied as additional regressor variable in the new prediction model. A grid data file of soil water-holding capacity in 50 m horizontal resolution was derived using Puhlmann and v.Wilpert's (2012) pedotransfer functions for the water-retention curve and for the unsaturated-hydraulic-conductivity curve applied to spatial predictions of soil physical characteristics obtained by the approaches shown in Zirlewagen and v.Wilpert (2012).

2.2. Survival data

The survival data are derived from annually repeated surveys on sample plots, which have been incorporated into the "Pan-European Programme for Intensive and Continuous Monitoring of Forest Ecosystems" (de Vries et al., 2003; Eichhorn, 2007), also called the Level-II Program. At each of the inventory occasions it is recorded for each tree whether it is dead or still alive. As outlined above, climate has merely a predisposing effect and may initialize a complex chain of other factors finally causing a tree's death. In the present paper mortality is modeled focusing on warmness and drought as explanatory variables. Because climate models can not credibly predict other meteorological variables, such as the snow depth, wind speed and thunderstorms, future predictions of tree mortality due to these factors would also become highly uncertain. Thus, trees having been killed by windthrow, snow breakage or lightning damage were treated as censored. The same applies to trees, which have been removed from the study by regular harvesting or simply because the entire observation plot is no longer surveyed.

Frailty models were built for four major tree species occurring in Baden-Württemberg. These are Norway spruce (*Picea abies* (L.) H.Karst.), silver fir (*Abies alba* Mill.), Scots pine (*Pinus sylvestris* L.) and common beech (*Fagus sylvatica* L.). The model data from the Level-II sample plots consist of repeated measurements of at least 1373 trees on 37 sample plots for Scots pine. 95 Scots pine trees died because of the above mentioned criteria and to 438 Scots pine trees censoring occurs due to competing events. For Norway