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Plant communities in relation to flooding and soil contamination in a lowland Rhine River floodplain

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Multiple contaminants and periodic flooding may pose cumulative stress to plants in lowland floodplains.

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ABSTRACT

Using canonical correspondence analysis (CCA), relationships were investigated between plant species composition and flooding characteristics, heavy metal contamination and soil properties in a lowland floodplain of the Rhine River. Floodplain elevation and yearly average flooding duration turned out to be more important for explaining variation in plant species composition than soil heavy metal contamination. Nevertheless, plant species richness and diversity showed a significant decrease with the level of contamination. As single heavy metal concentrations seemed mostly too low for causing phytotoxic effects in plants, this trend is possibly explained by additive effects of multiple contaminants or by the concomitant influences of contamination and non-chemical stressors like flooding. These results suggest that impacts of soil contamination on plants in floodplains could be larger than expected from mere soil concentrations. In general, these findings emphasize the relevance of analyzing effects of toxic substances in concert with the effects of other relevant stressors.

1. Introduction

During the past century, large amounts of sediment-bound heavy metals have been deposited on the lowland floodplains of the Rhine River (Middelkoop, 2000). As a result, heavy metal concentrations in the floodplain soils commonly exceed environmental quality standards, indicating potential toxicological risks for the organisms in these floodplains (Leuven et al., 2005). Although effects for invertebrate fauna seem mostly limited (De Jonge et al., 1999; Hobbelen et al., 2006; Ma, 2004; Notten et al., 2005; Schipper et al., 2010; Schipper et al., 2008b), several studies conclude that contamination levels may be high enough to induce adverse effects in vertebrates, including protected top predator species (Kooistra et al., 2001; Schipper et al., 2008a; Van den Brink et al., 2003; Wijnhoven et al., 2006). However, whereas potential impacts on animals have been studied extensively, little attention has been paid to plants. Plants may be very sensitive to surpluses of particular trace elements, with certain sensitive species showing signs of toxicity already at low heavy metal concentrations (Balsberg-Påhlsson, 1989; Kabata-Pendias and Pendias, 2001). This suggests that potential impacts of heavy metal contamination on the plant communities in the lowland Rhine River floodplains are not unlikely.

In general, potential effects of toxicants on biota are difficult to verify under field conditions (Chapman et al., 2002; Klok and Kraak, 2008). Obviously, under field conditions a wide variety of abiotic factors (e.g., physical–chemical conditions) and biotic processes (e.g., competition) jointly determine the presence and abundance of species (Ter Braak, 1987). Hence, the absence of species from contaminated sites does not necessarily reflect exclusion due to toxicity (Chapman et al., 2002). This implies that a simultaneous analysis of all relevant environmental factors is needed both to distinguish potential effects of soil contamination from the influences of other environmental factors and to place the effects of contamination in a realistic perspective (Loos et al., 2010; Van Straalen, 2003; Van Straalen and Van Gestel, 2008).

For plants in floodplains, periodical flooding is generally considered an environmental factor of major importance (Huber et al., 2009; Van de Steeg and Blom, 1998; Van Eck et al., 2004; Voesenek et al., 2004). Flooding fills the soil pores with water,

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which results in strongly reduced oxygen availability for the plant roots. This generates major stress particularly for plants without specific traits to withstand these conditions and could thus limit their distribution (Banach et al., 2009). In addition to this direct impact, flooding exerts indirect influences on plant species distribution, as it affects soil characteristics like pH and nutrient status (Beumer et al., 2008). Considering the importance of these direct and indirect influences of flooding on plant species distribution, flooding effects should be accounted for when analyzing potential impacts of pollution on plant communities in floodplains.

The present study aims to assess relationships between plant communities and soil heavy metal contamination in a lowland floodplain, while accounting for the concurrent influences of flooding and soil properties. Data were collected from 25 sites covering a range of site conditions in a moderately contaminated lowland floodplain along the Nederrijn River, which is one of the main Rhine River distributaries in The Netherlands. Canonical correspondence analysis (CCA) was used to relate plant species composition to the environmental factors investigated. Such a multivariate exploratory approach is considered particularly suitable to distinguish effects of contamination from possible influences of other environmental factors (Van Straalen and Van Gestel, 2008).

2. Materials and methods

2.1. Study area

The “Wolfswaard” floodplain area (51°57′19″ N; 5°39′30″ E) is located south of the city of Wageningen along the Nederrijn River (Fig. 1). The main part of the area is covered by semi-natural grasslands and meadows in use for cattle grazing. A small part of the grassland area is slightly elevated and surrounded by a hedgerow. This area contains some scattered fruit trees and is used for sheep grazing. The banks of the river are covered by willow pollards. In addition to the major embankment that protects the hinterland from flooding, there is a minor embankment parallel to the river at a distance of approximately 200 m from the middle of the channel. Sampling sites ($n = 25$) comprised a sub-set of sampling locations originally selected for another study (Schipper et al., 2010). The sites were distributed among the unembanked area ($n = 11$), the embanked area ($n = 7$) and the sheep pasture area ($n = 7$) and were thus expected to cover a range in conditions with respect to contamination levels, soil properties and flooding duration (Fig. 1). The coordinates of the sampling sites were recorded with a hand-held GPS with an accuracy of 1 m (Garmin Vista HCx).

