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Forest restoration with *Betula* ssp. and *Populus* ssp. nurse crops increases productivity and soil fertility

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ABSTRACT

The rapid re-establishment of forests following large disturbances is being seen as one option to increase the contribution of forests to climate change mitigation. The temporary inclusion of pioneer trees as nurse crops on disturbed sites can facilitate the establishment of target tree species and may additionally benefit productivity and soil fertility. In this study we compared productivity and nutrient cycling between stands of oak target species (*Quercus robur* and *Quercus petraea*) that were established with and without widely spaced *Betula* ssp. or *Populus* ssp. nurse crops. Simulation results for a full rotation of oaks (180 years) indicated that both types of forests, with and without nurse crops, have a comparable total productivity. However, stands with nurse crops supplied 59–96 Mg ha^{-1} harvestable biomass after 20 years, whereas the first harvest of biomass from stands without nurse crops would occur at least 30 years later. Nutrient element costs associated with the removal of *Betula* ssp. wood were low compared to *Populus* ssp. Also, nurse crop stands had up to 2.5 times larger pools of exchangeable base cations in top mineral soils (0–30 cm) compared to mono-specific oak stands. The high soil cation pools may have resulted from reduced leaching under nurse crops or the increased recycling of cations, also from deeper soil depth, via litter fall and fine-root turnover. Our results show that forest reestablishment with pioneer tree species may be a suitable tool for the rapid recovery of forest productivity and mitigation potential following disturbances while simultaneously helping to maintain or increase soil fertility.

1. Introduction

Climate change mitigation strategies in Europe aim to off-set fossil fuels and replace energy-intensive materials with wood. Therefore, the supply of biomass from forests is considered a crucial component within the set of renewable energy options (Wiesenthal et al., 2006; Stupak et al., 2007).

However, during the last few decades the intensity and frequency of disturbances caused by storms, droughts, fires, pest insect outbreaks or wet snow events in central European forests has risen measurably (Schelhaas et al., 2003; Nilsson et al., 2004). Thus, approximately 16,000 ha or 0.15% of the total forest area in Germany are annually disturbed considering the time between 1950 and 2012 (EFI, 2013). At the European level such disturbances are equivalent to 8% of the total annual fellings (Schelhaas et al., 2003). Natural forest disturbances are thus a relevant aspect of central European forest management (Schelhaas et al., 2003; Nilsson et al., 2004; Majunke et al., 2008; Mantau, 2012; Albrecht et al., 2013; Kraus and Krumm, 2013).

Pioneer trees could play a major role in the restoration of large disturbed areas as they can possibly accelerate forest recovery and therefore supply multiple benefits for productivity and ecosystem functioning (Alban, 1982; Man and Lieffers, 1999). Also, the cultivation of fast growing pioneer tree species such as *Populus* ssp. or *Betula* ssp. (Bazzaz, 1979; Pommerening and Murphy, 2004) may facilitate the adaptation of forests to environmental extremes and simultaneously favor the rapid sequestration of atmospheric carbon to mitigate climatic change (Messier et al., 2013; Brang et al., 2014).

However, in forests managed on a selection basis or close to nature, silvicultural systems with pioneers are typically avoided in central Europe (Bauhus et al., 2013) in favor of those with long-lived, commercially important tree species such as *Fagus*

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ssp., *Quercus* ssp. or *Picea* ssp. Often, forest restoration with these species is realized by planting mono-specific stands, which can suffer amongst others from late frost events in large forest openings (Lundmark and Hällgren, 1987; Örlander, 1993; Groot and Carlson, 1996; Örlander and Karlsson, 2000; Agestam et al., 2003). Therefore, the capacity of forests to provide biomass may be substantially reduced, if, following disturbances, regeneration is delayed and thus productivity reduced (Osterburg et al., 2013).

On the other hand, large open areas in forests offer opportunities for new, alternative and more resistant silvicultural systems. Hence, pioneer trees can be used as nurse crops, which are temporary mixtures of fast growing and light-demanding tree species in the overstorey and shade-tolerant target tree species in the understorey (Pommerening and Murphy, 2004). During the initial years of stand development, the pioneer trees facilitate the establishment of other tree species beneath their canopy. One possible nurse effect is the rapid recovery of forest micro-climate and thus the amelioration of environmental extremes, such as frost (Carlson and Groot, 1997; Schmidt-Schütz and Huss, 1998). Outside of central Europe, nurse crops are therefore commonly used for large or small scale reforestations (Pommerening and Murphy, 2004) following clearfelling (Keenan et al., 1995; Lieffers et al., 1996) or natural disturbances (Perala and Alm, 1990; Drouineau et al., 2000; Vallauri, 2005; Nelson et al., 2012) and for the afforestation of abandoned agricultural lands (Mander and Jogman, 2000; Gardiner et al., 2004; Uri et al., 2007).

Once trees of the target species have been successfully established and start to suffer from inter-specific competition from nurse trees, the latter are typically removed (Cotta, 1828; Shepperd and Jones, 1985). Often, however, the nurse trees are just killed and not commercially harvested, because it is feared that their felling and extraction might damage the established regeneration of target species.

