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Development of a soil-plant phosphorus simulation model for calcareous and weathered tropical soils

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Abstract

Phosphorus (P) is a limiting nutrient affecting crop yields in many regions of the world, in particular in areas with highly weathered acid soils and calcareous alkaline soils. Given the many factors associated with P behavior in a range of soil environments, there is a need to go beyond site-specific situations. The use of crop simulation models is a valuable tool to evaluate the efficacy of applying P fertilizers under different soil, management and climatic conditions. A computer model was developed to simulate P in the soil–plant system adapted to soils with high P limitations. The soil P module is operated with two comprehensive crop simulation models (CERES and CROPGRO) within the DSSAT software. The P module comprises inorganic and organic P pools estimated from measured P fractionation data and works on a daily time step. The rate constants for P movement between the pools follow first order kinetics. The P module was calibrated and tested using three data sets from Colombia, Syria, and Tanzania. The limited testing showed that the P module simulated accurately grain yield and P uptake by wheat grown under semi-arid conditions. The wheat crop responded little to fertilization although measured Olsen P was as low as 2.6 mg kg^{-1}. The P module overestimated

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P uptake for both soybean and bean crops grown in acidic soils, but predicted with a good degree of accuracy labile P in the soil and P uptake for maize grown under the same acidic conditions. Testing with more data sets is needed to improve model predictions.

Keywords: Soil models; Crop models; Phosphorus; Tropical acid soils; Semi-arid soils; Crop simulation models; Phosphorus simulation; Cereals; Legumes; Phosphorus availability in acid tropical soils; Phosphorus availability in alkaline semi-arid soils

1. Introduction

Managing soil phosphorus (P) for profitable crop production while protecting the environment is one of the more significant challenges facing soil scientists today. While chemical fertilization has been the driving force behind agriculture in the west for the past half century leading to increased P levels in soils, in lesser-developed countries the situation is different. In vast areas of Africa, the Middle East, and Latin America, the problem is reversed, and lower crop yields are often due to P deficiency.

In sub-Saharan Africa, P is a limiting nutrient in many soils of the semi-arid tropics and in acid, weathered soils of the subhumid and humid tropics (Buresh et al., 1997). Oxisols and Ultisols are major soils in the humid and subhumid tropics of Africa (Deckers, 1993) and are characterized by low total and available P content and high P retention capacity (Friesen et al., 1997). In addition, Andepts and oxic Alfisols have a high P-fixation capacity (Sanchez and Uehara, 1980). Many soils in the highlands of East and Central Africa are depleted of soil nutrients, particularly P (Jama et al., 1997). Most soils of the highland plateau of Ethiopia are P-deficient (Duffera and Robarge, 1996). Large areas of Africa, in particular the semi-arid tropics, are dominated by sandy soils that have low levels of P, but have a low sorption capacity and therefore low P fertilizer requirement (Mokwunye et al., 1986; Warren, 1992).

In acid soils, P is fixed into slightly soluble forms by precipitation and sorption reactions with Fe and Al compounds as well as crystalline and amorphous colloids (Sanchez and Uehara, 1980). Phosphorus sorption was highly correlated with the contents of clay and total free Fe-oxide content extracted by dithionite-citrate-bicarbonate (DCB) in Ultisols and Alfisols derived from acidic rocks from the savanna and rain forest zones of West Africa (Juo and Fox, 1977). Arduino et al. (1993) found that sorption capacity of acidic Alfisols from South Africa were highly correlated with the DCB extractable iron oxides and with amorphous Fe and Al oxides content (oxalate extractable). Based on P-sorption isotherms for 200 soils from west, east, and southern Africa, Warren (1992) concluded that fertilizer P requirements tend to follow the order Andisols > Oxisols > Ultisols > Alfisols > Entisols. With the exception of Andisols, there is, in general, a direct relationship between P sorption by soils and the surface area of Fe and Al oxides. Clay content in soils also affects P sorption. For example, millet-producing soils of West Africa in the Sudano-Sahelian agroecological zone are generally sandy in texture, have a low sorption capacity and only need low to medium inputs of P to maintain an adequate pool of labile P (Manu et al., 1991).

In calcareous alkaline soils, solid-phase $CaCO_3$ is the dominant factor affecting P availability. Data for 19 soils from different agricultural areas of West Asia and North Africa showed that $CaCO_3$, Fe oxides, amount and reactivity of silicate clays as well as P fertilizer addition rate and time after application affect the loss of availability of P in calcareous soils (Afif et al., 1993). Iron oxides, particularly the more reactive forms, have a modifying influence on P reactions in calcareous soils, despite the dominant influence of $CaCO_3$ (Ryan et al., 1985). With 20 calcareous soils in the USA, Sharpley et al. (1984) found a negative correlation between labile P and $CaCO_3$ content after 6 months incubation.

Extensive field experimentation is conducted every year to evaluate the efficacy of P fertilizers in relation to type, rate, and method of application in different soils, under different management systems and climates. Given the many factors associated with P behavior in a range of environments, there is a need to go beyond site-specific situations. The use of crop simulation models to aid in interpretation of research results, and in answering questions about the effects of various management scenarios on P availability would be greatly advantageous. Crop simulation models are increasingly being used for various purposes after numerous tests have demonstrated their capability to estimate crop yields as affected by nutrients and water inputs as well as management practices and climatic conditions. A group of models, CERES for cereal growth simulation and CROPGRO for legume simulation, have been used successfully around the world for various purposes (Tsuji et al., 1998). The CERES and CROPGRO models are important components of the Decision Support System for Agrotechnology Transfer (DSSAT), a product of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (Tsuji et al., 1994).

CERES and CROPGRO are two families of functional, deterministic, crop-soil-atmosphere models. The generic CERES version includes corn, wheat, sorghum, pearl millet, and barley models. The generic CROPGRO model includes soybean, peanut, and bean crops. The CERES models have been used worldwide. Kiniry and Jones (1986) presented test results for corn phenology, leaf area index, biomass, grain number, grain yield, total N uptake, grain N concentrations and grain N uptake. Vigil et al. (1991) tested the model for amount of mineralized N, and N recovered from residues by sorghum and wheat. The CERES models have also been used for risk analysis and multi-criteria optimization of production (Alocilja and Ritchie, 1990), and site-specific irrigation management (Ritchie and Amato, 1990).

CROPGRO has a complete soil-plant N balance, with N uptake and N_2-fixation, as well as N deficiency effects on photosynthetic, vegetative, and seed growth processes. Crop development during growth phases is differentially sensitive to temperature, photoperiod, water deficit and N stresses (Boote et al., 1998). CROPGRO has also been used for various purposes, for example, to improve soybean management under rainfed conditions (Ruiz-Nogueria et al., 2001), and to optimize the capacity of center pivot irrigation systems based on the dry bean model (Heinemann and Hoogenboom, 2000).

