

Modeling the phosphorus balance of different soils using the 4M crop model

G. Máthé-Gáspár, N. Fodor

Institute for Soil Sciences and Agricultural Chemistry, Centre for Agricultural Research, Hungarian Academy of Sciences, Budapest, Hungary

ABSTRACT

Our study focuses on the phosphorus (P) balance in two long-term fertilization experiments which were carried out in characteristic soils of Hungary with four fertilization treatments and four main crops. The objectives of this study are: (1) to quantify the P accumulation rate in the upper soil layers and (2) to calibrate and validate the P-balance module of the 4M crop model. The concentration of ammonium-lactate soluble P (AL-P) increased with time in both soils. The mean AL-P accumulation rates in the 0–20, 20–40 and 40–60 cm soil layers were 3.7, 0.7, 0.1 and 3.7, 4.3, 0.6 mg/kg/year in the chernozem and the sandy soil, respectively. The P accumulation rates in the top layers (0–20 cm) changed significantly in time as these gradually decreased from around 6.5 mg/kg/year to zero in about 26 years in both soils. The model results of the phosphorus content in different soil layers, as well as the plant phosphorus uptake were in good agreement with the observed values.

Keywords: long-term experiments; topsoil; plant; accumulation; migration

Phosphorus (P) is an essential nutrient for plants that can considerably affect the yield level and yield stability of many crops. Its interaction with nitrogen significantly contributes to optimum crop yield and nitrogen use efficiency (Usherwood and Segars 2001). Phosphorus can also be a harmful polluting agent of surface waters (Schröder et al. 2011).

It was reported several times that the systematic phosphorus fertilization increases the plant extractable soil phosphorus content (Lásztity and Csathó 1995, Blake et al. 2000, Izsáki 2009, Ma et al. 2009). The accumulation rate was found to be dependent on the soil type, cropping system, climatic conditions, as well as on the phosphorus dose. In European field experiments (three sites with different soils in the humid oceanic and humid continental climatic regions), where the annual P fertilizer dose ranged between 23 and 35 kg/ha, the soil phosphorus content did not increase significantly (Blake et al. 2000). On a chernozem soil (Hungary: temperate climate) a 100 kg/ha increase of the P balance raised the AL-P content of the ploughed layer by 3.1–4.4 mg/kg/year, when the different P fertilizer levels were compared (Izsáki

2009). At different sites in China having different soil types, with 65.5 kg/ha/year P fertilization dose accumulation rates of P_{Olsen} content varying between 0.95 and 1.24 mg/kg/year were observed (Ma et al. 2009).

The total soil P content (inorganic and organic forms) is usually divided into different pools (e.g. stable, labile, available) to ease the modelling of soil phosphorus balance (Jones et al. 1984). The primary purpose of crop simulation models is to describe the processes of the very complex atmosphere-soil-plant system using mathematical tools and to simulate them with the help of computers. There are many well-developed, user friendly software packages available (e.g. DSSAT, Jones et al. 2003). Though, there are some exceptions (Daroub et al. 2003, Dzotsi et al. 2010); many crop models do not include phosphorus, and therefore the effect of this nutrient is neglected during calculations.

In this study the 4M crop simulation model is presented and tested against measured data. Since 4M is a clone of the CERES model (Ritchie et al. 1998) originally, it did not have a P module, similarly to its ancestor. The objectives of this

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study are: (1) to quantify the P accumulation rate in three soil layers (0–20, 20–40, 40–60 cm) of two Hungarian soils in two long-term fertilizer experiments and (2) to calibrate and validate the newly developed P-balance module (Fodor et al. 2012) of the 4M crop model.

