Research Application Summary

Developing management options for optimising water and nitrogen utilisation for maize production in Malawi

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Abstract

Nitrogen (N) is the most important determinant of plant growth and crop yield. Plants lacking N show stunted growth and yellowish leaves. Plant growth and crop yield usually increase when N is added. However, too much N lead to weak stems in grain crops, reduce fruit quality, lower sugar content in sugar beets, accumulation of nitrate in the edible foliage of plants, and can contaminate groundwater. The crop production and environmental challenges associated with low and excess N prompt a need to generate knowledge of optimum amounts of N that can give desirable crop yields while avoiding excess N-induced problems. Owing to the complexity of soil, models can be used to infer N characteristics in soil and ascertain its disposition pattern within plant rooting zones. The aim of this study is to develop, calibrate and verify a model that will establish the disposition pattern of applied nitrogen in the rooting zones of cereal crops in relation to applied water so to maximize its uptake by plants roots and minimize leaching losses.

Key words: Cereal crops, disposition pattern, model, nitrogen, plants

Résumé

L'azote (N) est le plus important déterminant de la croissance des plantes et du rendement des cultures. Les plantes dépourvues d'azote N montrent un retard de croissance et les feuilles jaunâtres. La croissance des plantes et le rendement des cultures augmentent généralement lorsque l'azote N est ajouté. Cependant, une grande quantité d'azote conduit à des tiges faibles dans les cultures de céréales, réduit la qualité des fruits, diminue la teneur en sucre dans les betteraves à sucre, l'accumulation des nitrates dans les feuilles comestibles de plantes, et peut contaminer les eaux souterraines. La production agricole et les défis environnementaux liés à la baisse et à l'excès de N poussent à un besoin de générer des connaissances des quantités optimales d'azote N qui peuvent donner des rendements des cultures désirables tout en évitant les problèmes induits par l'excès de N. En raison de la complexité des sols,

les modèles peuvent être utilisés pour déduire les caractéristiques de N dans le sol et vérifier son type de disposition à l'intérieur des zones d'enracinement des plantes. Le but de cette étude est de développer, calibrer et vérifier un modèle qui permettra d'établir le type de disposition de l'azote appliqué dans les zones d'enracinement des cultures céréalières en rapport avec l'eau appliquée de manière à maximiser son absorption par les racines des plantes et minimiser les pertes par lessivage.

Mots clés: Cultures céréalières, type de disposition, modèle, azote, plantes

Background

Nitrogen (N) is the most important determinant of plant growth and crop yield. Plants lacking N show stunted growth and yellowish leaves. Plant growth and crop yield usually increase when N is added (Hodge, 2008). Nitrate readily moves with water through soils and can contaminate groundwater to a point at which it may become a health hazard (10 ppm). Ingestion of such high-nitrate foods and water can cause health risks for animals and humans such as methemoglobinemia (called the "blue baby" syndrome) which interferes with the blood's ability to carry oxygen. The problems posed to the environment occur when excess N in soils is carried away with surface runoff and water moving through soils and then finds its way to water and contributes to eutrophication and air pollution. The problems associated with low and excess N prompted scientists to generate knowledge of optimum amounts of N that can give desirable crop yields while avoiding excess N-induced problems. Owing to the complexity of soil and crop systems, it was difficult to use generated knowledge to infer behavioral characteristics of N in soil and plants, to account for the observed N responses, and to ascertain that specified output is the result of a specified input (Haefner, 1996). In order to reduce these problems, soil and crop simulation models were developed to represent the reactions that occur within the plant and the interactions between the plant and its soil (Passioura, 1973, 1996). Since then, several simulation models have been developed, utilized, adopted, modified, and development of new ones is still taking place.

The movement of N in the soil is governed by advection and dispersion equations. The majority of nitrate ions (NO_3-) do not bind to the soil solids because they carry negative charges and are greatly influenced by advection (defined as the flux of solute due to the movement of water containing the solute) and is expressed by:

$$\left(\frac{\partial c}{\partial t}\right)_m = q_w c \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

while ammonium ions (NH4 +) bind to the soil's negatively-charged cation exchange complex (CEC) are greatly influenced by dispersion (defined as spreading out of solute due to variations in water velocity within individual pores, across pores with differing sizes and shapes, and across interconnected pore pathways with different geometries) and is expressed as:

$$\left(\frac{\partial c}{\partial t}\right)_h = -D_h \left(\frac{\partial c}{\partial x}\right) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (2)$$

The general advection-dispersion solute transport equation is expressed as:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} - N_u(c, x_i, t) \quad \dots\dots\dots\dots(3)$$

Understanding the movement and disposition pattern of nitrogen in soil will help to establish amount of water that can be applied in water-regulated farming to ensure that nitrogen is distributed within the rooting zone of the plants to facilitate its uptake and reduces losses.

