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Effects of farmland shelterbelts on accumulation of soil nitrate in agro-ecosystems of an oasis in the Heihe River Basin, China

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ABSTRACT

Using tree shelterbelts to protect adjacent crops from the destructive effects of wind, wind-driven particles, direct sunlight, and extreme climatic conditions is a common agricultural practice. Trees and crops, however, will inevitably compete for the same water and nutrient resources, especially along their common border. This study evaluated the effects of shelterbelts on the amounts of nitrate and water in the adjacent cropland soils under field conditions in an oasis-desert ecotone in the Heihe River Basin, China. Nitrate contents were measured in an experimental plot during the cropping season to a depth of 300 cm in a poplar/wheat system at distances of 2, 14, 29, and 42 m from the shelterbelt with three replicates in the soil profiles. Both soil-water content and crop yield increased with distance from the shelterbelt. Nitrate concentrations in the soil, however, generally decreased with distance from the trees and with depth. Nitrate concentrations in the 200–300 cm layer were much higher at distances from the shelterbelt of 2 and 14 m than at 29 and 42 m, indicating that more nitrate accumulated in deeper layers closer to the shelterbelt. A survey of nitrate accumulation in nearby fields supported these findings. The higher amount of residual nitrogen (N) closer to the shelterbelt was due to the shading of the crop by the trees that reduced N uptake, mineralization of soil organic matter, and accumulation of litter and increased the lateral movement of nitrate. The accumulated N compensated for the N lost due to the interception and uptake by nearby trees. Nitrates likely leached into and polluted the groundwater. Decreasing N fertilization near the trees and partial replanting of the shelterbelt should be considered for managing nitrate levels in the region.

1. Introduction

Trees and crops interact when grown in close proximity. The effects of this interaction on crop growth can be either beneficial, such as when soil fertility or microclimatic conditions are improved, or detrimental, such as during competition for water, light, and nutrients. Trees can act as protective windbreaks (Peri and Bloomberg, 2002; Brandle et al., 2004), but many studies have suggested that competition between shelterbelts and crops can decrease crop yields (Matta-Machado and Jordan, 1995; Heinemann et al., 1997). Reductions in crop yields have been associated with reduced soil water due to the uptake of water by tree roots, shading by nearby trees, and competition with trees for soil nitrate-nitrogen (e.g. Lisanework and Michelson, 1993; Onyewotu et al., 1994; Kowalchuk and de Jong, 1995). Soil-water content (SWC) and nitrate concentrations (NCs) consequently tend to decrease with increasing proximity to shelterbelts, especially in alley cropping systems (Miller and Pallardy, 2001; Liversley et al., 2002; Liversley et al., 2004; Shen et al., 2014). The integration of perennial trees in a farming system, however, can also increase agricultural productivity (Bird, 1998; Nuberg, 1998; Campi et al., 2009), mainly due to the beneficial effects that trees can have on the conservation of soil water in cropland. Shading and reductions in wind speed can reduce evaporation, and infiltration can be increased by the presence of mulch layers created by litter from the trees that, together with the tree roots, can improve soil structure (Torquebiau and Kwesiga, 1996; Young, 1997; Brandle et al., 2004). Cannell et al. (1996) formulated the central hypothesis of agroforestry that trees must acquire resources that a crop would otherwise not use. Minimizing resource competition between trees and crops, while maximizing the use of available resources, is thus central to improving yields and overall productivity in agroforestry systems.

The competition for water between trees and crops is the principal determinant of crop productivity in agroforestry systems in semi-arid regions (Liversley et al., 2000; Muthuri et al., 2005).

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Both above- and belowground competition between trees and crops occur in agroforestry systems. Yield suppression within a zone of competition is most likely due to the competition for soil water between crops and shelterbelts (Jose et al., 2000a; Hou et al., 2003), in which N plays a relatively minor role (Jose et al., 2000b). The zone of competition is partly formed in cropland areas by adjacent trees that have extended their roots laterally for a few meters to use the water and other resources in the cultivated soils; trees with deeper roots can also take up groundwater from deeper layers (Shen et al., 2014; Woodall and Ward, 2002). SWC in an alley cropping system varies with the distance from a tree row (Liversley et al., 2004). Planted trees can considerably reduce losses of water by drainage, so tree roots may also take up nutrients that would otherwise be lost due to leaching (Shepherd et al., 1996; Liversley et al., 2002).

The availability of water is a limiting factor for plant production in the arid regions of northwestern China (Feng et al., 2000; Wang and Cheng, 2001). Rainfall in the Hexi Corridor desert oasis in China is insufficient to meet the evapotranspiratory demands of the atmosphere, but irrigation and fertilization in this area supply sufficient water and nutrients for agriculture (Ding and Su, 2010). Gansu Poplar (*Populus gansuensis* C. Wang and H.L. Yang), characterized by rapid growth and development, has been planted to create farmland shelterbelts on more than 50 000 ha in the Hexi Corridor desert oasis. These shelterbelts are vital for improving the environment and the sustainability of the ecosystem of the central Heihe River Basin, but the poplars also require a considerable amount of water to maintain their growth and/or to ensure their survival. Sap flow in irrigated poplar shelterbelts is as high as $233 \pm 82\,kg\,m^{-2}\,h^{-1}$, but the tree roots are able to reach the groundwater when SWC is insufficient to support transpiration, as reported by Chang et al. (2006) for field experiments in the same area as our study.