MATERIAL AND METHODS

4M is a daily-step, deterministic crop simulation model (Fodor and Kovacs 2005, Fodor and Pásztor 2010). It simulates the major processes of the atmosphere-soil-plant system including human activities (Figure 1). The P module of 4M, which was based on the work of Jones et al. (1984), is able to handle a practically infinite number of soil layers. Since every described pool and process occur in every single layer, for the sake of simplicity, the following description refers to one particular layer and day. The phosphorus turnover model breaks up the soil-plant system into three pools (Figure 2): (i) a stabile pool that comprises any phosphorus form that cannot be taken up by plants; (ii) a plant extractable nutrient pool that is postulated to be equivalent with the AL soluble soil phosphorus fraction; and (iii) a plant nutrient pool. Within

the module, the following processes are described between the pools: (1) the plant nutrient uptake determined by the demand-supply relations. The P demand depends on genetic factors as well as on the development stage of the plant, while the supply of the soil depends on the amount of phosphorus in the extractable pool, as well as on the soil water content and temperature; (2) the aging of the ‘fresh’ soil phosphorus content; (3) the nutrient immobilization and release of nutrients. Though phosphorus is usually considered to be an immobile element in the soil in coarse textured soils P leaching cannot be neglected (Matula 2009). Thus, the downward movement of phosphorus is also simulated. A detailed description of the phosphorus turnover module can be found in Fodor et al. (2012).

Data for calibrating and validating the phosphorus balance module were collected from two experimental sites having calcareous chernozem soil at Nagyhörcsök (NH) and calcareous sandy soil at Órbottyán (OB) (Table 1). Daily maximum and minimum temperature and precipitation were measured at the sites. As required by the 4M model, daily global radiation was estimated using these variables by the S-shape method (Fodor 2012).

Crops of the long-term experiment (1984–2008) were maize, winter wheat, spring barley and win-

