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THE POTENTIAL FOR POPLAR AND WILLOW SILVOPASTORAL SYSTEMS TO MITIGATE NITRATE LEACHING FROM INTENSIVE AGRICULTURE IN NEW ZEALAND

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Abstract

In New Zealand, nitrate (NO_3^-) leaching is a major environmental problem associated with intensive agriculture. Research suggests that plants with deeper roots and high evapotranspiration rates, such as poplars (*Populus)* and willows *(Salix)*, may reduce NO_3^- leaching. In New Zealand, willows and poplars have largely been studied in relation to their soil conservation benefits, use as stock fodder, biomass production and phytoremediation of contaminated soil. This review compiles information on the use of poplars and willows in agricultural systems and explores their potential application to the management of NO_3^- leaching. Studies show reduced NO_3^- leaching under short rotation coppice willows. However, the establishment and harvesting phases are risk periods for NO_3^-leaching where nitrogen application should be avoided. A case study has identified a potential for role of poplar and willow silvopastoral systems on intensively-managed irrigated farms of the Canterbury Plains. Height restrictions due to overhead irrigation, stock fodder value and the need to restrict light competition with pastures suggest *Salix viminalis* (with annual coppicing) is the most suitable species for integration into these farms. Further research is needed to quantify both the possible reduction in N losses and the additional on and off-farm benefits of poplar and willow silvopastoralism in the context of intensive farming in New Zealand.

Introduction

In New Zealand, nitrate (NO_3^-) leaching is a major environmental problem associated with intensive agriculture. Nitrogen (N) inputs have increased in line with recent conversion of dryland farms to high-production irrigated agriculture, particularly dairy farming (Ministry for the Environment, 2007). Pastures are often not able to utilise all the N received as fertilisers, effluents or animal excreta, and despite best management practices, a portion is leached into ground and surface waters (Cameron, Di, & Moir, 2013). Such N losses not only endanger human health and the environment but also reduce soil fertility, plant yield and economic gains (Cameron et al., 2013).

Silvopastoral systems that combine livestock, pasture and trees could reduce total farm NO_3^- losses, while incurring a minimal reduction in grazeable land (Bambo, Nowak, Blount, Long, & Osiecka, 2009). Potentially, trees can reduce NO_3^- leaching through soil compared with pastures.

Plant uptake and transpiration, as well as root-induced changes to the physical, chemical and microbial properties of soil may influence nitrogen transport.

Poplars (*Populus spp.*) and willows (*Salix spp.*) are promising tree species for silvopastoral N management systems in New Zealand. Both are members of the Salicaceae, introduced to New Zealand in the 1800's. These species are fast growing and easy to propagate vegetatively (Dickmann & Kuzovkina, 2008). Following unsuccessful cultivation for timber, poplars and willows became widely used for erosion control, river bank stabilisation and for shelter (Wilkinson, 1999). A wide variety of poplar and willow clones have been developed for growth in New Zealand (Wilkinson, 1999).

Poplars and willows have high biomass production, which may facilitate N extraction (Rockwood et al., 2004). In addition, these trees have deeper root systems than pasture species, thus are able to capture N draining through soil at depths unreachable for common agricultural plants (Licht & Schnoor, 1993; Pilipovic, Orlovic, Nikolic, & Galic, 2006). Both are phreatophytes and are also known to remove NO_3^- locally present in groundwater, either via uptake processes or enhanced denitrification aided by root exudates (Hirsh, Compton, Matey, Wrobel, & Schneider, 2003; Schnoor, Light, McCutcheon, Wolfe, & Carreia, 1995). A reduction in NO_3^- leaching following land application of dairy-farm effluent can be achieved through irrigation onto a field planted with poplar and willow species under short-rotation, as an alternative to pasture application (Roygard, Clothier, Green, & Bolan, 2001). The N retrieved in plant biomass can then be fed back to the animals as fodder (Robinson et al., 2003).