The objective of this study was to determine the effect of shelterbelts on the crops and soils of adjacent farmland, including the effects on the variations in SWC and NC with distance from the shelterbelt. SWC and NC were measured to a depth of 300 cm in 2013 and 2014. We hypothesized that trees with larger nutrient uptakes would have a greater competitive effect on the adjacent crops, which would lead to reductions in SWC and nutrients near the trees.

2. Materials and methods

2.1. Study site

The study was conducted at the Linze Inland River Basin Comprehensive Research Station in the center of the Heihe Basin, 2 km northeast of the town of Pingchuan in Linze County, Gansu Province, China (39°18′–39°24′N, 109°56′–100°10′E; 1374 m a.s.l.) (Fig. 1a). The area has a continental arid temperate climate. The mean annual precipitation is 117 mm; 60% of the total precipitation, which is generally of low intensity, falls during July-September, and only 3% falls during winter (Zhao et al., 2010). The annual air temperature is 7.6 °C, the mean annual open water evaporation is 2390 mm, and the area has 165 frost-free days (Chang et al., 2006). The main land uses are crops of maize (*Zea mays* L.), spring wheat (*Triticum aestivum* L.), and cotton (*Gossypium hirsutum* L.), forests (shrubland areas, poplar shelterbelts, and riparian zones), unused land (Gobi desert, wilderness, and desert), wet areas (wetlands and reservoirs), and residential areas (Liu et al., 2010).

The soils in the area were sandy and tended to have higher clay and silt contents below about 140 cm. The higher sand contents in the upper layers in the oasis were due to the deposition of fine sandy windborne material from the desert area on top of the loessial soils. The soils were well drained, especially the upper layers, and had high saturated hydraulic conductivities ($50\,cm\,d^{-1}$) but also low water-holding capacities. The gravimetric SWC at saturation was $0.35\,cm^3\,cm^{-3}$ and the field capacity was $0.21\,cm^3\,cm^{-3}$ in the 0–140 cm layer.

2.2. Experimental plot site

2.2.1. Plot location

The field experiments were conducted in a 48 × 20 m experimental plot in a selected cropland/shelterbelt system at the edge of a new oasis established in the 1960s. A narrow shelterbelt (two rows) had been established on the west side of a cropland in the 1970s by manually planting seedlings of Gansu Poplar. The border of the plot was approximately 0.9 m from the trees. The mean tree diameter at breast height and the mean height were 244 mm and 20 m, respectively, at the time of the study.

2.2.2. Cultivation

The plot had been uniformly planted with maize prior to growing spring wheat during March to July from 2011 to 2014. The plot was surrounded by a maize border (Fig. 1b). Wheat was seeded at a rate of $140\,kg\,ha^{-1}$ and was fertilized with 170 kg $(NH_4)_2HPO_4\,ha^{-1}$ and 135 kg $NH_4NO_3\,ha^{-1}$ at the time of sowing in March; the fertilizer was mixed with the seed so was applied immediately below the soil surface at the same depth as the seeds. An application of 150 kg $CN_2H_4O\,ha^{-1}$ was manually broadcast over the plot in May. A total of $150\,kg\,N\,ha^{-1}$ was thus applied to the plot each year of the study period. The plot was irrigated during the growing season with 90 mm of well water on 20 April, 23 May, 9 June, and 29 June in 2013 and on 7 May, 30 May, and 20 June in 2014. The plot was irrigated twice with river water in March (before sowing) and in October (before the soil froze). The entire cropland area was tilled annually in October before the soil froze. The wheat was harvested on 26 July 2013 and 15 July 2014.

2.2.3. Soil sampling and groundwater-level monitoring

Soil samples were collected from the plot at distances of 2, 14, 29, and 42 m from the shelterbelt; three replicates were collected along a row of wheat perpendicular to the shelterbelt (Fig. 1c). These distances were used because of their proximity to temporary groundwater wells used for water sampling. The samples were collected from 300-cm soil profiles at depth intervals of 20 cm at each of the four distances on four occasions (21 July and 19 September 2013, and 17 April and 10 May 2014), 8–9 days after irrigation. The samples were analyzed in the laboratory for gravimetric SWC and NC. Gravimetric SWC was determined from the loss of mass during complete oven-drying at 105 °C and expressed as a percentage indicating the ratio of the mass lost to the dry-soil mass. A 10-g subsample of each sample was extracted with 50 mL of $1\,mol\,L^{-1}$ KCL for 30 min, and nitrate-N and ammonium-N concentrations were measured using an Autoanalyzer 3 digital colorimeter (Bran + Luebbe, Norderstedt, Germany). One of the replicate samples collected in May 2014 was also analyzed for total C and N. Total C concentration was determined by digesting samples with potassium dichromate and H_2SO_4 followed by automatic titration, and total N concentration was determined by digesting the samples with H_2SO_4 followed by distillation, and the total carbon:nitrogen (C:N) ratio was then calculated.

Four temporary wells for monitoring groundwater levels had been established in the plot in 2011. The wells were close to the rows used for soil sampling at four distances from the shelterbelt. The groundwater level was automatically recorded hourly by a HOBO U20-001-04 water-level logger (Onset Computer Corporation, Bourne, USA). The groundwater level in the four wells had a