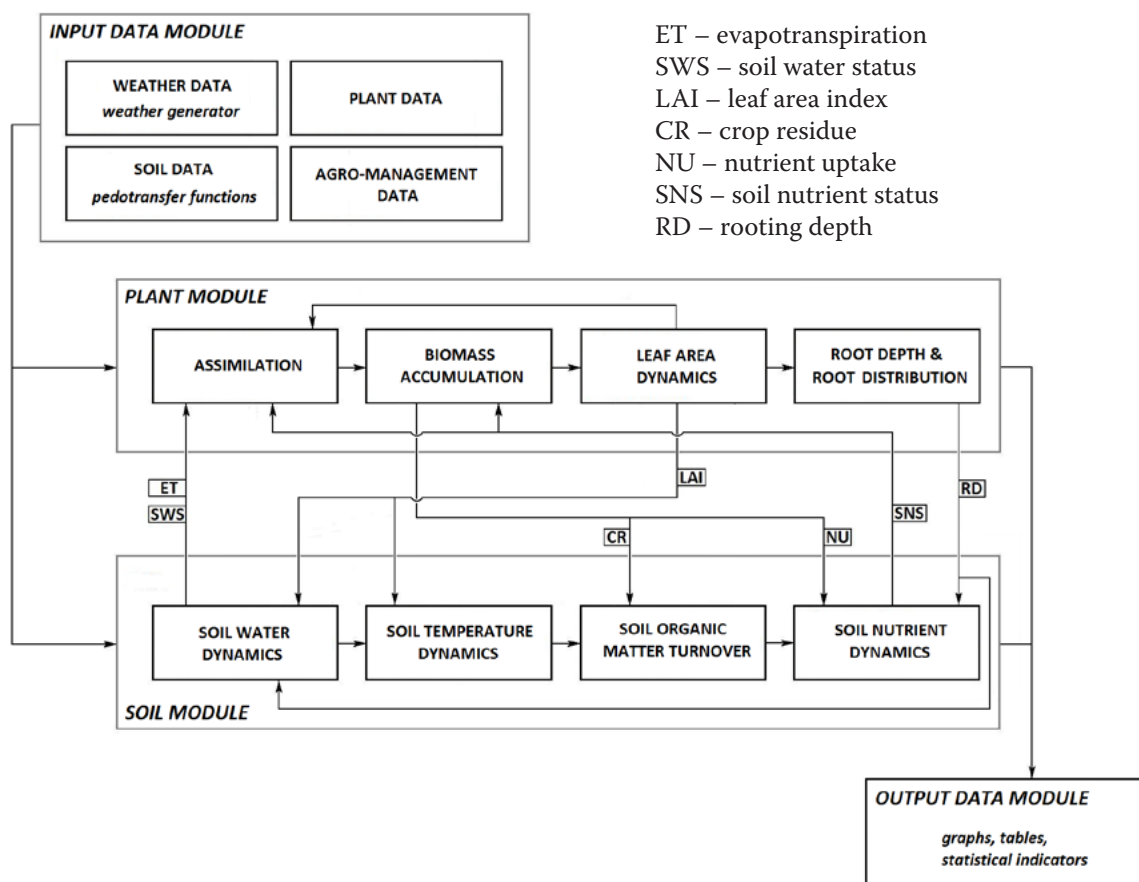


Figure 1. Simplified flowchart of the 4M crop model

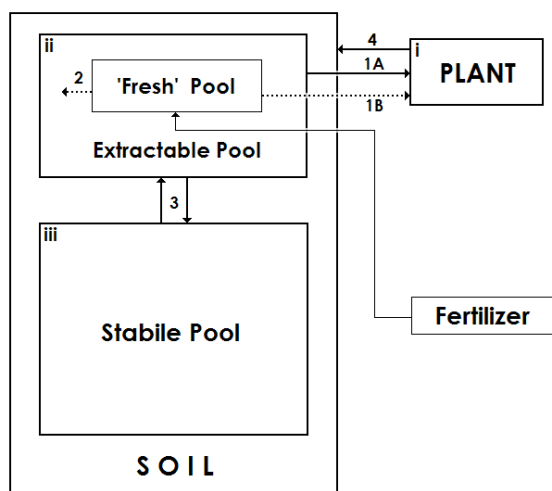


Figure 2. Simplified flowchart of the soil-plant phosphorus module. (1A and 1B) plant nutrient uptake; (2) aging of 'fresh' soil phosphorus content; (3) nutrient immobilization and release of nutrients

ter rape. Four fertilization treatments were set up receiving uniform 44 kg P/ha and 166 kg K/ha doses each year along with 0, 150, 300 and 450 kg N/ha doses, respectively. Soil samples were taken in four replicates from all treatments from the 0–20, 20–40, 40–60 cm soil layers in 1984, 1990, 1995, 2003, 2004, 2005, 2007 and 2008. Plants were sampled each year following harvest.

The nutrient content of plants was measured with ICP-OES method (Matula 2010) after plant digestion by cc. HNO_3 . Soil ammonium lactate soluble P fraction was determined according to the method of Egner et al. (1960): Add 100 mL ammonium-lactate solution, pH 3.70 (0.1 mol/L ammonium-lactate and 0.4 mol/L acetic acid) to 5 g air dried soil, shake for 2 h and filtrate, determine P using ICP-OES (Jobin Yvon Ultima 2

Manufactured by HORIBA Scientific, Longjumeau, France).

The changes of the phosphorus accumulation rate in the 0–20, 20–40 and 40–60 cm soil layers were investigated. A second order polynomial function (f) was fitted on the measured soil AL-P values (Figure 3). This function can be used for extrapolating the accumulation rate values beyond the ending date of the experiment. The date of saturation, when the accumulation rate becomes zero, can be determined by finding the date satisfying the $f' = 0$ condition, where f' denotes the first derivative of the f function.

The plant production data (planting date, plant density, fertilization doses, etc.) were recorded in each year. In Table 2 only the characteristic values are presented since the actual dates were subject to change due to environmental (e.g. water content of the topsoil) and technical (e.g. availability of machinery) factors.

The plant specific parameters of the model were adjusted by inverse modeling (Soetaert and Petzoldt 2010) so that the simulated occurrence dates of the major phenological stages as well as the calculated yield and biomass values would be in the best agreement with the observed values. To carry out this procedure the length of the phenophases, the light use efficiency and the matter-area conversion factor for calculating LAI development were altered systematically till the difference between the observed and calculated values reached its minimum.

Measured soil AL-P contents of the N150 and N300 treatments were selected for NH (chernozem) and OB (sand), respectively, because the highest average yields were observed in these treatments. Four parameters (Table 3) of the P module were adjusted in order to achieve the smallest average

Table 1. Parameters of the investigated soils in the 0–20, 20–40 and 40–60 cm soil layers at the beginning of the long-term experiment (1984, Nagyhörcsök (NH) and Örbottyán (OB), Hungary)