Several P simulation models have been developed earlier; however most of these models either had specific applications or were not part of comprehensive crop models. For example, mathematical models were developed to simulate the P flux to plant roots (Caassen and Barber, 1976; Barber and Cushman, 1981). A mechanistic multi-step model for the transformation and transport of applied P under steady-water-flow conditions in uniform soils was described by Mansell et al. (1977). The Erosion-Productivity Impact Calculator (EPIC) simulates erosion and its effects on the long-term productivity of soils through the loss of nutrients, including P (Jones et al., 1984). The EPIC model requires estimates of initial sizes of labile, active inorganic, stable inorganic, fresh organic, and stable organic P pools in the soil (Jones et al., 1984, 1985). The CENTURY model was developed to simulate the dynamics of C, N, P, and S in cultivated and uncultivated grassland soils (Parton et al., 1988). The CENTURY model employs inorganic P pools (labile, secondary, and occluded), organic pools (active, slow, and passive), and plant residues (divided into structural and metabolic pools) (Parton et al., 1988). Little applicability of the CENTURY model, however, was found on highly weathered tropical soils, as most of the information on soil–P dynamics used in formulating the P sub-model in CENTURY was obtained from soils of the North American Great Plains (Gijsman et al., 1996). The CENTURY model was mainly developed for soils where N is the most-limiting nutrient and this limited its applicability in P-limited soils (Gijsman et al., 1996). The CENTURY model also uses a monthly time step (Parton et al., 1988), while simulations on a daily time basis is important for annual crops. Probert (1985) described a conceptual model to simulate the amount of effective P in the soils. The model gave good responses when tested with growth of tropical legume pastures.

P modeling strongly depends on accurate simulation of plant growth and development because plant uptake is an important component of the P cycle. Our objective was to develop a P model that is able to simulate P in the soil–plant system and can be adapted to soils where P deficiencies seriously limit crop yields and agricultural production (mainly high pH, calcareous soils; and low pH, highly weathered soils). We linked the model with comprehensive crop simulation models (CERES and CROPGRO), which take into consideration the phenology of the crop, climatic conditions and soil properties. These models simulate the effects of cultivar, planting density, weather, soil water and nitrogen on crop growth, development and yield. They do not simulate the effects of pests, nutrients (except N) or catastrophic weather. The models simulate multi-year crop rotations (Tsuji et al., 1994). These models, however, have not taken into consideration the effects of P on crop growth, and therefore were not adequate for use in areas where P availability is low and adversely affect yields.

In this paper, we describe the structure of the P module, as well as the testing done, using data sets from humid tropical and semi-arid areas where P deficiencies are widespread. To simulate the loss of available P with time, different pools of P that represent different solubilities and therefore availability in the soil are simulated, and rate constants for P movement between pools are estimated from experimental data and from the literature.

2. P module structure

2.1. Phosphorus pools

Three inorganic-phosphorus (Pi) pools (labile, active and stable Pi) and two organic-phosphorus (Po) pools (active and stable Po) are represented in the P module (Fig. 1). Soil solution P is part of the labile P pool. In addition, there is a fertilizer-P pool, a slow-cycling plant-residue pool, and a fast-cycling plant-residue pool. Phosphorus taken up by the plant is stored as live-plant P and is taken out of the cycle when the plant is harvested. The labile-P pool is the most dynamic pool, which includes both soil-solution P and loosely sorbed P on soil colloids; plants take up P from the soil solution pool. Soil-solution P is defined as a fraction of labile P in the soil solution, and can be changed by users in the soil-chemical parameter file depending on local soil properties. Labile-P depends on the sorption capacity of the soil, which is influenced mainly by clay content, Fe and Al oxide concentration, and $CaCO_3$ concentration. The active Pi and Po pools serve as medium- to slow-changing pools that replenish the labile pool and are sinks for P from the labile pool. Finally, the stable Pi and Po pools are very-slowly changing pools, but may increase or decrease in size, depending on the rate and frequency of P-fertilizer application. Different forms of Pi and Po extracted by a sequential extraction procedure (Hedley et al., 1982) are used to initialize the pools. Once the model is initialized at the beginning of the run, the output data are given in amounts of P in the different pools.

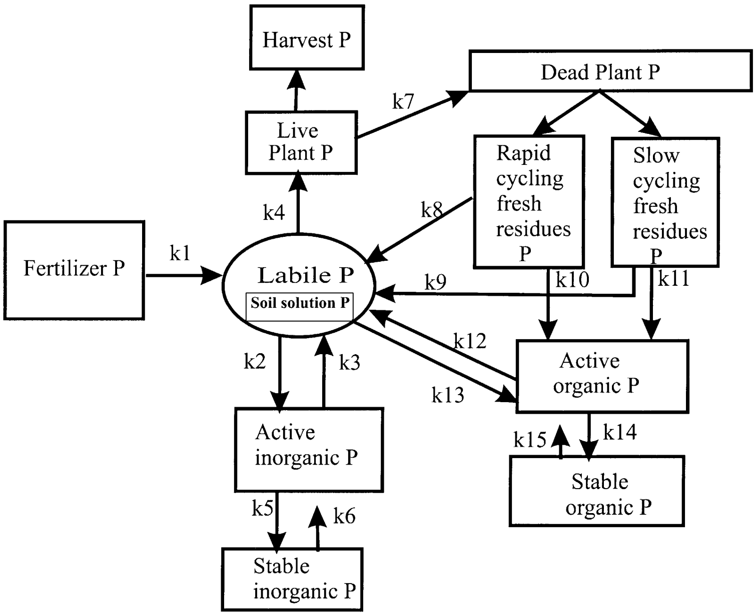

Fig. 1. Phosphorus pools employed in the P model.

Table 1
Relation of theoretical P pools to measured soil P fractions employed in the model[a]

P pools	Measured P fractions			
Labile P	Resin Pi			
Active Pi	$NaHCO_3$ Pi	NaOH Pi		
Stable Pi	S.NaOH Pi[b]	HCl Pi	Hot-HCl Pi	1/2 residual P
Active Po	$NaHCO_3$ Po	NaOH Po		
Stable Po	S.NaOH Po[b]	Hot-HCl Po	1/2 residual P	

[a] The model also accounts for total P in agroecosystem including P in residues and live plants.

[b] NaOH extraction with sonication.

Characterization of soil Pi and Po pools is fundamental for understanding P cycling in the soil-plant system. To initialize the different P pools, we used the P fractions extracted by the procedure developed by Hedley et al. (1982) and Tiessen et al. (1984) to estimate the size of the different pools in the model (Table 1). These sequential fractionation procedures extract the different forms of Pi and Po in the soil, starting with labile forms and ending with the more-stable forms. The Pi fractions include P extracted by resin, $NaHCO_3$, NaOH, NaOH with sonication, and HCl. The Po fractions include Po extracted by $NaHCO_3$, NaOH with sonication and NaOH. Residual P, not extracted by previous chemicals, contains Pi and Po that are resistant to decomposition. Residual P is measured after digestion of the soil with sulfuric or perchloric acids. The Hedley fractionation also includes microbial P (both Pi and Po), which is not included separately in the P module, but as part of the $NaHCO_3$ fraction. Tiessen and Moir (1993) added a hot-HCl Pi and P extraction step, which may be important in tropical soils. In the P module, it could be added to the HCl fraction.

Although this fractionation procedure does not define the components of each group, it relates to the pools of rapid and slow cycling and allows for the detection of changes in P cycling within an intermediate time frame (Daroub et al., 2000, 2001). We assigned the different fractions to corresponding P pools (Table 1) according to what is best described in the literature. For example Resin-extractable Pi is considered to be the most available to the plant (Amer et al., 1955; Sibbesen, 1977), and therefore is considered labile P. Organic-P compounds, like ribonucleic acid and glycerophosphate, are extracted by $NaHCO_3$ (Bowman and Cole, 1978) and are considered in the module as active Po. Phosphorus released after fumigation with chloroform and extracted with $NaHCO_3$ can constitute up to 40% of the microbial P present in the soil (Hedley and Stewart, 1982). The NaOH-extractable Pi and Po fractions are moderately-labile-P and are P chemisorbed on Fe and Al oxides (Ryden et al., 1977). Sonication with NaOH extraction allows for the release of physically protected Pi and Po (Hedley et al., 1982).