Land conversion to intensive agriculture provides an opportunity to implement poplar and willow plantings for NO_3^- management in strategic locations on farms. Poplars and willows are capable of regrowth following cutting (coppicing) or grazing. Maintenance at a low stature through regular coppicing would allow planting in an intensive silvopastoral system, where an irrigation system could pass overhead.

This review compiles local and international information on the impact of poplars and willows on NO_3^- leaching and provides an overview of the additional value these species could provide to agricultural systems. Through a case study, we explore their potential role in NO_3^- management in Canterbury, New Zealand.

Impact of poplars and willows on nitrate leaching

Plantations receiving fertilisers

Plantations of poplars and willows established for biomass production have often been fertilised with N to enhance growth. Data from fertilisation trials offers information on the potential of these species to intercept N in soil drainage waters and thereby reduce NO_3^- leaching in silvopastoral systems. Greater NO_3^- losses have been observed from blocks of poplar (*P. maximowiczii* × *P. nigra*) than willow (*S. viminalis*) following fertilisation over the first 2 years of growth (Balasus, Bischoff, Schwarz, Scholz, & Kern, 2012). Leaching was low (<7 kg N ha^{-1} $year^{-1}$) when up to 120 kg N ha^{-1} $year^{-1}$ was applied to *S. viminalis* × *S. schwerinii* during the productive growth phase, but higher rates of 240 and 360 kg N ha^{-1} caused leaching of 66 and 99 kg N ha^{-1} $year^{-1}$, respectively (Sevel et al., 2014). In the third year post-establishment leaching from an *S. viminalis* plantation treated with 75 kg N ha^{-1} was low and similar to an unfertilised control plantation (Mortensen, Nielsen, & Jorgensen, 1998). Goodlass, Green, Hilton, and McDonough (2007) note that the consistently low levels of leaching observed during the productive management phase of plantations receiving low-moderate fertiliser rates indicates that these species have a potential role in N management.

Plantations receiving effluents and wastewater

Improved management of N in land-applied wastes has been achieved through planting poplars and willows as short rotation forests (Kutera & Soroko, 1994; Roygard et al., 2001; Sims & Riddell-Black, 1998). In Poland, reductions in N load of up to 75 % were achieved by flood irrigating municipal sewage to *P. gelrica* plantations (Kutera & Soroko, 1994). In New Zealand, lysimeter trials have shown that less N leaching occurs beneath *S. kinuyanagi* receiving dairy effluent compared with two eucalyptus species, however, the larger drainage volume from *S. kinuyanagi* meant total N losses were similar (Roygard et al., 2001). An average of 35 kg N ha^{-1} yr^{-1} was leached beneath *S. kinuyanagi* when effluent was applied at 612 kg N ha^{-1} yr^{-1}; this resulted in drainage water NO_3^--N concentrations that were below the limits for New Zealand drinking water (Roygard et al., 2001). Comparatively higher rates of 70 and 90 kg N ha^{-1} yr^{-1} were leached from *S. viminalis* receiving wastewater at only 320 kg N ha^{-1}, on clay and sandy soils respectively (Dimitriou & Aronsson, 2004).

Potential for nitrogen uptake in biomass

Nitrogen uptake from effluent and wastewater is highest in high biomass producing tree species used as short rotation energy crops, resulting in lower NO_3^- leaching (Guo, Sims, & Horne, 2002; Pandey, Singh, Srivastava, & Vasudevan, 2011; Tzanakakis, Paranychianakis, & Angelakis, 2009). A range of New Zealand-based studies report increased yields following effluent application to poplars and willows and large amounts of nutrient storage, particularly for species with high growth rates (Guo et al., 2002; Nicholas, 2003; Roygard et al., 2001; Sims & Riddell-Black, 1998). High growing-season biomass of a *Populus* sp. riparian buffer planting has been shown to facilitate the immobilisation of more N in plant material than grass buffer zones or adjacent crop fields (Tufekcioglu, Raich, Isenhart, & Schultz, 2003).

