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Intercropping reduces nitrate leaching from under field crops without loss of yield: A modelling study

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Abstract

A model of soil nitrogen dynamics under competing intercrops is described and used to interpret two sets of experimental field data from the literature. In one series of experiments, maize received slurry and mineral nitrogen (N) fertiliser or mineral N alone and was grown either alone or intercropped with undersown grass or with a subsequent rye catch crop during 7 years continuously. In the second system, the model compares field beans intercropped spatially at different densities with winter wheat.

The model suggests that undersowing grass between the rows of an established maize crop can reduce concentrations of nitrate in water draining from soils during winter by 15 mg l^{-1} compared with a conventional catch crop and by more than 20 mg l^{-1} compared with a fallow soil. The model further suggests that the yield and profitability of mixed stands of commercial crops is inversely related to the residual nitrate at harvest (potential leaching). It is concluded that intercropping may be a useful means to reduce nutrient pollution from farming while maintaining yields.

Keywords: Intercropping; Model; Nitrogen; Leaching; Environment

1. Introduction

Farming profitably within increasingly stringent environmental norms is becoming difficult. Although some crops such as cereals and sugar beet leave little soil mineral nitrogen (N) behind at harvest, other crops such as maize, potatoes, vegetable crops and legumes either leave considerably more or leave residues that release N during the winter. Where excess winter rainfall is less than 100–200 mm, even water leaving land that has grown cereals is at risk of having a concentration of nitrate in it that exceeds limits in current water quality legislation (Anon., 2000; Whitmore and Addiscott, 1986).

Intercropping, defined here as any system of multiple cropping in space, has a long and successful history in tropical regions (e.g. Trenbath, 1993; Tsubo et al., 2005). Not only has the technique been shown to increase yields (De Wit and Van Den Bergh, 1965) but it is also a useful means of spreading risk: if one crop fails another may still provide sufficient food until the next harvest (e.g. Trenbath, 1999). In developed countries and conventional cropping systems, monoculture has proved the rule, with the exception of some grass–clover mixtures, probably because of the ease of combining or lifting a single crop with machinery. Despite this, theoretical and experimental work has pointed to the potential benefits of mixtures of species or varieties. De Wit and Van Den Bergh (1965) showed that where two annual grasses do not compete for a resource, yields per m^2 may be significantly greater than under monocropping; Bulson et al. (1997) and Hauugaard-Nielsen et al. (2006) have demonstrated this more widely. However, Ghaffarzadeh et al. (1997) who investigated water supply, and Ayisi et al. (1997) and Lesoing and Francis (1999) who both investigated N supply, have shown that these benefits may not extend further than one row where species intercropped with one another do not alternate row by row. Intercropping has also been shown to control the spread of pests and disease (Trenbath, 1993; Zhu et al., 2000) and has been suggested as a means to help control erosion (Lesoing and Francis, 1999). These results point to clear benefits in productivity by planting intercrops that do not compete with each other, because resources are used efficiently. This raises the question as to whether crops that *do* compete for a nutrient might be successfully intercropped with one another in the field in order to control environmental losses of that nutrient.

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Schröder et al. (1996) have shown that undersowing maize with a grass crop can recycle N that would otherwise leach in winter. Known as a relay crop, the grass is an intercrop while the maize is in the ground, but is largely out-competed. The relay crop then remains in the soil during the winter as a sole crop. Schröder et al. also included a conventional catch crop in their experiments. The extra N-supply from the winter crops could be detected in maize crops given less N the following year than expected for maximum growth, implying that the winter crops could replace fertiliser N. Hauugaard-Nielsen et al. (2003) found a small reduction in nitrate leaching ($kg\,ha^{-1}$) from lysimeters cropped with a pea–barley mixture compared with sole crops, although much of this difference may be attributable to differences in the N-content and rate of decomposition of roots and residues. Where the intercrops have a sequential demand for that nitrogen, yields (and profit) might be maintained but the losses of N reduced.

This article describes the adaptation of an existing computer simulation model (Addiscott and Whitmore, 1987; Whitmore et al., 1991; Whitmore, 1995, 2007) to intercropping systems and an analysis of the potential of intercropping to reduce nitrate leaching from modern-day agriculture. Although there are other potential benefits of intercropping such as the prevention of the spread of disease, management of risk, or suppression of weeds (e.g. den Hollander et al., 2007) these benefits will not be quantified here. Others have published models of intercropping and nitrogen dynamics (Berntsen et al., 2004; Brisson et al., 2004). We differentiate our research from this earlier work by focussing chiefly on the soil processes and analysing both soil mineral N and leaching losses of N.