To ensure that this biomass of nurse trees is not wasted but used, a new approach to establish widely-spaced nurse crops for the purpose of woody biomass production has been developed (Unseld and Bauhus, 2012). This approach is based on the assumption that the temporary inclusion of fast growing pioneer tree species may facilitate an early harvest of biomass and thus an earlier return of investment of stand establishment costs to the land owner. Additionally, the overall stand productivity may increase through competitive reduction between tree species (Vandermeer, 1989; Man and Lieffers, 1997) and thus a complementarity in resource use, which typically occurs when mixing light demanding overstorey with shade-tolerant understorey trees (Man and Lieffers, 1999; Richards et al., 2010; Forrester, 2014). To achieve this, nurse crops are managed on rather short rotations and a wide tree spacing is employed that facilitates harvesting of nurse trees with minimal damage to the regeneration (Unseld and Bauhus, 2012).

Nurse crops may also improve nutrient cycling following forest disturbances, when the situation is often characterized by high mineralization rates of organic matter and reduced uptake of water and nutrients. This can lead to high rates of leaching of nutrient elements such as calcium (Ca), potassium (K), magnesium (Mg) and nitrogen (N) and consequently a reduction in soil fertility (Hornbeck et al., 1986; Hendrickson et al., 1989; Bauhus and Bartsch, 1995; Yanai, 1998). These nutrient element losses may be aggravated, if the sites are subsequently used for intensive production and harvesting of biomass in nurse crops and nutrients contained therein (Sverdrup et al., 2006; Worrell and Hampson, 1997).

Owing to the rapid growth and canopy closure of pioneer tree species, they have a higher nutrient and water uptake, thus reducing leaching, soil temperatures and mineralization rates, when compared to slower growing tree species (Prescott, 2002). Interactions between nurse and target tree species may further accelerate these processes and result in greater resource availability, uptake and growth (Rothe and Binkley, 2001; Forrester, 2014).

While there have been many studies on the productivity or nutrient cycling in mixed-species forests (Richards et al., 2010), we are not aware of any studies that have focussed on temporary mixtures of target species such as *Quercus* ssp., *Fagus* ssp. or other with *Populus* ssp. or *Betula* ssp.

Therefore, the first objective of this study was to assess whether forest restoration with widely spaced nurse crops can facilitate early biomass harvests, increase the overall stand productivity, and whether it thereby also intensifies harvest-related exports of nutrient elements such as Ca, K, Mg, N, and P when compared to conventional restoration of forest stands with the target species *Quercus robur* and *Quercus petraea*. The second objective was to study possible effects such nurse crops may have on ecosystem nutrient cycling. Thus, we hypothesize that nurse crops of broad-leaved pioneer tree species can buffer disturbance-induced and/or harvest-related reductions in soil fertility. Additionally, the study also investigated options to reduce harvest-related nutrient costs in nurse crop systems. For this purpose, the nutrient costs of biomass harvest from *Populus* ssp. or *Betula* ssp. were compared with those of several other important tree species and at different harvesting intensities. Thus, this study is the first to examine productivity as well as nutrient cycling and conservation in widely spaced, short-lived *Populus* ssp. or *Betula* ssp. nurse crops, providing the foundation for the short-term sustainable production of woody biomass from disturbed forest areas in central Europe.

2. Materials and methods

2.1. Study area and trial forests

This study was carried out in the German federal state of Rhineland-Palatinate. Here, nurse crop trials were established in 1991 following large scale wind throw of *Picea abies* (L.) Karst. The trials originally aimed to study the effects of nurse crops of pioneer tree species on the survival, growth and quality of site adapted target tree species such as oak (here: *Quercus robur* and *Quercus petraea*) when planted at water logged sites under open field conditions. Thus, the trials included oak stands planted as conventional monocultures and oak stands that were planted under a sheltering nurse crop of pioneer tree species (Schmidt-Schütz and Huss, 1998). Treatments were randomly assigned. Between 1991 and 1998 weed was controlled manually, dead tree saplings were replaced and naturally regenerated trees were removed. Between 20% and 70% of the nurse tree seedlings died between 1991 and 1994 and were replaced in 1994 (Schmidt-Schütz and Huss, 1998).

For the purpose of this study, we used two of the original trials, Kirchberg (N 49.98°, E 7.32°; 450 m a.s.l.) and Sobernheim (N 49.86°, E 7.69°; 420 m a.s.l.), for soil and biomass sampling in 2011. We selected 16 plots equally spread across both trials (study sites). Hence, we selected eight plots with oak monoculture and eight plots with oak growing under a nurse crop shelter (Fig. 1).

Among the plots selected in Kirchberg, two were originally established as nurse crops with *Populus tremula* L. x *Populus tremuloides* Michx. Astria and two were established as nurse crops with *Betula pendula* Roth x *Betula pubescens* Ehrh. *Quercus robur* L. was the original target species in Kirchberg. It was used to establish the mono-specific oak plots as well as the understorey of nurse crop plots. In Sobernheim two plots were established as nurse crops with *Populus tremula* L. x *Populus tremuloides* Michx. Astria and two as nurse crop with *Betula pendula*. The target tree species here was *Quercus petraea* (Mattuschka) Liebl., which was likewise planted in monocultures as well as in the understorey of nurse crops. In our statistical analyses we examined whether the