Soil parameters	Chernozem (NH)			Sand (OB)		
	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
$\text{pH}_{\text{H}_2\text{O}}$	7.29	7.24	8.10	7.17	7.23	7.31
Humus content (%)	2.74	2.17	1.06	1.0	0.9	0.8
Bulk density (g/cm^3)	1.38	1.42	1.40	1.65	1.67	1.59
CaCO_3 content (%)	9.5	9.5	10.8	8.7	8.7	8.9
Clay content (%)	24	24	24	5	7	5
Field capacity (cm^3/cm^3)	0.323	0.323	0.328	0.155	0.189	0.172
Wilting point (cm^3/cm^3)	0.125	0.131	0.130	0.040	0.055	0.050
Saturated hydraulic conductivity (cm/day)	12	8	10	105	75	95

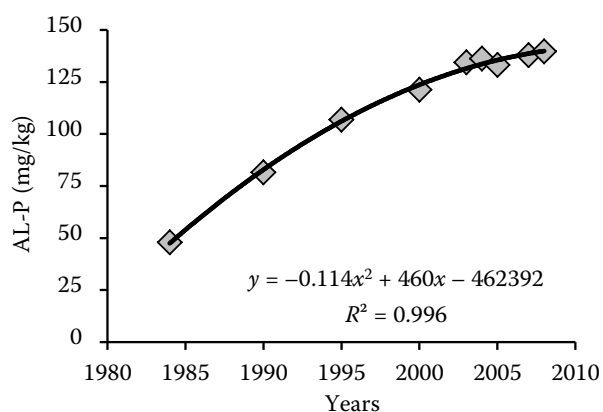


Figure 3. Measured soil AL-P values and the fitted polynomial function in the N450 treatment at Nagyhorcsök (chernozem), Hungary

difference between the measured and calculated soil AL-P contents.

The very same model parameter values that were determined during the calibration were used for validation. The simulation results and the observed soil P and plant uptake values were compared using graphical and statistical indicators.

RESULTS AND DISCUSSION

The P accumulation rates in the topsoil changed significantly during the long-term fertilization experiments. According to the applied extrapolation method (polynomial fit) the saturation of the 'extractable' P-pool of the topsoil (0–20 cm) required about 26 years in both soils. The initial and the average rates were 6.5 and 3.7 mg P/kg/year, respectively, for both soils. In the second layer (20–40 cm), the AL-P accumulation process differed significantly for the two soils. The phosphorus accumulated almost 6 times faster in the sandy soil (average rate: 4.3 mg P/kg/year) than in the loamy, chernozem soil (average rate: 0.7 mg P/kg/year). Similar observations were made by Lásztity (1991) for sandy soils. In this layer, the accumulation rates were practically invariant during the time span of the experiment for both

soils. The AL-P content of the deeper (40–60 cm) soil layer did not change in the chernozem soil, but in the sandy soil it was increasing slowly but continuously.

Significant differences could be observed between the N0 and N150 treatments as far as the plant P uptake was concerned. In the N0 treatments 711 and 400 kg/ha total phosphorus uptakes were observed at the NH and OB sites, respectively during the 24 years of the experiments. In the N150 treatments the corresponding values were 1014 and 576 kg P/ha for the two sites. In the treatments with higher N doses no further significant change in the plant P uptake was observed. Total plant P uptakes from the applied amount (2400 kg P/ha in 24 years) were the following: OB – 16.7, 24.0, 26.7 and 26.8%; NH – 29.6, 42.3, 41.0 and 41.2% for the 0, 150, 300 and 450 treatments, respectively.

The similar rates (3.7 mg P/kg/year) of phosphorus accumulation in the 0–20 layers did not reflect the different phosphate fixation capacity of the two soils. This could be explained by the higher phosphorus leaching rate in the sandy soil. The lower phosphate absorption capacity of the sandy soils together with the lower plant P uptake allow more phosphorus to freely migrate downward with the percolating soil water.