Literature Summary

Nitrogen and water management. Nitrogen management is a key component in maize production because of the relatively large N inputs that are used, the high cost of N fertilizer, and public concerns over reactive N in the environment. Letey *et al.* (1983) reported that N management is inextriciably linked to irrigation water management. They argued that proper water management is the key to greater nitrogen use efficiency and water use efficiency in irrigated agriculture. Poor N nutrition may be due to inadequate N fertilization or temporal mismatch between N availability in soil solution and crop uptake needs. Matching N availability in soil solution and crop uptake needs is critical to improving maize production. Bauder *et al.* (2008) reported that best nitrogen and water management practices can reduce the probability of nitrate leaching into groundwater and maintain profitable yields. The majority of nitrogen available to plants is in the form of inorganic NH_4^+ and NO_3^- forms. Ammonium ions (NH_4^+) bind to the soil's negatively-charged cation exchange complex (CEC) while nitrate ions (NO_3^-) do not bind to the soil solids because they carry negative charges.

Since none of the nitrate is adsorbed to soil particles it is abundant in the soil water and the movement of the nitrate to the root rarely limits its uptake.

Nitrogen movement in the soil. Nitrate nitrogen movement in soil can be described by the phenomenon of solute transport in soil. Due to the soluble nature of nitrate, the transport of NO_3-in soil is governed by water flow within the soil pore spaces (Nielsen *et al.,* 1986). Therefore, the modes of nitrate transport in soil are predominantly by advection and dispersion (Jury *et al.,* 1991; Leij and van Genuchten 1999; Vitousek *et al.,* 2002). Advection is defined as the flux of solute due to the movement of water containing the solute. It is expressed as the product of water flux and the solute concentration (*c*) and is expressed as (Nielsen *et al.,* 1986):

$$\left(\frac{\partial c}{\partial t} \right)_m = q_w c \qquad \text{................…………......…………..} \quad (4)$$

$$q_w = -K \nabla H \qquad \text{…………........................……..……….} (5)$$

where $("c/"t)_m$ is the advective flux; q_w is the water flow per unit cross sectional area per unit time, *K* is the soil hydraulic conductivity, which is a non-linear function of soil moisture content (*è*) and matric potential ($Ö_m$); and "*H* is the three-dimensional hydraulic gradient in x, y, and z directions. In a case where the soil moisture content is constant, the water flux is expressed as (Vitousek *et al.,* 2002):

$$q_w = v \theta \qquad \text{…………...............……………......……..} (6)$$

where *v* is the pore water velocity. Advective transport of solute occurs through the soil pore spaces, and therefore depends on matrix flow of soil water. Chemical transport by advection is based on the assumption that both solute and water travel through uniform straight-line flow paths in the soil pores, leading to piston flow (Vitousek *et al.,* 2002). In reality, flow paths are usually irregular and tortuous. As such, the solute fronts are variably localized within the pore channels (Lal and Shukla, 2004). Due to the irregular soil pore space geometry, some of the incoming solution may be ahead or behind relative to the resident solution. The process of solute transport in soil also involves diffusion and dispersion. Diffusion is the spontaneous movement of solute along a concentration gradient based on random, thermal

("Brownian") motion of solute molecules. According to Fick's Law, the diffusive transport of solute in one dimensional (x-coordinate) direction is described as (Lal and Shukla, 2004):

$$\left(\frac{\partial c}{\partial t}\right)_d = -D_d \left(\frac{\partial c}{\partial x}\right) \quad \text{.................……..…………..} (7)$$

where $\left(\frac{\partial c}{\partial t}\right)_d$ is the diffusive flux; D_d is the diffusion coefficient in soil; and $\left(\frac{\partial c}{\partial x}\right)$ is the concentration gradient. The diffusion coefficient can be influenced by other factors such as the diffusion coefficient of the solute in pure water, the tortuosity of the flow paths in soil (D_o), shear strength of the soil (ô), as well as the soil moisture content (è) (Lal and Shukla, 2004):