The NaOH–P fraction was found to be a sink pool after the addition of ^{33}P-labeled soybean residues to three soils from Michigan, USA (Daroub et al., 2000). But Ball-Coelho et al. (1993) found that NaOH–Po undergoes seasonal transformation in tropical soils. The NaOH–Pi fraction increases in importance with increased soil weathering, due to increased Fe and Al oxides and sorption of P (Buresh et al., 1997). NaOH–Pi was the dominant fraction related to the availability of P to plants in an 18-year old continuously cultivated and fertilized cropping system on an Ultisol (Beck and Sanchez, 1994). The NaOH–Po and total residual P levels fluctuated during the year in different biological and conventional treatments in temperate soils indicating that P in these fractions might be involved in short-term transformations (Oberson et al., 1996). Calcium phosphates are mainly extracted with HCl. Residue P may contain both Pi and Po that is resistant to decomposition. The hot-HCl step (Tiessen and Moir, 1993) extracts residual P also, including Po involved with particulate organic matter, which may participate in short-term transformations. Guo and Yost (1998) used the Hedley fractionation procedure and grouped the P fractions of similar availability into three functional pools, readily available, reversibly available, and sparingly available. In highly weathered soils, the readily available pool is comprised of Pi extracted by the Fe-oxide strip and $NaHCO_3$. The reversibly available pool is comprised of Po extracted by $NaHCO_3$ and NaOH in addition to Pi extracted by NaOH. The sparingly available pool included residual P (Guo and Yost, 1998).

The assignment of the fractions to different pools (Table 1) is empirical and may need to be modified for different soils. Therefore, we allow the users of the model to change the assignment of fractions to pools in the chemistry file according to their local conditions. If P fractions data are not available, the program can estimate those fractions for tropical soils from the literature (Ball-Coelho, 1993; Beck and Sanchez, 1994; Tiessen et al., 1992). Also the program can initialize the labile pool using a soil-P test; Bray-1 (Bray and Kurtz, 1945), Olsen et al. (1954), Colwell (Colwell, 1963), Melich III (Melich, 1984), and Troug (Ayers and Hagihara, 1952); using equations adopted from Sharpley et al. (1984, 1989). Sharpley et al. (1984) used regression analysis to predict labile P, organic P, and a P sorption index from soil chemical and physical properties, using a database with 78 soils in the US and Puerto Rico. Later these equations were modified for calcareous and highly weathered soils (Sharpley et al., 1989).

2.2. Soil P dynamics

The mass transfer of P from one pool to another is calculated as a first-order reaction. Flow of P between any two pools is calculated for each layer as follows:

$$\text{P Flow (Pool}_1\text{ to Pool}_2) = K_1 * C_1 * T_f \tag{1}$$

$$\text{P Flow (Pool}_2\text{ to Pool}_1) = K_2 * C_2 * T_f \tag{2}$$

where: P Flow is P moved from one pool to another (mg $kg^{-1}day^{-1}$), K is a rate constant (day^{-1}), C is concentration of P (mg kg^{-1}) in the respective pool, and T_f is a temperature-reduction factor. The total P is the sum of labile Pi, active Pi, stable Pi, active Po, stable Po, P in residues that decompose rapidly, P in residues that decompose slowly, fertilizer P, and P in live plants. Values for the transfer rates

Table 2
Parameters of the P module: Estimates of rate constants (day^{-1}) between inorganic pools, and the fraction of labile P in solution in the two soil groups used in the study

Description of transformation constants		Soils	
		Low-pH weathered soils	High-pH calcareous soils
Inorganic			
K_1	Fertilizer to Labile	0.3	0.3
K_2	Labile to Active Pi	0.008	0.007
K_3	Active Pi to Labile	0.002	0.001
K_5	Active Pi to Stable Pi	0.0004	0.0006
K_6	Stable Pi to Active Pi	0.0003	0.0001
Solution P			
	Fraction of labile P in solution	0.015	0.02

between inorganic pools are presented in Table 2. No rates are presented here for organic P transformations, but the model will be linked to the DSSAT-CENTURY model (Gijsman et al., 2002) for the simulation of plant residue decomposition and organic P.

The rate constants of P movement between pools (Table 2) are described in the chemical parameters file and can be changed by the user when soils with different properties are used. Due to insufficient data to correlate these rates with specific chemical properties like iron and aluminum oxides and calcium carbonates, we estimated these rates from the literature, and the best fit we obtained with the data. For example, Jones et al. (1984) estimated a rate constant K5 for movement of P from the active inorganic soil pool to the stable inorganic soil pool to be 0.00076 day^{-1} for calcareous soils. We used a similar value (0.0006 day^{-1}) for the calcareous soils. Jones et al. (1984) estimated a rate of P movement from inorganic labile pool to inorganic active pool to be 0.1 d^{-1}. However, we found this rate constant to be too high when we used it in all of our data sets, especially since we do not limit our pool sizes and therefore do not allow them to get to equilibrium quickly.

2.3. Plant P uptake

Daily P uptake by the plant is equal to either soil supply or plant demand, whichever is less. The soil supply is the weighted sum of labile P in every layer and is constrained by the fraction of P in the soil solution. The weight for each layer is a combination of the effect of root-water uptake (rwu) and root-length density (rlv). For each layer, a 0 to 1 root water uptake factor (Wf) is calculated that potentially constrains soil P supply. The Wf is proportional to Delta_RWU, the difference in soil water content (cm^3 cm^{-3}) due to daily root water uptake. Delta_RWU is equal to RWU_layer/D_layer, where RWU_layer is the daily root water uptake from the layer (cm) and D_layer is the thickness of the layer (cm). A root density factor (RDF) is calculated that is inversely proportional to the depth to the bottom of the layer Z_layer (cm) and increases with RLV_layer (cm cm^{-3}):

$$\mathrm{RDF} = (\mathrm{Z\_1}/\mathrm{Z\_layer}) * (1 - \exp(-6 * \mathrm{RLV\_layer})) \tag{3}$$

where Z_1 is the depth to the bottom of the top layer (cm).

The weight W_layer that defines P supply per soil layer is the minimum of the water factor (Wf) and the root density factor (RDF). Then P supply per soil layer (kg ha^{-1}) is defined as follows:

$$\begin{aligned}\mathrm{P\_supply\_layer} = {} & \mathrm{W\_layer} * \mathrm{P\_labile\_layer} * \mathrm{ppm2kg\text{-}layer} \\ & * \mathrm{fr\_labile\_in\_sol}\end{aligned} \tag{4}$$

where P_labile_layer is labile P concentration (mg kg^{-1}), ppm2kg_layer is the conversion factor from units of concentration to units of mass, and fr-labile-in-sol is the fraction of labile P that actually is in soil solution. Generally, the weight decreases with depth, which is meant to approximate the P supply from the point of view of the plant. Mycorrhizal elongations of the root system can increase P uptake by plants in low P native soils. DSSAT does not simulate mycorrhizae or the effect of acid excretions on P uptake. Simulation of these factors is an idea worth pursuing but currently beyond the scope of the DSSAT models.