The parameter results of the model calibration are presented in Table 3. The model outputs were plotted against the measured values in Figure 4. The P module of the 4M crop model could simulate the trends of the soil phosphorus content and the plant uptake at an acceptable level. The model was successful in differentiating between the two soils regarding their phosphorus accumulation characteristics which are considerably different especially for the 20–40 cm layer. The calculated soil AL-P values were within the measurement error defined range of the observed values except for the bottom layer (40–60 cm) of the sandy soil in the first period of the experiment (Figure 4). This deviation could be explained by the overestimation of the plant P uptake in this period. Though, in general, the model slightly overestimated the plant P uptake, there was

Table 2. Agro-management data of the investigated crops. Dates are averages for the 1984–2008 period

Crops	Date of sowing (DD/mm)	Date of harvest (DD/mm)	Plant number/m ²	Date of fertilization (DD/mm)	
				autumn	spring
Maize	30/04	25/10	6	01/11	25/04
Spring barley	05/04	25/07	400	01/11	25/03
Winter rape	15/09	15/07	80	05/09	20/03
Winter wheat	25/10	25/07	500	20/10	20/03

Table 3. Values of the calibrated parameters of the phosphorus module

Parameter	Value	
	chernozem	sand
Maximum P transformation rate between the extractable and stabile pools (kg/ha/day)	0.00055	0.0001
Equilibrium ratio of the extractable/stabile pools	1/8	1/4
P release rate from the extractable pool (kg/ha/day)	0.0008	0.0012
P drainage rate (kg/ha/day/mm)	0.003	0.010

one particular year (1993, indicated in Figure 4) when the simulated crop was failed resulting in practically zero estimated phosphorus uptake. 1993 was a year with severe drought with only 166 mm precipitation in the vegetation period (maize; April 20th–September 20th). Despite this fact the real plants took up 56 and 30 kg/ha phosphorus at the NH and the OB sites, respectively.

Using the calibrated parameter values the model provided good estimations of the soil phosphorus accumulation and plant phosphorus uptake (Figures 5

and 6) for the rest of the treatments at both sites. The average relative difference between the observed and calculated uptakes for the 24 years of the experiments ranged between 5 and 17% for the 6 (3 + 3) treatments. The model was able to simulate the phosphorus saturation in the 0–20 cm at Nagyhörcsök (chernozem) as well as in the 0–20 and 20–40 cm layers at Örbottyán (sand). The model was also able to predict the considerable downward flow of phosphorus in the coarse textured sandy soil.