Amongst poplar and willow species and cultivars, annual biomass production is likely linked to N uptake rates. A European study of six *Salix viminalis* clones found that with annual coppicing all clones produced a similar annual yield, 15 t ha^{-1} yr^{-1} of dry material (Stolarski, Szczukowski, Tworkowski, & Klasa, 2008), so little difference in N uptake is expected between these species. Snowdon, McIvor, and Nicholas (2013) suggest that with new clonal material being released, improved silvicultural techniques and better pest and disease management strategies dry yields between 12 and 18 t ha^{-1} $year^{-1}$ should be possible under New Zealand conditions. In a trial near Taupo, *S. schwerinii* produced 14 t ha^{-1} yr^{-1} and *S. viminalis* 11.9 t ha^{-1} yr^{-1} (Snowdon et al., 2013). 'Tangoio' willows (*S. matsudana* x *S. alba*) irrigated with effluent equivalent to 250 and 500 kg N ha^{-1} yr^{-1} produced 13 t ha^{-1} and 24 t ha^{-1} biomass respectively during the first year of growth, with proportionally higher N uptake into plant material at the higher N application rate (Snow et al., 2003).

Variation in foliar N concentration may additionally contribute to species-specific N uptake rates. The N stored in above-ground biomass of *S. kinuyanagi* has been reported at 122 g N $tree^{-1}$, higher than the *Eucalyptus* species in the same study (Roygard et al., 2001). Leaf nitrogen concentrations were higher for poplars (3.5-3.7 %) than willows (2.8-3.2 %) receiving 500 kg N ha^{-1} yr^{-1} and there was a trend of increasing concentration with increasing N application rate (Snow et al., 2003).

Nitrate leaching under short rotation coppice poplars and willows

Much of the research quantifying the effects of poplar or willow on NO_3^- leaching relates to short rotation coppice (SRC) systems in the Northern Hemisphere. A range of studies observe a spike in NO_3^- leaching during establishment of SRC willow plantations and conclude that nitrogen application should be avoided in the year of planting (Aronsson & Bergström, 2001; Goodlass et al., 2007). The first year after planting *S. viminalis* on high-nutrient agricultural soils in Denmark, an average of 32 kg N ha^{-1} was leached in excess of that from unfertilised trees (Mortensen et al., 1998). A flush of mineralisation and increased NO_3^- leaching was observed following the complete removal of a *P. deltoides* coppice block (Goodlass et al., 2007). Given the life-span of SRC (15-30 years), the relatively large NO_3^- losses on establishment and coppice removal needs weighing against the reduced losses during the active growth phase (Goodlass et al., 2007). Fertilisation is not recommended in the first year following coppice or the final year before harvest to avoid high soil N levels at times when minimal plant growth occurs.

Role of denitrification

Denitrification is a desirable mechanism for N removal from soil because this bacterial process converts NO_3^- to N gases, permanently removing N from the soil-water system (Martin, Trevors, & Kaushik). Increased denitrification has been observed in soils beneath poplars compared with pasture (*Lolium perenne*). This was attributed to leaf litter organic C inputs (Haycock & Pinay, 1993). In another study denitrifiers were significantly more abundant in the rhizosphere of poplars compared with surrounding soils (Jordahl, Foster, Schnoor, & Alvarez, 1997). The production of nitrous oxide (N_2O) during denitrification is less desirable than N_2 production, as N_2O is a potent greenhouse gas. Fertilisation of *S. viminalis* with 50 kg N ha^{-1} yr^{-1} caused an increase in N_2O of 0.1–0.2 kg N ha^{-1} yr^{-1} above control levels, but poplars (*Populus maximowiczii* × *P. nigra*) showed a lesser increase (Balasus et al., 2012). Despite an increase in N_2O following N application to poplars or willows, this may be less than that experienced in the surrounding pastures of a silvopastoral system. Nitrous oxide emissions of 1.0-3.7 kg N ha^{-1} have been recorded from grazed pastures following fertilisation at 50 kg N ha^{-1} in New Zealand(L. Smith, deKlein, & Catto, 2008).