Phosphorus available for uptake in the soil solution is calculated as a fraction of the labile pool, and therefore is dependent on the quantity of labile-P. Estimates of this fraction for acidic and calcareous soils are represented in Table 2, and can be changed by the user depending on the soil type in relation to the soil buffering capacity. This can be done once for a certain soil, and the settings should be used for further model runs. The supply of P to the roots is not only governed by concentration of P in the soil solution, but also by the quantity of labile-P, the soil buffering capacity, and the diffusion coefficient of P (Olsen and Khasawneh, 1980).

Phosphorus demand of the crop is computed from P concentrations that are normally found in the plants under optimal conditions. Optimal P concentrations were taken from the literature for maize (Jones, 1983), wheat and barley (Bauer et al., 1987a, b; Schulthess, 1992), soybeans (Hanway and Weber, 1971), chickpeas (Rashid and Bughio, 1993; Weber et al., 1992), millet (Gregory, 1979; Buerkert, 1995; Rebafka et al., 1994), dry beans (Rweyemamu, 1995) and peanuts (Bunting and Anderson, 1960). Optimum and minimum P concentrations for Maize and Soybean are shown in Fig. 2. We estimate the potential (tentative) P concentration in plant tissue after the addition of new biomass on a given day by the following formula:

$$\mathrm{P_{CPOT}} = \mathrm{P_{LP}}/(\mathrm{BIO_{AG}} + \mathrm{BIO_{BG}}) \tag{5}$$

where: $\mathrm{P_{CPOT}}$ is potential P concentration in mg kg^{-1}; the potential P concentration indicates tentative concentration and not maximum; $\mathrm{P_{LP}}$ is P mass in live plants in kg ha^{-1}, and $\mathrm{BIO_{AG}}$ is aboveground biomass and $\mathrm{BIO_{BG}}$ is belowground biomass both

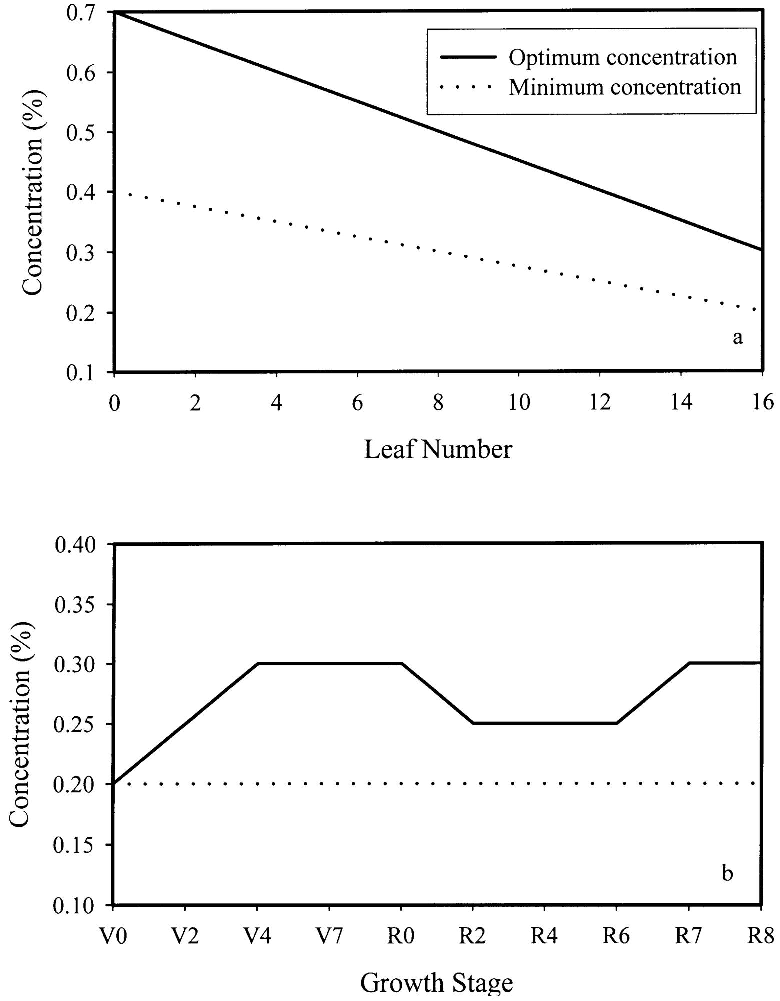

Fig. 2. (a) P concentrations in maize shoots as a function of leaf number, up until the end of istage 2 in CERES (end of vegetative growth). The equation of the optimum concentration is $y=0.7-0.025\ x$. After the end of istage 2, optimum concentration is assumed to be 0.2%. The minimum concentration is calculated as 60% of the optimum. Adapted from Jones (1983). (b) *P* concentrations in whole soybean plants as a function of growth stage in GRO. Adapted from Hanway and Weber (1971).

in kg. The potential concentration is compared with the optimum concentration, and plant P demand is thus defined. The optimal P concentration in the model varies with plant development stage. We have developed functions of plant P concentration with development stage from the literature (Fig. 2 for maize and soybean). The wheat optimum P concentration in the straw is the highest of (0.85–0.0625*leaf number) or 0.35% from emergence to end of leaf growth, and it ranges from 0.35 to

0.03% from end of leaf growth to maturity (Bauer et al., 1987b). Optimum P concentration in the grain is 0.34%. The minimum P concentration for wheat is taken as 60% of optimum. Where the concentration is given at discrete stages, we use linear interpolation to calculate the concentration between the discrete stages. Generally, P concentration in vegetative parts declines with plant age, whereas P concentration in reproductive organs increases with plant age.

A stress factor ranging from 0 to 1 is calculated, where 0 is maximum P stress and 1 is no P stress. The ratio of P supply to P demand is calculated. If that ratio exceeds 1, then the ratio is set equal to 1, and the P stress factor is equal to 1. The P stress factor for the day is not proportional to the ratio_(supply_to_demand); it is 1 at values of ratio_(supply-to-demand) just below 1. The lower the ratio_(supply_to_demand), the more proportional it is to todays_stress:

$$\text{P\_stress factor for the day} = 1 - \left[1 - \text{ratio}_{(\text{supply\_to\_demand})}\right]^4 \tag{6}$$

To reduce photosynthesis, DSSAT uses the lowest of the temperature, drought, and N deficit factors. We introduce a new factor, the P deficit factor. The modified DSSAT uses the lowest of temperature, drought, N, and P deficit factors. This factor is multiplied by the amount of potential C assimilation for the next day. In the case of severe P deficit, growth rate will be reduced or stopped. After plant uptake is calculated, labile-P in the soil is reduced accordingly and P in senesced tissue is calculated. Plant uptake for the whole profile is the minimum of supply and demand. Soil labile P must be reduced by the amount of actual P uptake. In each soil layer, labile P is reduced by the amount (supply_per_layer/whole_profile_supply) *whole_profile_uptake. In other words, the amount that the labile P is reduced per layer is proportional to the contribution of that layer to the whole profile supply. Labile P per layer cannot drop below the minimum concentration that has been set for the labile pool (zero by default, or a positive value set by the user). The mass of P in dying roots is proportional to the P in live tissue and inversely proportional to the root density in a soil layer.