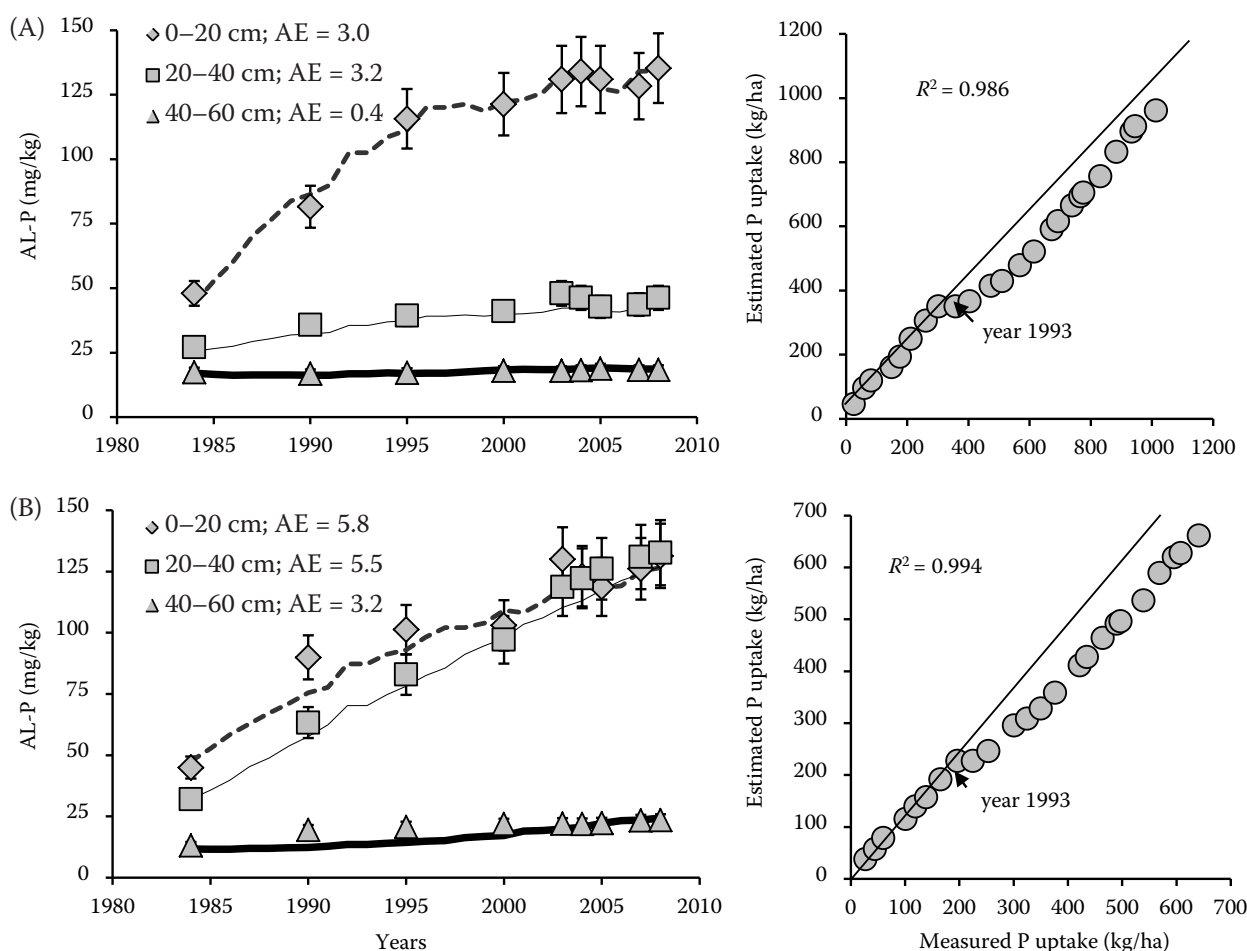


Figure 4. Measured (dots) and simulated (lines) soil AL-P values as well as the cumulative plant phosphorus uptake in the N150 treatment at (A) Nagyhörcsök (chernozem) and in the N300 treatment at (B) Örbottyán (sand), Hungary. The dimension of the average error (AE) values is mg/kg. Vertical error bars on the soil AL-P graphs denote the measurement error ($\pm 10\%$)

On the other hand, the comparison of the model and experimental results revealed some weaknesses of the model. Possible explanations for the deviations that could be observed in the graphs are the following. (1) There is only a smaller amount of available measured data for the early but more dynamic period (1984–2000) of the accumulation process which made it more difficult to accurately calibrate the model. (2) Due to the crop rotation

(plants with early and late harvest alternated) the soil sampling could not be carried on the same date in each year. Differences in the environmental circumstances (e.g. soil moisture content) at sampling may affect the soil AL-P content (Štípek et al. 2004). (3) Both soils have horizons with smooth transitions which had to be simplified by defining distinct soil layers with sharp boundaries for the simulations. (4) The model parameters