Due to the inverse relationship between the tortuous flow paths and the diffusion coefficient in soil, D_d is usually less than D_o. Dispersion is the spreading out of solute due to variations in water velocity within individual pores, across pores with differing sizes and shapes, and across interconnected pore pathways with different geometries (Mulla and Strock, 2008). By mathematical definition, dispersive flux is expressed as (Mulla and Strock, 2008):

$$\left(\frac{\partial c}{\partial t}\right)_h = -D_h \left(\frac{\partial c}{\partial x}\right) \quad \text{..............................…………..} (8)$$

where $\left(\frac{\partial c}{\partial t}\right)_h$ is the solute flux due to dispersion; D_h is the dispersion coefficient, which increases linearly with increase in the velocity of pore water: Diffusion and dispersion produce similar effects on solute transport in soil, i.e. they both tend to mix and eventually eliminate non-uniformity in solute concentration in the soil solution. However, the basic mechanisms by which they occur are different. While diffusion process is predominant at low to zero soil water flow velocity, hydrodynamic dispersion exceeds chemical diffusion at high flow velocity particularly in large pore spaces. Advection, chemical diffusion, and hydrodynamic dispersion are the three basic mechanisms of solute transport in the soil. The general equation for one dimensional solute transport with a steady water flow in a homogeneous porous medium is described by advection-dispersion equation (Mulla and Strock, 2008):

$$R\frac{\theta \partial c}{\partial t} = \theta D_w \left(\frac{\partial^2 c}{\partial x^2}\right) - q\left(\frac{\partial c}{\partial x}\right) + Fc + G \quad \text{...........................} (9)$$

Where c is the solute concentration in the liquid phases; q is the volumetric water flux density; D_w is the dispersion coefficient for the liquid phase; R is the retardation factor which equals to unity for non-reactive tracers; F and G are coefficients defining the first-order decay term and zero-order decay term in the solute transport equation, respectively. A few examples of mechanistic models commonly used for predicting nitrate movement and solute leaching in soils are LEACHMN (Hutson and Wagenet 1993), RZWQM (Hanson *et al.,* 1999; Ahuja *et al.,* 2000), NLEAP (Shaffer *et al.,* 1991), and HYDRUS program (Simunek *et al.,* 1998; 1999; 2005; 2006).

Study Description

The study site is in Kasungu, Malawi situated at Lat. of 12^035' S and Long. of 33^031' E, at 1186 m asl. The area has a unimodal rainfall with annual mean of 800 mm. Plot size is 10 by 5 m with ridges spaced at 75cm. The plots are separated from one another by a 2-metre boundary to avoid 'sharing' of responses. A seed of hybrid maize (SC 407) is planted per hole spaced at 25cm. Four water (W) application regimes are used: full water requirement regime (FWR), farmers' practice (FP), 60%, and 40% of FWR. A FWR was determined by using proceducure of FAO Paper 56. The blanket recommended N application rate for maize in Malawi is 92 kg N/ha (GoM, 2007). The 3 N regimes to be used are: 125%, 75, and 50% of the recommended regime. The Triscan Sensor is being used to monitor applied N movement. The N reading are being taken at 3 soil depths of 30, 60, and 100 cm. At corresponding profile depth, 3 lateral N concentrations taken at 0, 5 and 10 cm are being recorded. Data being collected are: number of leaves, canopy height, depth of roots, yield, plant density, grain number, individual grain weight, actual N uptake into plant, cumulative water uptake and N at each point, soil moisture content, distances from the N placement point, and thickness of each soil layer.

Research Application

Understanding the disposition pattern of nitrogen in soil will help to establish amount of water to apply to the soil that will ensure that nitrogen is distributed within the rooting zone of the plants to facilitate its uptake. The disposition of nitrogen outside plant rooting zone represent losses to the farmers and contribute to contamination of groundwater. The model is being developed to help farmers to know the movement of applied nitrogen and determine the effective distance of point of nitrogen application distance to a maize plant in different soil types in order to enhance maximum uptake by the plant, optimum amount of irrigation water to be applied to minimize nitrogen leaching, the time and

amount of nitrogen to be applied during any maize growth stage to maximize roots N uptake. With the knowledge that 75 % of plant roots (especially cereals) are concentrated in the upper soil layers (FAOSTAT, 2000), the model will help farmers to apply water that will make N to be deposited within upper plant rooting zones. Application of this model will present opportunity to farmers different combination scenarios of nitrogen and water that maximize nitrogen uptake and minimize nitrogen losses through leaching.

Recommendation

The development of the model is still continuing, however currently it is able to model 60% of the observed data. The model is indicating that the general movement of N and W is inclined to plants roots.

Acknowledgement

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