2.4. Links to crop models

The P module is linked with two comprehensive crop models in DSSAT: CERES and CROPGRO. At the present time, the model is able to simulate P uptake of the following crops: wheat, barley, maize, millet, soybean, dry bean, chickpeas, and peanuts. The P module receives the following information from the CERES and CROPGRO crop models: treatment number, current date, first day of simulation, soil bulk density (to compute mass of soil in each layer), number and thickness of soil layers, above- and below-ground biomass (to compute potential tissue concentration), plant development stage (to compute uptake), planting density, and root length volume (to compute uptake and root senescence P). The P module affects the crop models through the stress factor CH_STRESS, a 0 to 1 multiplier that affects daily carbon fixation. Additional plant variables are crop P (total, grain, and vegetative), and total P uptake.

2.5. Input data

The P module is used within a software called the decision-support system for agrotechnology transfer (DSSAT), which includes crop simulation models, databases for weather, soil, and crops and strategy-evaluation programs. For a description of DSSAT and the minimum dataset needed to run the general models, we refer to Jones et al. (1998). The additional data required to operate the P model are the rate, date and type of P fertilizer applied, and the initial values of soil P in each pool. Contents of Fe and Al oxides, or Al saturation (for acidic soil) and $CaCO_3$ content (for alkaline soils) are desirable. Soil pH and texture are required as part of the minimum dataset for DSSAT.

2.6. Capabilities of the P module

There are several analysis options that can be used in the module depending on the objectives of the user. The two most commonly used are sequence and seasonal analyses.

2.6.1. Sequence analysis

The P module within DSSAT is capable of simulating crop rotations or crop sequences, where each crop uses P left over from the previous crop, using the sequence analysis option. The model will simulate the carry-over of residue from one crop to the next in the DSSAT sequencing. This is a necessary feature for realistic simulations in low-P soils, where the return from previous-crop residues contributes considerably to the next crop's P nutrition. The model carries over not just leftover P but also N and water status.

2.6.2. Seasonal analysis

The P module within DSSAT can also be used with the seasonal analysis program that allows the user to perform comparisons of simulations obtained by running the models with different combination of inputs. Seasonal refers to the fact that what is being run are experiments of a single-cropping season with no carryover from one season or crop to the subsequent season or crop. Seasonal analysis is useful for comparing methods for managing a crop in particular environment, for example, fertilizer application regimes and planting dates.

3. Calibration and testing

Data sets to calibrate and test the model were collected from three regions of the world, Colombia, Syria, and Tanzania. In each of these regions, P deficiencies are common and vary in extent. Also, the crops grown are different as well as the extent of application of P fertilizers.

3.1. Experimental data

3.1.1. Syria (West Asia)

Two separate experiments conducted at the International Center for Research in the Dry Areas (ICARDA) in northwestern Syria were used for calibrating and testing the model for wheat (*Triticum turgidum* spp. durum*)*. The experiments were conducted at two research stations of ICARDA in Tel Hadya (36°01′N, 36°56′E), and Jindiress (36°26′N, 36°44′E). The Tel Hadya location has a very fine clay, montmorillonitic, thermic Calcixerollic Xerochrept soil with a pH of 7.9, a $CaCO_3$ content of 21% at 0–20 cm, and a mean annual rainfall of 328 mm per year. Jindiress has very fine clay, montomorillonitic, thermic, Chromic Calixerert with a pH of 8.0, a $CaCO_3$ content of 22% at 0–20 cm and a mean annual rainfall of 446 mm per year (Ryan et al., 1997).

For calibration of genetic coefficients, growth data of two wheat cultivars (Cham 1 and Hourani) grown in Tel Hadya for three growing seasons (1989–1992) were used. Details of these experiments are published elsewhere (Pala et al. 1996). The no-stress treatment was used for calibration of the genetic coefficients; this treatment included the application of 100% of crop water requirement, 100 kg ha^{-1} of N applied in split top-dressing, half at planting and the other half at tillering, and 22 kg ha^{-1} of P applied at planting.

The data used for model testing were from an experiment established in 1987 in Tel Hadya and Jindiress with the objective of monitoring long-term changes in available P (Olsen P) in relation to the rate of yearly application of P fertilizer (Ryan et al. 1994). The second objective was to determine the yearly application of P needed to maintain the level of available soil P that maximizes economic yields. The study measured the effect of annual and residual P applications on yields of wheat and lentil (*Lens culinaris*). Only data on wheat (variety Cham 1) only will be presented in this paper. Crop rotations in Tel Hadya and Jindiress were wheat/lentil, except for 1987/1988 when it was wheat/chickpea (*Cicer arietinum* L) in Tel Hadya. The study was conducted for 8 years in both locations. Five of the 10 treatments reported here include annual applications of P in the form of Triple Super Phosphate (TSP) at 0, 6.5, 13, 20, and 26 kg ha^{-1} broadcast applied before planting each crop. The other five treatments comprised a one-time application of P at 87 kg ha^{-1} in 1986, and an annual application of 0, 6.5, 13, 20, and 26 kg ha^{-1} broadcast applied before planting each crop.

All locations were rainfed. Fertilizer N was broadcasted and incorporated in all treatments at a rate of 60 kg ha^{-1} before sowing of the cereals in the rotation. The experimental design was a split plot with two replications per treatment. Before planting in the 1987/1988 season, Olsen P was 6.1 mg kg^{-1} in Tel-Hadya and 2.85 mg kg^{-1} in Jindiress. Olsen P was measured before planting each year. Total P was 525 mg kg^{-1} in the upper 12 cm in Tel Hadya and 488 mg kg^{-1} in the upper 18 cm in Jindiress. To estimate P concentrations in the different pools, resin P was calculated from an empirical equation correlating resin and Olsen P in these soils (Afif, 1992), and data on organic and residual P were obtained from Ryan et al. (1994).

3.1.2. Colombia (South America)

Two separate experiments were used for calibrating and testing the P model for maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr] in Colombia. Both experiments were carried out at the International Center for Tropical Agriculture (CIAT)-CORPOICA Experiment Station in Carimagua (4°30′N, 71°19′W) on the eastern plains of Colombia. Rainfall averages 2240 mm annually, falling mainly from late March to mid- December. Mean annual temperature is 27 °C. Soils are well-drained silty clay isohyperthermic Tropeptic Haplustox (Friesen et al., 1997), with an Al saturation of 50% in the 0–15 cm layer and 85% at lower depths. The data used for estimating genetic coefficients were from the "Culticore" experiment from 1994 to 1996, established to investigate crop rotation and ley farming systems for the acid-soil savannas. The treatment used was a maize (variety Sikuani)-soybean (variety Soyica Altiuanura 2) rotation where P fertilizer was applied in the form of TSP at 60 and 40 kg ha^{-1} for the maize and soybean crops, respectively. Other nutrients were applied at adequate levels.

Data used to test the model were taken from the "Fosforo Residual" experiment with a maize–soybean rotation established in 1993 to 1997. This experiment included an annual application of P as TSP at 0, 5, 10, 15, 20, 30, or 50 kg ha^{-1} at maize planting, and treatments that had one application of P (residual treatments) at 10, 20, 30, 40, 60, 80, 120, 160, or 200 kg ha^{-1} in 1993. The sequence analysis option was used to run simulations for crop rotations of 3.5 years. The P pools were initialized once, at the beginning of simulation, using measured P fractions data. Before the establishment of the study, Bray-2 was 1.6 mg kg^{-1} at the 0–10 cm depth and 1.2 mg kg^{-1} at the 10–20-cm depth.