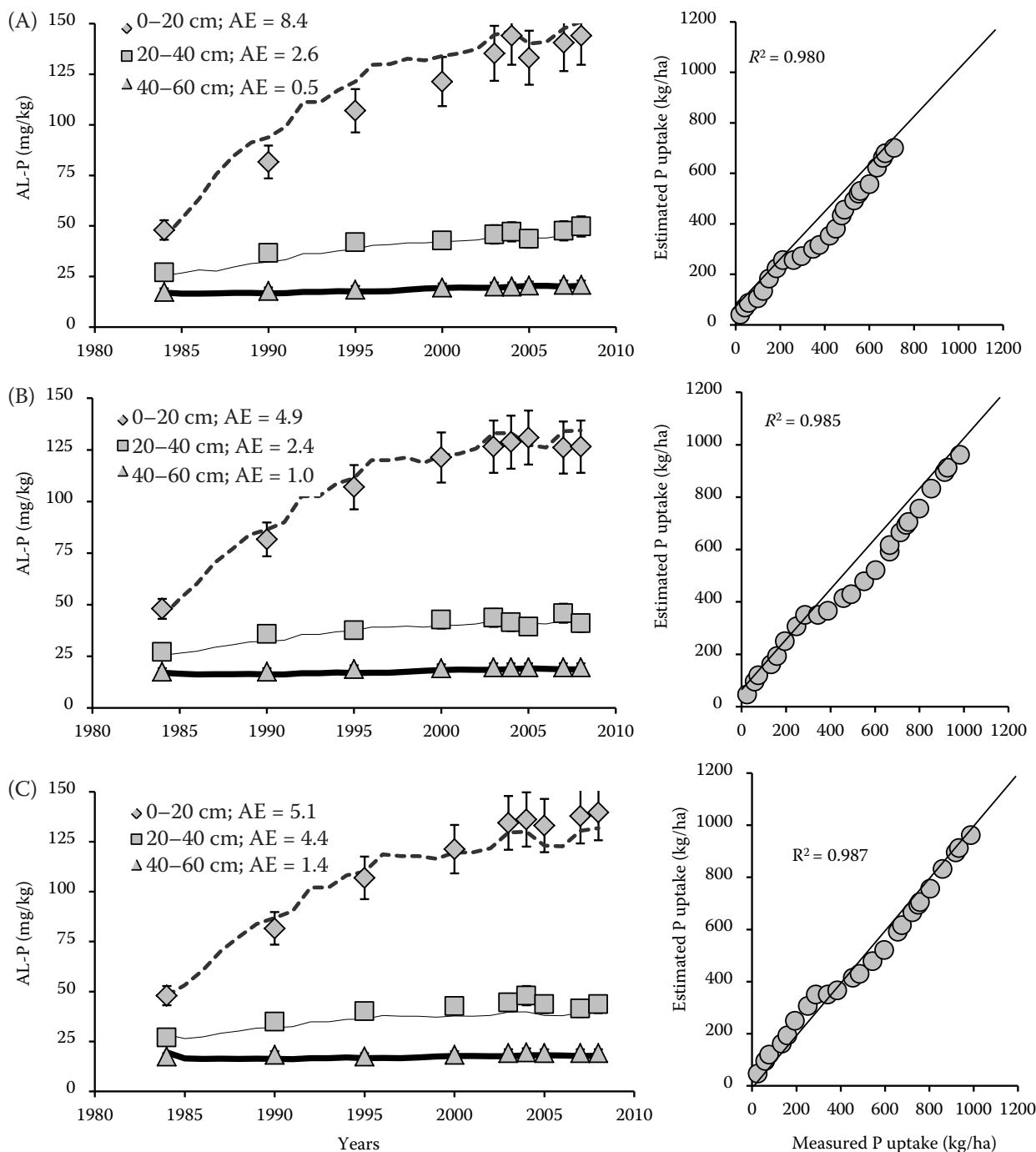


Figure 5. Measured (dots) and simulated (lines) soil AL-P values as well as the cumulative plant phosphorus uptake in the (A) N0; (B) N300, and (C) N450 treatments at Nagyhorcsök (chernozem), Hungary. The dimension of the average error (AE) values is mg/kg. Vertical error bars on the soil AL-P graphs denote the measurement error ($\pm 10\%$)

describing the phosphorus balance of the simulated soil-plant system were considered to be invariant for the 24-year-long experiments though these parameters could be subject to change as they are interdependent on other system variables (Helal and Dressler 1989).

During the timeframe of the experiment the measured humus content increased significantly in the highest N fertilizer treatment on sandy soil

(from 1% to 1.3%), but the simulated humus content of this treatment did not increase with the same intensity (from 1% to 1.15%) which could cause the underestimation of the soil P content as it can be seen in Figure 6. The higher soil organic matter content results in higher water storing capacity which affects (stimulates) soil microbial activity (Szili-Kovács et al. 2007), plant growth and consequently the soil phosphorus balance as well.