Additional value to agricultural systems

Poplars and willows may provide a range of other services within an agricultural system, which may enhance farm productivity and provide incentives to convert to a silvopastoral system (summarised in Table 2).

Reduced soil erosion

Poplars and willows have proved effective in reducing soil erosion on pastoral slopes (Ball, Carle, & Del Lungo, 2005). They achieve this through the development of an extensive root system which interconnects with root systems of adjoining trees to form a reinforcing network across a slope (Wilkinson, 1999). Controlling erosion reduces soil losses and retains the nutrients and organic matter in topsoil on-farm to contribute to pasture production (Wilkinson, 1999).

Value as stock fodder

Willow and poplar tree fodders constitute a valuable feed supplement for livestock grazing summer-dry pasture as they are highly digestible with beneficial concentrations of condensed tannins (McWilliam, Barry, & López-Villalobos, 2005). Kemp, Mackay, Matheson, and Timmins (2001) found the edible forage dry matter of 5-10 year old poplar and willow trees ranged from 2–22 kg per tree and no differences in digestibility, crude protein and metabolisable energy between cultivars. Analysis of condensed tannins among willow cultivars identified *S.viminalis* as highly digestible (J. Smith, Kuoppala, Yáñez-Ruiz, Leach, & Rinne, 2014).

Provision of shade and shelter for livestock

Dairy cows in New Zealand that have access to shade have been shown to increase milk solid production by 3% (Goulter, 2010). Bloomberg and Bywater (2007) suggest that shade can eliminate heat stress in cows and that shelter from wind is also beneficial. Use of coppiced willow or poplar in planted rows is likely to reduce the wind speed experienced by the cows. This reduction in wind speed may also help mitigate irrigation losses through evaporation which can be as high as 10% in sprinkler systems during strong winds (Millner, Roskruge, & Dymond, 2013).

Use of wood waste for stand-off pads and bedding

Farmers are increasingly moving cows out of paddocks and onto stand-off pads or out-wintering pads, an outdoor wintering system for cattle to protect wet soils from damage and excess N losses during winter (Luo, Donnison, Ross, Ledgard, & Longhurst, 2006). Stand-off pads can be built by placing a layer of wood residue over an artificially drained surface. The wood residue traps animal excreta to control solid and liquid wastes from animal confinement (Augustenborg, Carton, Schulte, & Suffet, 2008). Poplar and willow grown in short-rotation systems could be chipped to provide wood residue for out-wintering pads or barn bedding, a valuable on-farm use for this biomass.

Potential income through off-farm production

Poplar and willow are grown commercially for biofuel due to their rapid growth rate and favourable energy ratio. Snowdon et al. (2013) suggest farmers could diversify their business and create resilience by growing willow and targeting the expanding energy biomass market. The extraction of xylitol from willow biomass for use in the food and pharmaceutical sectors offers another potential income stream once techniques are refined (Snowdon et al., 2013).

Table 2 Summary of the benefits of planting set-aside pastoral land with poplar and willow identified by Snowdon et al. (2013) and Young (1997).

Potential Benefits	Potential Adverse Effects
Reduced environmental impact	Reduction in land for grazing
Nitrate management	Shading of pastures
Effluent and waste water treatment	Less water for pasture
Phytoremediation	Competition for nutrients
Reduced greenhouse gas emissions	Allelopathy
Reduced erosion and sediment transport	
Enhanced on-farm production	
Shelter and shade for stock	
Wood chip for bedding or standoff pads	
Soil conservation	
Supplementary stock fodder	
Water holding capacity	
Soil organic matter	
Off farm productive uses	
Production of bioenergy	
Pulp and paper industry	
Ecosystem services	
Habitat for native biodiversity	
Soil faunal diversity and activity	

Further considerations for implementation

Potential interactions between willows or poplars and pastures in dairy grazing systems may arise from competition for water, light or nutrients, reducing the growth of surrounding pasture. The spatial arrangement and structure of tree plantings influence the degree of tree/crop interactions. Manipulation of shade levels through tree stocking rate, directional orientation of rows, thinning, and pruning management have potential to minimise impacts on pasture production (Power, Dodd, & Thorrold, 2001). *Salix viminalis*, which has a relatively low leaf area, many thin stems and few side branches may be a good choice to minimise the impact of tree shade (McIvor, Snowdon, & Nicholas, 2009).

