Forest Ecology and Management 255 (2008) 3893–3903

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effects of flooding on the recruitment, damage and mortality of riparian tree species: A field and simulation study on the Rhine floodplain

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ARTICLE INFO

Article history:
Received 13 December 2007
Received in revised form 19 March 2008
Accepted 21 March 2008

Keywords:
Flooding
Stem damage
Mortality
Trees
Saplings
Floodplain
Riparian forest
Simulation model
ForGEM
Washlands

ABSTRACT

The extensive flooding by the river Rhine on May 12 1999 provided an opportunity to investigate the impact of such an extreme event in terms of damage and mortality of adult trees in floodplains. Such data is highly valuable for determining the potential impact of climate change on the zonation of tree species along rivers. We analysed an extensive dataset of the damage and mortality suffered by groups of adult trees of the following species as a consequence of this flood: the hardwoods *Acer campestre* L., *Acer platanoides* L., *Acer pseudoplatanus* L., *Alnus glutinosa* (L.) Gaertn., *Carpinus betulus* L., *Fagus sylvatica* L., *Fraxinus excelsior* L., *Juglans nigra* L., *Prunus avium* (L.) L., *Quercus robur* L., *Tilia cordata* Mill., *Ulmus laevis* Pall. and *Ulmus minor* Miller, and the softwoods *Salix* spp. L. and *Populus* spp. L.

A logistic survivorship curve revealed that mortality of *A. platanoides*, *A. pseudoplatanus* and *T. cordata* increased significantly with increasing duration of flooding; *C. betulus* and *F. excelsior* showed a significant increase of damage and mortality with increasing flooding depth. There was no mortality of *Salix* spp. and *Populus* spp. in either the flooded or unflooded areas. No statistically significant relationships were found for the other tree species. Multivariate analysis revealed that flooding duration, flooding depth and flooding velocity explain 19%, 11% and 8%, respectively, of the variation in damage and mortality of trees.

The survivorship curves of adult trees obtained in this study were combined with similar curves of saplings based on an earlier study and applied in an individual-tree, process-based simulation model. The simulated effects of flooding on an initial random distribution of trees species on a hypothetical floodplain resulted in a realistic zonation of tree species along the river. When extreme events were simulated, the zonation shifted upward. This demonstrates the model's usefulness in assessment and planning studies of the impacts of climate change on tree species composition in river floodplains in north-west Europe.

1. Introduction

Throughout western and central Europe, plans have been developed for the creation of water retention areas (e.g. in Germany: Armbuster et al., 2006; Vieser et al., 1999) and for enlarging washlands (e.g. in the Netherlands: Buijse et al., 2002; Klijn et al., 2004) to protect the hinterland from periodic floods. In Germany, the impetus for the plans was the extreme flooding of the rivers Oder (in 1997), Rhine (in 1983 and 1999) and Elbe (in 1993) (Kreuzwieser, 2006) that led to economic losses of several billion euros and more than 100 deaths (IKSR, 1988; IKSE, 2004). In the Netherlands, the impetus was the threat of major floods in 1993 and 1995, which led to the precautionary evacuation of 250,000 people (Klijn et al., 2004).

Extreme flooding events are expected to occur more frequently as a consequence of climate change. An increased frequency of zonal circulations of clouds in Central Europe between 1889 and 1990 resulted in a statistically significant increase of precipitation during winter and spring (Bardossy and Caspary, 1990; Werner et al., 2000) and a statistically significantly higher total annual rainfall in northern Europe (Hegerl et al., 1994). Global circulation models predict that it is very likely that higher amounts of precipitation will occur (IPCC, 2007) in this region, especially during winter and spring, considerably increasing the risk of flooding in Central and Northern Europe (IPCC, 1997, 2007; ICPR, 1998, 2006). Though the number of rain days is predicted to decrease, the number of days with heavy rain events (exceeding 20 mm d^{-1}) is predicted to increase (Kunstmann et al., 2004),

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doi:10.1016/j.foreco.2008.03.044

paradoxically leading to more summer droughts as well as more extreme flooding events during summer.

As most of the forests in the new water retention areas have never previously been exposed to flooding, the zonation of species along riverine floodplains is likely to undergo a major change in the composition of woody plant species (Trémolières et al., 1993, 1998; Deiller et al., 2003). The zonation of woody species along natural floodplains is largely determined by flooding frequency and duration (e.g. Ellenberg, 1988; Blom and Voesenek, 1996), as flood tolerance varies – even among closely related species (Kozlowski, 2000). Different responses have been found both to direct effects, such as the restricted oxygen exchange and waterlogging (Hughes et al., 2001; Kreuzwieser et al., 2002), uprooting (Karrenberg et al., 2003), and burial by sediments (Barsoum, 1998; Marigo et al., 2000), as well as to indirect effects, including the creation of bare substrates due to sedimentation (Johnson, 2000; Karrenberg et al., 2002), decreased vegetation cover (Siebel, 1998; Siebel and Blom, 1998; Siebel et al., 1998), and increased nutrient supply (Thoms, 2003).