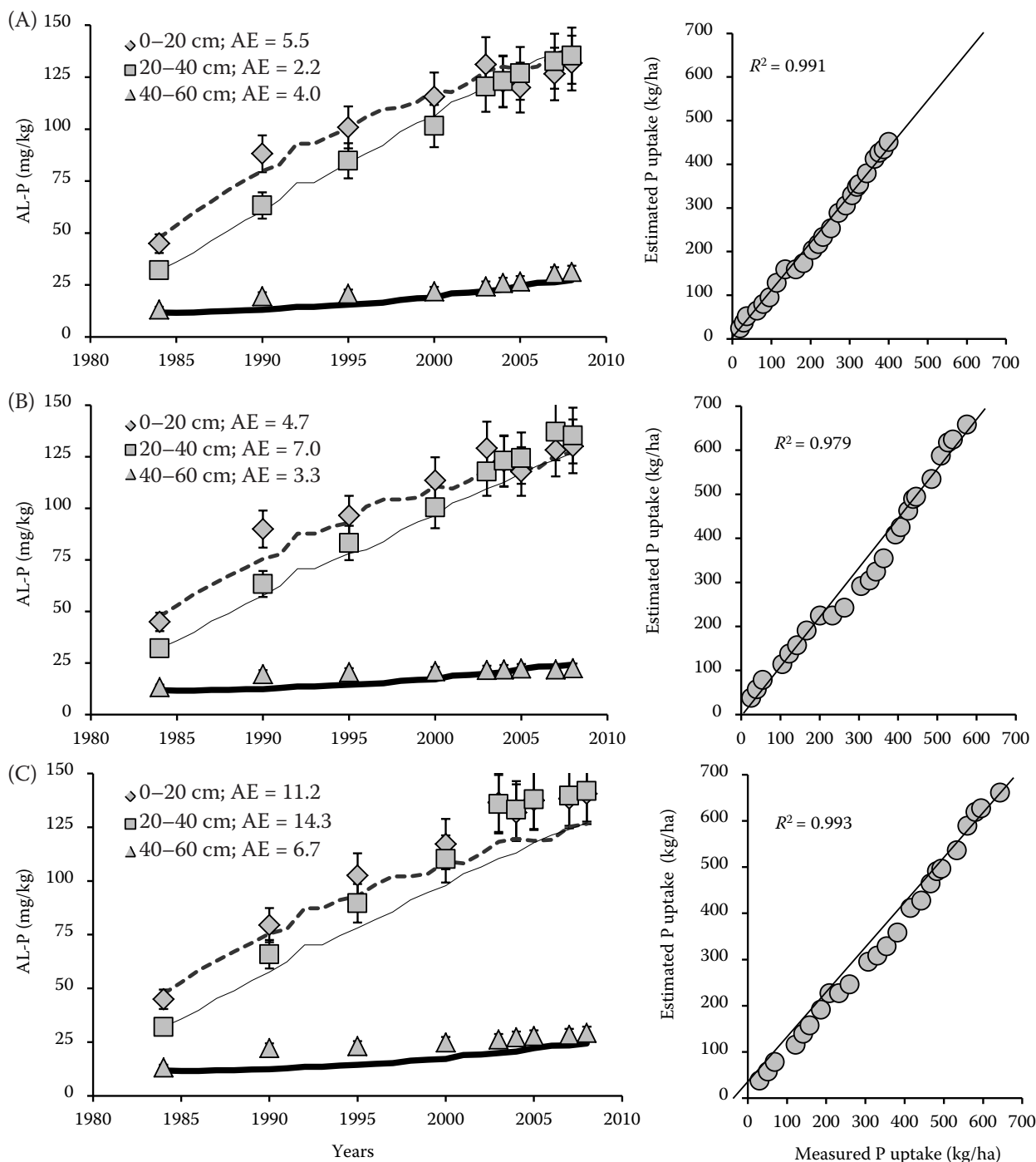


Figure 6. Measured (dots) and simulated (lines) soil AL-P values as well as the cumulative plant phosphorus uptake in the (A) N0; (B) N150, and (C) N450 treatments at Örbottyán (sand), Hungary. The dimension of the average error (AE) values is mg/kg. Vertical error bars on the soil AL-P graphs denote the measurement error ($\pm 10\%$)

The accuracy of the P module is interdependent on other modules of the crop model, thus the predictions of the P balance could be enhanced by improving the interrelated modules or by better parametrization of the functions describing the connections between the modules. The model could be further developed by enabling it to use parameters changing in time. According to the results, the capability of the model to handle/simulate extreme climatic events (e.g. severe drought) should be enhanced as it is a weak point of crop models in general (Van der Velde et al. 2012).

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Corresponding author:

Nandor Fodor, Ph.D., Centre for Agricultural Research of the Hungarian Academy of Sciences, Herman Ottó str. 15., H-1022 Budapest, Hungary
phone: + 36 208 863 720, e-mail: fodor.nandor@agrar.mta.hu