3.1.3. Tanzania (Africa)

A field study was conducted during the March-to-June rainy season in 1993 and 1994 at the Sokoine University Agricultural farm (6°50′S, 37°39′E at 525 m altitude) in the Morogoro region in Eastern Tanzania (Rweyemamu, 1995). The objective of the study was to evaluate the P model under Tanzanian conditions for beans (*Phaseolus vulgaris* L.), cultivar "Canadian Wonder", grown with different levels of P fertilizer under both rainfed and irrigated conditions. The rainfed experiment was sown on a sandy loam Oxisol with a pH of 4.5, and a Bray-1 extractable P of 1.2 mg kg^{-1} in the 0–12 cm surface layer. The irrigated experiment was sown on a sandy clay loam Alfisol with a pH of 5.4 and a Bray-1 extractable P of 2.83 mg kg^{-1}. The irrigated site was 800 m from the rainfed site.

Two sources of fertilizers were used, TSP and Minjungu phosphate rock (MPR). The P rates were 0, 22, 44, and 88 kg ha^{-1} applied as TSP and 22, 88, and 176 kg ha^{-1} applied as MPR, which was found to be highly reactive, using the neutral ammonium acetate method with a value of 6.7% P_2O_5 with a second extraction. However, the degree of CO_3 substitution for PO_4 in the apatite indicated that the MPR was only a medium-to-low reactive rock (Rweyemamu, 1995).

The genetic coefficients were estimated using data from the high-fertilized treatment (88 kg ha^{-1}) as TSP in the irrigated experiment. The rest of the treatments in both sites from the two years were used for model testing. Bray-1, total Po, and total

P data were available. To estimate the different pools, equations from Sharpley et al. (1984) were used to estimate labile and inorganic active pools. Other pools were estimated taking into consideration that the sum equals measured total P. The dissolution rate of P from MPR was estimated to be 0.0014 kg day^{-1} as 40% of the rock P applied is estimated to be released in the first year.

3.2. Parameters to test the model

The principal parameter used in the comparison of simulated to observed values is the root mean square error (RMSE), which estimates the variation, expressed in the same units as the data, between simulated and observed values (Loague and Green, 1991; Xevi et al., 1996). This parameter is defined by the following formula:

$$\mathrm{RMSE} = \left[\sum_{i=1}^{n} (S_i - O_i)^2 / n\right]^{1/2}$$

where: O and S are observed and simulated values, respectively. The RMSE tests the accuracy of the model, which is defined as the extent to which simulated values approach a corresponding set of measured values (Loague and Green, 1991).

The second parameter used is the coefficient of residual mass (CRM) (Xevi et al., 1996). A negative CRM indicates a tendency of the model for overestimation; likewise, positive CRM indicates a tendency of the model for underestimation. The CRM is defined by the following formula:

$$\mathrm{CRM} = 100 * \left[\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i\right] / \sum_{i=1}^{n} O_i$$

4. Results

One of the main objectives of the P model was to e to predict accurately crop yields with the input of P fertilization and soil test P levels. The data employed to test the model are from three different regions of the world with different cropping systems, and soil and climatic conditions. This allowed us to test the validity of predictions under various conditions. Since none of the data sets were complete, estimations or data from the literature were used especially for initializing the P pools. Other problems involved the variability of the data among replications. In our description of the results, we explain problems encountered in each data set used to test the model.

4.1. Syria

Data on observed and simulated grain yields as well as uptake of P by wheat are presented in Fig. 3(a,b). The variability of the simulated grain yields was about 20% of the observed yields, as indicated by the RMSE (Table 3). The model slightly overestimated grain yields (CRM = −2.7%). Simulated P uptake by wheat was close to the observed value (RMSE = 18%; CRM = 0.24%). Wheat grain yields varied considerably with different years of the experiment depending on rainfall amounts and distribution. Yields were in general higher in Jindiress, where rainfall is higher compared to Tel Hadya.

Although the wheat experiments in Syria were P-response experiments, crop yield responded little to P fertilization even when extractable Olsen P was as low as 3.5 mg

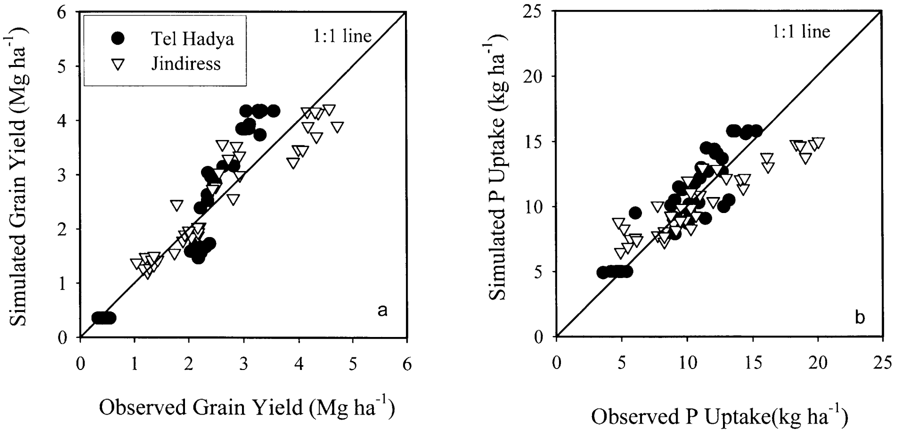

Fig. 3. Simulated and observed grain yield and P uptake by wheat grown in two locations (Tel Hadya and Jindiress) in northwestern Syria from 1987 to 1994 using 10 treatments from a P crop response experiment.

Table 3

Comparison of simulated means of grain yield and P uptake, RMSE, and CRM for the four crops used in testing the model

Parameter	Location	Mean observed	Mean simulated	RMSE (kg ha^{-1})	RMSE[a] (%)	CRM
Wheat grain yield	Syria	2316	2379	474	20	−2.7
Maize grain yield	Colombia	1438	1490	591	41	−3.6
Soybean grain yield	Colombia	487	483	200	41	0.7
Bean grain yield	Tanzania	647	609	140	22	5.9
Wheat P uptake	Syria	10.3	10.3	1.93	18	0.24
Maize P uptake	Colombia	6.6	7.9	2.7	41	−19.5
Soybean P uptake	Colombia	2.6	5.2	2.8	107	−102
Bean P uptake	Tanzania	3.4	4.4	1.65	48	−29

[a] RMSE (%) = (RMSE/Mean Observed)*100

kg^{-1} for Tel Hadya and 2.5 mg kg^{-1} for Jindiress (Fig. 4). The critical value for the region's rainfed soils is around 6 mg kg^{-1}, below which a response to P fertilization is expected (Ryan et al., 1997). The lack of response to P fertilization maybe due to two reasons. First, wheat plants are able to extract P from deeper layers in the soil, and therefore show no deficiency at the low extracted-P values in the surface layer of the soil. The soils in the Tel Hadya location (Block B) are deep soils with a Bk2 horizon to 150 cm, and are rather moist from 40 cm downward. The soils in Jindiress are also deep clay soils with an Ak3 horizon to 130 cm depth (Ryan et al., 1997). Phosphorus in deeper layers may be contributing to the nutrition of wheat. The second possibility is that Olsen P may not be a reliable soil test for these Vertisols. Afif (1992) suggested that Olsen P underestimates available-P status at Tel Hadya, possibly due to the high buffering capacity of the soil in that location.