Most of the studies on the flood tolerance of trees native to western and central Europe have focussed on softwood species of the genera *Salix* and *Populus* (e.g. Barsoum and Hughes, 1998; Siebel, 1998; Van Splunder, 1998; Hughes et al., 2001; Karrenberg et al., 2002, 2003) because these species dominate the active floodplains in this geographic zone (Malanson, 1993). Only a limited number of studies have included hardwood species such as *Quercus, Acer, Fraxinus* and *Fagus* (Frye and Grosse, 1992; Harper et al., 1997; Küssner, 2003; Vreugdenhil, 2004; Kuiters and Vreugdenhil, 2005; Vreugdenhil et al., 2006). Furthermore, only a few of these studies on softwood and hardwood species have addressed mature trees, because these are generally expected to be less sensitive to flooding than seedlings or saplings (see Glenz et al., 2006) for a recent review). In an earlier paper (Vreugdenhil et al., 2006), the data we presented on the flood tolerance of saplings went some way to remedying the lack of data indicated by Glenz et al. (2006). We now present new data on the flood tolerance of mature trees of several species native to central and north-western Europe.

Another conclusion from Glenz et al. (2006) was that it would be very useful to develop a dynamic simulation model that can predict the woody species composition of water retention areas or restored floodplains on the basis of flooding characteristics including the duration, depth and velocity of the flooding. Such a model could be used to incorporate possible future climate change into proposed riverine forest management and landscape planning. We addressed this by using the survivorship curves obtained from the aforementioned data on juvenile and mature trees in an existing individual-tree simulation model (referred to as ForGEM, Kramer et al., submitted for publication; Kramer, 2004). This allowed us to predict the dynamics of future woodland under a range of flooding regime scenarios.

Based on our previous study on saplings (Vreugdenhil et al., 2006) and on the literature on the species that we studied, we set up four hypotheses: (1) mature trees of the softwood species, such as *Salix* spp. and *Populus* spp., will be less affected by flooding than trees of hardwood species, such as *Quercus robur*, *Fraxinus excelsior*, *Fagus sylvatica*, *Tilia cordata* and *Carpinus betulus*; (2) the primary explanatory variable with respect to damage and mortality of mature trees will be flooding duration, the next most important explanatory variable will be flooding velocity and the least important will be flooding depth; (3) the zonation of trees species along rivers is the result of differential damage and mortality in relation to the abovementioned flooding characteristics; (4) that, consequently, a change in flooding regime will alter the zonation of tree species along a river.

2. Materials and methods

2.1. Data and data analysis

On 12 May 1999, the discharge of the Rhine at Basel rose from 2000 $m^3\ s^{-1}$ to 5000 $m^3\ s^{-1}$ within 24 h (Spät, 2002). This resulted in hardwood forests in the floodplains in southern Germany being inundated from 12 May until the end of June 1999. In July 1999 it became clear that this flood had resulted in severe damage and mortality of trees and shrubs. The Gewässerdirektion Südlicher Oberrhein/Hochrhein ordered the documentation of the damage resulting from this flood: 6877 trees in total on the sites that had been flooded were monitored annually during the period 1999–2001; during 2003, only 298 trees at Leimersheim were monitored where the flooding had been particularly severe (Armbuster et al., 2006). As it soon became clear that trees in areas that were flooded by seepage from under the dikes were also affected, four forest sites and 24 plots inundated by seepage water due to the 1999 flood were also investigated. Henceforth in this paper we will refer to these four sites as indirectly flooded sites.

The methodology of observation was as follows (Armbuster et al., 2006): on the directly flooded sites, single-species groups of trees were selected on homogeneous spots at which all trees were at the same elevation above the river. The number of trees per group was not constant. The lower section of the stem of each tree in the group was inspected and classified as "no damage", "stem damage" or "dead". On each tree the maximum flood depth was recorded, based on flood marks (sediment on the bark); flooding duration was calculated from flooding data from the nearest gauge station. The water velocity at the gauge was an additional variable used in the analysis (see below).

At the sites indirectly flooded by seepage water, a distinction was made between severe stem damage and slight stem damage. Severe stem damage was defined as cracks in the bark longer than 10 cm; trees with slight stem damage had shorter cracks. Weekly measurements of water tables were geometrically corrected between stations. The flooding velocity at the sites flooded by seepage water was taken to be zero. We analysed the percentage of trees that had been damaged or killed by the 1999 flood, using three explanatory variables: flooding velocity (v), flooding duration (d) and flooding depth (h). Table 1 presents an overview of this dataset.

After a first analysis, we decided to pool the data with respect to the following aspects. Firstly, we pooled the damage classes because the distribution of the four observed classes (no damage; slight damage; severe damage; dead) was too unbalanced to allow statistical analysis (Table 1). We created two classes: "no damage" and "damaged or dead". "Damaged" included both slight and severe stem damage for the indirectly flooded sites plus the damage class that did not differentiate between slight and severe damage for the directly flooded sites. Secondly, we pooled the two *Ulmus* species because even though they may occupy different positions ecologically, there were very few observations per species (this pooling was thus not based on preliminary statistical tests). Thirdly, we pooled the data of the directly and indirectly flooded sites, because we could not find statistically significant differences between these modes of flooding for each of the tree species. Hence, the observations on the trees outside the floodplains were pooled with the observations within the floodplains with velocity class zero.

We used only the data collected during 1999, as we had no information on possible later floods and could therefore not correctly analyse the long-term effects of the 1999 flood. As no trees of *Salix* spp. and *Populus* spp. were damaged or killed by the 1999 flood we could not apply logistic regression to these species. In the simulation model case study we assumed that these two species did not have increased mortality as a result of any of the flooding characteristics.