The windbreak effect can reduce evapotranspiration and the tree roots can aid soil water infiltration, leading to positive effects on pasture growth (Wallace, Young, & Ong, 2005). However, in regions with low rainfall, trees are more prone to compete with pasture for water (Young, 1997). In such environments, systems with composite hedges (e.g., two lines of trees) and wide alleys will aid pasture growth (Young, 1997).

Substantial competition with pasture for nutrients has not often been demonstrated for poplars and willows, as pastures have shallower roots minimising competition (Young, 1997). Allelopathy is also not of concern, with both willows and poplars frequently grown successfully in association with pastures.

Case study: Poplars and willows to mitigate nitrate leaching from stony soils on the Canterbury Plains, New Zealand

Irrigation is essential for intensive dairy farming in the dry Canterbury Plains region of South Island, New Zealand, yet leads to increased NO_3^- leaching, particularly on light stony soils (Lilburne, Webb, Ford, & Bidwell, 2010). The vulnerability of these soils to NO_3^- leaching may make it difficult for land owners to meet increasingly stringent water quality regulations under current management practices. Currently many stony soils previously under forestry or low-intensity agriculture are being converted to irrigated dairy farms. Willows and poplars could be planted to reduce NO_3^- leaching on stony soils. These trees could be maintained at a low height through regular cutting, allowing centre-pivot irrigators to pass overhead, or alternatively planted in paddock corners, edges or as set-aside blocks.

Precision application of irrigation water and fertiliser to match plant growth requirements currently forms a major component of farm NO_3^- leaching mitigation. Complementary leaching mitigation strategies should account for the requirements of overhead spray irrigation equipment. Therefore the height of planted poplars and willow must be constrained to <1.75-2.0 m for low-profile pivots, <2.75-3.0 m for standard profile pivots, and <3.9-4.0 m for high profile pivots. *Salix viminalis* is a suitable species for this situation and provides high stock fodder value. The clone 'Gigantea' is the most studied and understood in New Zealand, however it is possible that other clones available either locally or internationally may be more suitable.

In the areas outside the overhead irrigator, more traditional coppicing rotations with triennial harvesting may be possible. Excess dairy effluent could be sprayed into these stands to recycle the nutrients and promote growth, without causing excess NO_3^- leaching. Although traditional rotations may produce higher total biomass from each tree, this fodder would not be available consistently year-on-year.

Despite the high initial investment in planting poplars and willows in a silvopastoral system, the wide range of uses for the biomass produced may increase the economic viability. In particular, the use of the plant materials produced as stock fodder and as wood residue for feed pads and wintering sheds, provides a way to recycle nitrogen within the farms system, reducing other costs.

Conclusions

Poplars and willows have the potential to provide a low nutrient-emitting yet commercially viable land use, thereby reducing the impact of intensive agriculture on surface and groundwater quality. Current land clearance during conversion to intensive agriculture, such as that occurring on the Canterbury Plains, provides an opportunity to implement poplars and willows for strategic NO_3^- management. These deep rooting species could intercept leached N at greater depths than the root zone of pastures and their high growth and evapotranspiration rates are likely to enhance N uptake. The nutrients incorporated into above-ground biomass may then be harvested for on-farm uses, such as stock fodder and bedding, or processed for off-farm commercial uses. Short rotation crops also have potential to treat wastewaters such as dairy-effluents. There is a need to both quantify the possible reduction in N losses when poplars and willows are used in intensive silvopastoral systems and quantify the economic benefits provided through on and off-farm uses.

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