4.1.1. Colombia

The sequential analysis option of the P model was used to simulate the experiment from Colombia. This option allows the user to initialize soil parameters, including water, N, and P, once at the beginning of the simulation. For the "Fosforo Residual" experiment, the model was initialized in 1994 for the annual treatments and in 1993 for the residual treatments, before the application of the P fertilizers that year. The model simulated 3.5 years of a continuous maize–soybean rotation. Measured

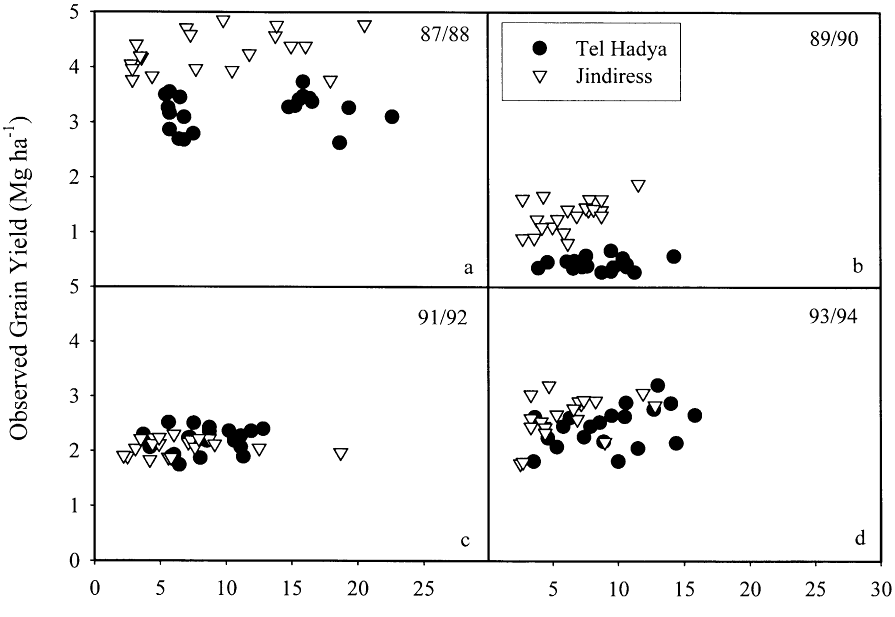

Fig. 4. Olsen P and observed grain yield of wheat grown in two locations (Tel Hadya and Jindiress) in northwestern Syria in (a) 1987/1988, (b) 1989/1990, (c) 1991/1992, and (d) 1993/1994 seasons using 10 treatments from a P crop response experiment. Individual replicates are plotted.

and simulated grain yield and P uptake are presented in Fig. 5 for maize. When the means are compared for all replications and years for maize, the model overestimated grain yields by 3.6% and overestimated P uptake by 19.5%, as indicated by the CRM (Table 3). The RMSE was high for both grain yield and P uptake (41% for both). The high RMSE is a reflection of the variability in measured values between replications and years, which the model cannot replicate. Part of this variability was caused by extraneous factors that influenced yields, such as weed and insect infestation. The model does not take such factors into consideration.

Simulated and measured soybean grain yield and P uptake are plotted in Fig. 6. The CRM was low for grain yield, as the mean simulated values were close to the

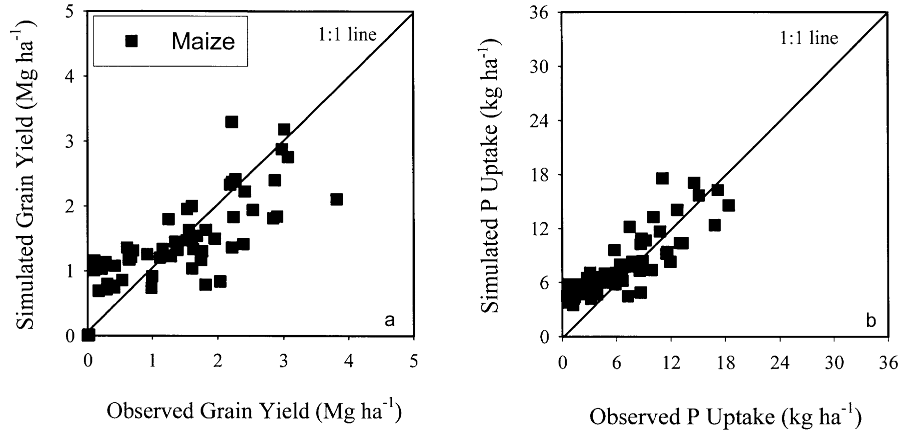

Fig. 5. Simulated and observed (a) maize grain yield and (b) plant P uptake by using sequential analysis on a maize–soybean rotation for 3.5 year from the Fosforo Residual (FR) experiment in Carimagua, Colombia.

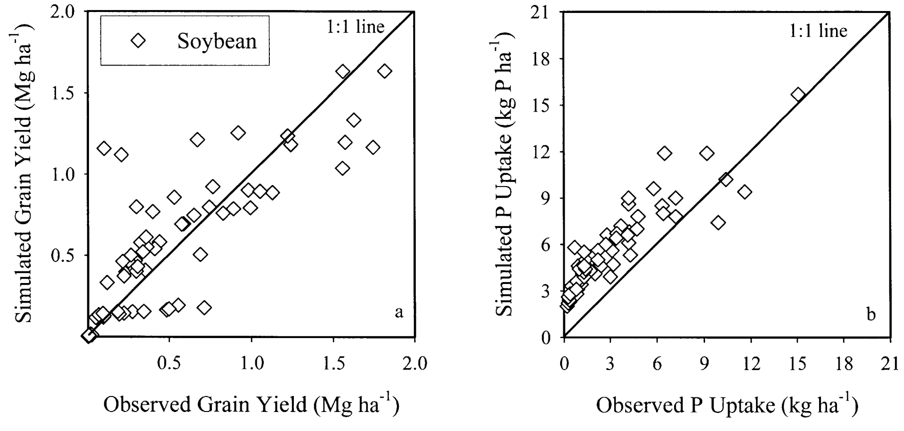

Fig. 6. Simulated and observed soybean (a) grain yield and (b) P uptake in a sequential analysis done on a maize–soybean rotation for 3.5 year from the FR experiment in Carimagua, Colombia.

measured values, but the RMSE was high (41%) (Table 3). In addition, the mean observed value for P uptake for soybean was 2.6 kg ha^{-1}, while the simulated value was double that value, yielding a CRM of −102%. The model assumes that soybean needs more P than is actually taken up by the plant to attain the observed yield levels. Plant P uptake in the model is based on values taken from the literature for varieties grown under optimum conditions. The Soyica Altiuanura 2 variety was bred to withstand acidic conditions and may actually produce higher yields with