2. Methods

2.1. The model

The model used in this study has been described by Addiscott and Whitmore (1987) with some adaptations by Whitmore et al. (1991) and Whitmore (1995) and by Whitmore and Schröder (1996) for maize, but will be described here briefly for completeness sake. The model system now incorporates organic nitrogen dynamics as described by Whitmore (2007).

2.1.1. Leaching

Addiscott and Whitmore (1987) describe a dual-porosity model of the leaching of solutes added to soil. Moisture in soil is held either between aggregates (mobile water, w_m) and can be displaced by incoming water, or held within aggregate pore space (retained water, w_r). For the 50 mm layers employed in the model the following definitions apply, where θ_{FC} is the volumetric moisture content of soil at −5 kPa ($mm^3\,mm^{-3}$), $\theta_{200\,kPa}$ the volumetric moisture content at −200 kPa and $\theta_{1.5\,MPa}$ the volumetric moisture content at −1.5 MPa:

$$w_m = 50(\theta_{FC} - \theta_{200\,kPa}), \qquad w_r = 50\left(\theta_{200\,kPa} - \frac{\theta_{1.5\,MPa}}{2}\right) \tag{1}$$

Solutes move down the profile with the mobile water, w_m, as described by Addiscott and Whitmore (1987). A fast leaching routine is incorporated (Addiscott, 1977) in order to simulate bypass flow following heavy rainfall.

2.1.2. Crop growth, N uptake and development

Dry matter production is estimated from a simple relationship with incoming radiation (Whitmore, 1995). N uptake and rooting depth are estimated using a simplified logistic function (Whitmore and Addiscott, 1987):

$$Y = (A^{-1/n} + e^{-kx})^{-n} \tag{2}$$

where Y is the N uptake or rooting depth, n distorts the symmetry of the curve and was set at 1.5 for all crops (Whitmore and Addiscott, 1987), k a rate constant and x is the thermal time (the accumulation of the average daily temperature above 0 °C). The parameter A is the maximum value Y is allowed to take: 200, 250, 250 or 250 $kg\,N\,ha^{-1}$ for N uptake with wheat, grass, maize or beans, respectively. The maximum potential rooting depth of winter wheat, maize and the rye catch crop was set at 150 cm, and at 50 cm for beans and for grass. The amount of root in each layer declines with depth of soil exponentially in the manner proposed by Gerwitz and Page (1974) with values of the depth containing $1/e$ of the total potential proportion of roots being 43 cm for wheat, maize and rye and 20 cm for grass and beans. For crop N uptake and rooting, k was set at 0.003 and 0.005 $°C^{-1}\,day^{-1}$, respectively.

Crop development follows that proposed by Weir et al. (1984). Growth and development of maize and allocation of assimilate to roots and below-ground exudation for all crops is as described by Whitmore and Schröder (1996) using parameters derived from Van Diepen et al. (1989). Development of beans follows that proposed by Bouniols et al. (1991).

Winter crops are susceptible to cold but may also develop acclimation (Pomeroy et al., 1975). These processes were modelled as proposed by Fowler et al. (1999) who describe the calculation of the temperature LT_{50} that kills 50% of a crop. Because we are interested here in the death of a proportion of the crop, these LT_{50} values were scaled back arbitrarily by the ratio of the actual temperature to the LT_{50} value and crop die-back calculated whenever the minimum temperature fell below −3 °C.

2.1.3. Organic matter turnover and mineralization–immobilization turnover of N

A part of the soil organic matter turnover in soil is envisaged in the model (Whitmore, 2007; Whitmore et al., 1997; Vinten et al., 2002) to be physically protected (Hassink and Whitmore, 1997) from microbial attack (Whitmore, 1996a,b; Whitmore and Groot, 1997). The rate of protection is proportional to the fraction of the maximum amount, X, of organic carbon that the soil may stabilise that is already occupied by soil organic carbon (SOC). Values of X, which was found to be a function of clay content, are given in Section 2.2. Whether N mineralizes or is immobilized during the turnover of each compartment depends on the C:N ratio of each compartment (Whitmore and