2.2. Hydro-topographic setting and flooding duration

The position of each sampling site relative to the river channel was determined by calculating the Euclidian distance (m) to the middle of the channel in a geographic information system (GIS; ArcMap 9.1). The elevation of each sampling site was obtained from The Netherlands 5 × 5 m digital elevation model (www.ahn.nl). The average yearly flooding duration (days per year) was derived from daily river water level data from 1999 to 2008 (www.waterbase.nl). River water levels at the study area were based on measurements obtained at a gauging station approximately 10 km upstream, assuming an average water level drop of 3.8 cm/km. This water level drop was calculated by linear interpolation of the average water levels measured at the upstream gauging station and at a gauging station approximately 20 km downstream. The unembanked sampling sites and the sites higher than the minor embankment were assigned the duration of river water levels exceeding their elevation; the embanked sites were assigned the duration of water levels exceeding the height of the embankment (9.10 m).

2.3. Soil properties

The top soil layer (0–5 cm) was sampled in August 2007. Within a radius of 1 m from the centre of each site, three soil samples were collected. The samples were pooled per site, mixed, and air-dried for 48 h at ambient room temperature. The pH was measured in a suspension of 10 g air-dried soil in 25 ml deionized water (<10 μS/cm), mixed 24 h before the measurements. The soil moisture content was determined from the weight loss of air-dried samples upon 24 h at 105 °C. Soil organic matter content (%) was determined from the weight loss upon ignition (4 h at 550 °C) of ~10 g oven-dried samples. The particle size distribution of the soil was analyzed by means of laser diffraction (Malvern Master Sizer 2000 with Hydro 2000 G) performed on oven-dried samples sieved over 2000 μm. Prior to this analysis, samples were treated with 30% H_2O_2 and 10% HCl for detaching coagulating particles and dissolving organic matter. To determine the soil metal concentrations, 0.2 g dw of each sample was weighed on a Sartorius LA310S mass balance and digested in a mixture of 4 ml 65% HNO_3 and 1 ml 30% H_2O_2 using a Milestone Ethos-D microwave. As a quality check for this procedure, two blank samples were treated similarly to the soil samples and included in the series. Total concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) were determined with ICP-MS (X Series; Thermo Electron Cooperation). Concentrations in the blank samples generally comprised maximum 2.5% of the concentrations measured in the soil digests, except for Hg (40%) and Cu (47%), indicating that Hg and Cu concentrations in soil samples may be overestimated. Total soil heavy metal concentrations were compared with soil quality standards corrected for clay and organic matter content (VROM, 2000). These standards include so-called target values, i.e. reference values for clean soil, and intervention values, which represent soil metal pollution levels above which soil remediation measures should be considered (VROM, 2000). To reveal whether the soil concentrations were high enough to induce toxic effects in plants, a tentative comparison was made with reference values for phytotoxicity reported in the literature. As these reference values are commonly expressed as plant tissue concentrations, total soil concentrations measured in the “Wolfswaard” floodplain were translated to plant tissue concentrations with floodplain- and species-specific bioaccumulation factors (Schröder, 2005). To obtain an indication of the bioavailability of the heavy metals, we estimated soluble concentrations of Cd, Cu, Pb and Zn from total soil concentrations, soil organic matter content and pH using the regression equations of Sauvé et al. (2000).

2.4. Plant communities

Plant communities were recorded in 3 × 3 m plots in May 2008. Vascular plant species were identified according to Van der Meijden (2005); the cover of each species was estimated according to a modified scale of Braun-Blanquet (Barkman et al., 1964). At each site, vascular plant species richness and diversity were determined. Diversity was calculated according to the Shannon–Wiener index (Shannon, 1948) based on the midpoints of the Braun-Blanquet classes (Wikum and Shanholtzer, 1978). Plant community composition was related to the environmental conditions with canonical correspondence analysis (CCA) using Canoco 4.0 (Ter Braak and Šmilauer, 1998). Distributions of the environmental variables were

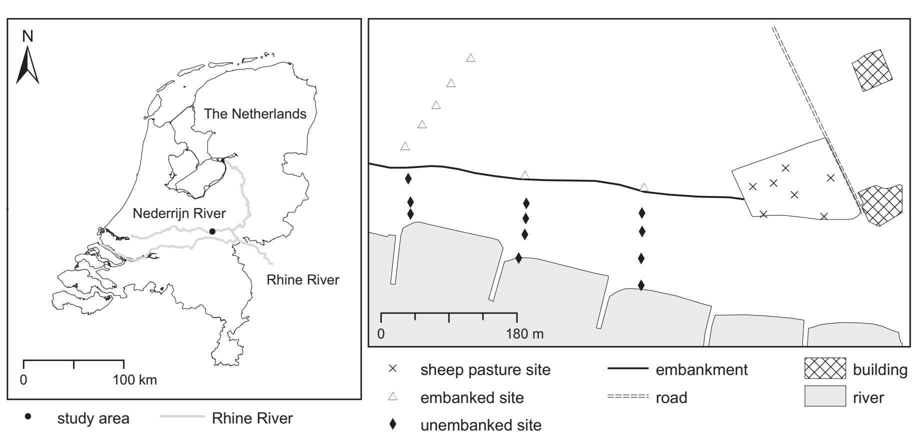

Fig. 1. Location of the “Wolfswaard” floodplain (left) and sampling sites (right).