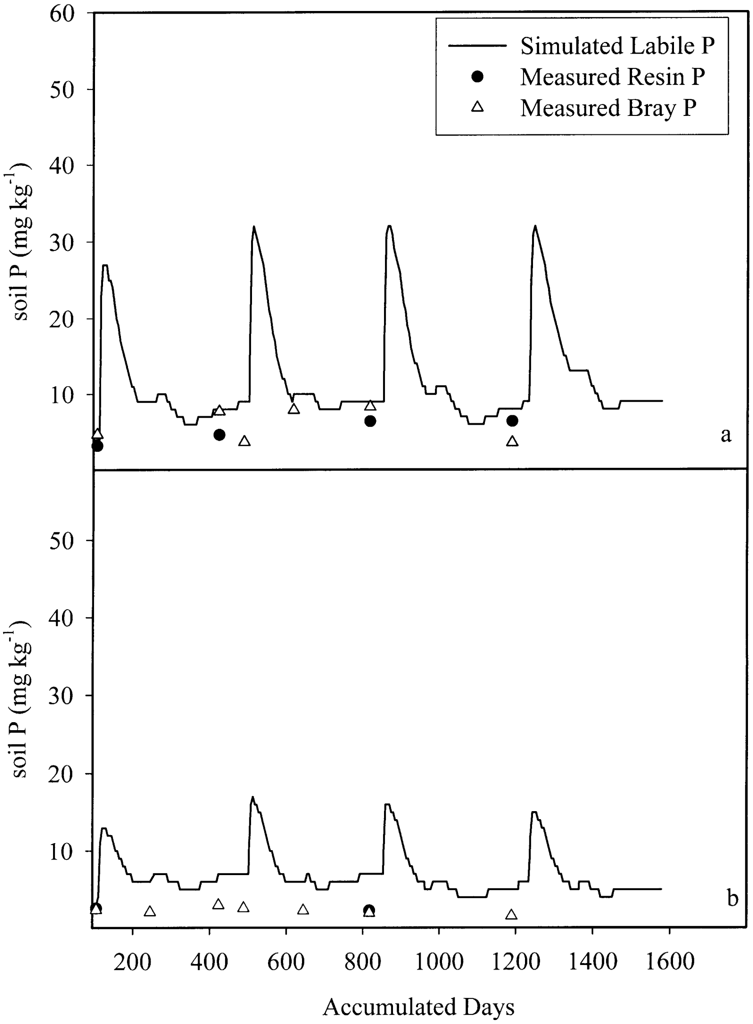

Fig. 7. Simulated labile P plotted against measured resin and bray P values for a period of 3.5 year from the FR experiment in Carimagua, Colombia for (a) 50 kg P ha^{-1} annual application, and (b) 20 kg P ha^{-1} annual application. Beginning of simulation was 17 April, 1994.

lower amounts of P taken up. The P module does not take into consideration differences between varieties or crops in terms of P efficiency at the present time.

To test how well the model performs in predicting labile soil P, data on simulated labile P over a 3.5-year period were plotted and compared to measured resin P and Bray-2 for two treatments (Fig. 7). Labile-P was equated to resin-P to estimate initial conditions on 17 April 1994. The simulated peaks shown in the graph correspond to application dates of P fertilizer with 50 kg ha^{-1} (Fig. 7a) and 20 kg ha^{-1} (Fig. 7b). Simulated labile-P decreased rapidly in the soil as it was transformed to less labile forms and taken up by the plant. The model does a good job in predicting labile P, as compared to resin and Bray-2.

4.1.2. Tanzania

Simulated versus observed drybean grain yields and P uptake are presented in Fig. 8. The model gave good predictions of grain yield of dry bean grown under both rainfed and irrigated conditions with two P fertilizer sources (RMSE = 22%; CRM = 5.9%) (Table 3). However, simulated P uptake had a high RMSE (48%), and was overestimated (CRM = −29%) (Table 3). Measured P uptake by dry bean was low. The model did not predict this low uptake very accurately, even when labile P in the soil was very low. This experiment had a number of problems that reduced the yield in some plots; for example, beanfly, termite and rodent attack in the irrigated site, and weed problems in both sites (Rweyemamu, 1995). Also, the plant population was reduced by disease (*ascochyta* blight) attack to the seeds. Although this does not explain the discrepancy in P uptake, it shows the experimental errors encountered. With respect to P uptake, the optimum concentrations used in the model were from varieties grown in Iowa (Hanway and Weber, 1971). This may not be very realistic in simulation of varieties bred and grown under highly weathered acidic soil.

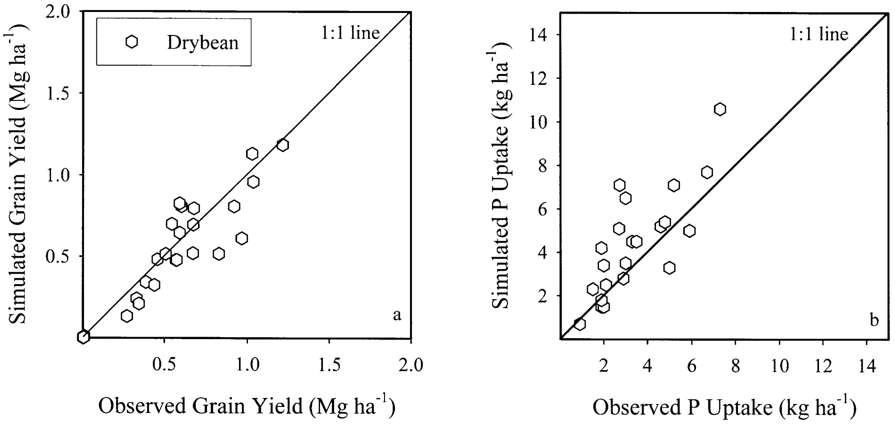

Fig. 8. Simulated and measured grain yield and P uptake by dry beans using all treatments from a P crop response experiment over two years under irrigated and rainfed conditions in Eastern Tanzania.

5. Conclusions

We designed a soil–plant P module to simulate P dynamics and P uptake by crops for highly weathered acidic soils and alkaline calcareous soils. The P module is linked with comprehensive crop simulation models that take into account the development and growth of the crop, as well as weather and soil conditions. The P module was tested with three data sets from tropical and arid areas. In general, the model does a good job in predicting yields under a variety of soil, crop, and weather conditions. However, plant P uptake was overestimated in acidic soils. This could be due to the fact that the plants adapt to low-P conditions and are more efficient in P uptake. They are able to produce grain yield with lesser amounts of P needed under temperate and less-acid soils. Another factor leading to overestimation is that the model does not take into consideration the effects of variety differences.

The P module simplifies soil–P transformations, and certain model parameters may need to be adjusted to make model more site independent. The reasonable accuracy with which the model simulates the response to P fertilizers, especially in long-term experiments, however, may justify the simplification. Additional testing is needed to improve model predictions and make sure it is more adaptable to a wide variety of soil, weather, and crop conditions. In particular, model testing of organic P mineralization is important for accurate predictions in areas where organic P is an important source of labile P.

Several areas in the model need further development. The next step in the development of the model is the introduction of a soil expert system that would integrate the initialization of the pools and rate constants of P movement between pools and arrange them in major soils categories. Soil properties that are taken into consideration include pH, clay content, $CaCO_3$ content, Fe and Al oxide content and Al saturation. This will be done after more testing has been done on the P model using additional data sets. Addition of a sub-model that simulates the dissolution of rock phosphate taking into consideration factors like the reactivity of the rock, and pH of the soil is also needed.

5.1. Availability and system requirements

The P module has the same system requirement as DSSAT v.3.5. The P module software and short documentation are published on the web and can be downloaded. The address is: http://nowlin.css.msu.edu/software/P_model_form.html (Verified 21 March, 2002).

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