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Efficiency of phosphorus resource use in Africa as defined by soil chemistry and the impact on crop production

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Abstract

By 2050 the global population will be 9.7 billion, placing an unprecedented burden on the world's soils to produce extremely high food yields. Phosphorus (P) is crucial to plant growth and mineral fertilizer is added to soil to maintain P concentrations, however this is a finite resource, thus efficient use is critical. Plants primarily uptake P from a labile (available) P pool and not from the stable solid phase; transfer between these pools limits bioavailability. Transfer is controlled by soil properties which vary between soil types. The dynamic phosphorus pool simulator (DPPS) quantifies crop production and soil P relationships by utilising the transfer. This approach effectively models crop uptake from soil inputs, but it does not quantify the efficiency use. This study incorporates geochemical techniques within DPPS to quantify the efficiency of fertilizer-P use based on soil chemistry.

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Keywords: phosphorus; soil; DPPS; soil resources; modelling;

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Nomenclature

S	Stable phosphorus pool size which is unavailable to crops (kg/ha)
L	Labile phosphorus pool size which is available to crops (kg/ha)
k	Reactivity constant (unitless)
M	Concentration of oxalate iron and aluminium (kg/Ha)
a	Rate constant (kg.yr/Ha) (for this study = 1)
t	Time (yr)
f_x	Flux to or from x (kg/ha/yr)
r_x	Rate from x (yr^{-1})
F,c,A	Inputs fertilizer, crops, agricultural products (manure, litter, *etc.*)

1. Introduction

Soil phosphorus (P) is a critical resource for crop and food production. In essence it can be thought of as two resources: firstly "natural" soil P which exists due to biogeochemical soil forming processes, and secondly anthropogenic P (fertilizer and manure) which is added to the soil during agricultural processes. Today, due to the need to produce high yields to feed the high contemporary global population, most agricultural systems around the world cannot be sustained on natural soil P alone and rely heavily upon anthropogenic P, in particular P-fertilizer [1–3]. Population growth is set to increase and this in turn will increase demands on ecosystem services including soil, thus increasing demands for P-fertilizer [4]. This is cause for concern given that P-fertilizer is mined from geological resources and is therefore a finite resource for which the estimates of remaining supply range from the next couple of decades [5] to a century or so hence [6]. Thus globally the efficient use of P in agricultural systems is of paramount importance when meeting the challenge of feeding the growing global population.

Throughout the 20th century different areas of the world have had very different P histories. As continents Europe, North America, Asia and Oceania have increased soil P concentrations dramatically with heavy (and in some cases excessive) use of P fertilizer, South American soils have had low to moderate increases in soil P concentrations. Africa is notable because it is the only continent which has not increased soil P concentrations throughout the 20th century, and in many cases has a negative P budget [1,3]; this P history is reflected in lower food yields than most of the rest of the world [7]. The lack of P increase in African soils is caused by low fertilizer inputs due to socio-economic factors [5].

Within Africa a general trend of intensification of farmed areas has occurred [1,3]. Between 1970 and 2000 total P uptake by plants nearly doubled from 295,000 tons of P in 1970 to 540,000 tons in 2000. In 1970 the distribution of uptake was even across the continent, however by 2000 large areas of central tropical regions like D. R. Congo and Central African Republic lacked significant P uptake (Figure 1A & B). The continental increase in P uptake corresponds to a 30% increase in croplands between 1970 and 2000, up from 1.55×10^8 ha to 1.99×10^8. However, like the distribution of uptake, the croplands have become restricted to fewer regions and the central tropical region of the north Congo lack significant areas of croplands (Figure 1C & D) [1,3].

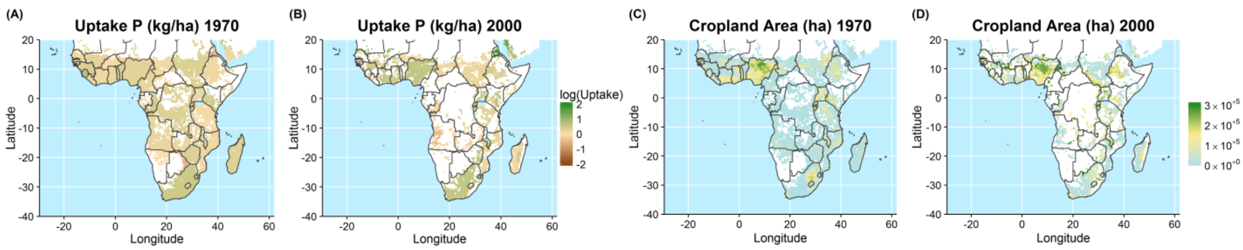

Figure 1 (A) Total P uptake (Kg/ha) across Sub-Saharan Africa for 1970 and (B) 2000; (C) Total cropland area (ha) for 1970 and (D) 2000 [1,3].

However, regardless of anthropogenic processes, natural soil geochemical processes will also limit the amount of P available to plants. Soil P exists within the soil in different forms called pools. At the simplest conceptual level two pools can be considered [1–3]: firstly a labile pool from which plants can uptake P [8,9], and secondly a stable pool which is unavailable to the plants [10]. These pools are not fixed and there is transfer between the pools which is largely controlled by geochemical processes [11]. When P fertilizer is added to soil it is added to the labile pool where it can be utilized by crops. However due to the transfer effect some of the fertilizer will be sequestered by the soil and become unavailable to plants. Because this transfer is controlled by soil geochemistry, soils with contrasting geochemistries will have different rates of transfer [11]. Thus it can be considered that fertilizer P efficiency varies with soil geochemistry.

Current global P soil modelling has focused on calculating the amount of P required to feed the global population by 2050 [1–3]. This research has revealed important insights including the effect of changing dietary habits on P sustainability [1]; however these studies do not consider the geochemistry of the soil in their calculations, instead relying on history matching to calculate the transfer rate. This means that the studies cannot provide estimates of the efficiency of soil P use with respect to soil geochemistry. The aims of this research are to: 1) provide a geochemical framework with which to improve the quantification of efficiency in P use in agricultural systems based on the soil geochemistry; and 2) use case studies from a subset of African countries to indicate the benefits of this approach in terms of modelling P resource efficiency.

2. Methods

2.1 Approach

A simplified version of the dynamic phosphorus pool simulator (DPPS) was developed to model crop uptake and changes in soil P pool sizes for given inputs and outputs [1–3,12]. This version of DPPS considers two pools: labile (or available) P (L) from which plants can uptake P [8,9] and a stable pool (S) from which they cannot uptake and is relatively fixed. No external stresses on the stable pool are assumed, and neither is any runoff: these are major simplifications with respect to earlier models (Figure 2). Transfer between the labile and stable pool is controlled by a geochemical model and is considered irreversible [11] to distinguish this DPPS from earlier versions – we will call this Geochemical-DPPS (G-DPPS). There is likely to be a separate, unrelated transfer from the stable pool to the labile through different processes (e.g. mineral dissolution). In Nigerian soils this would be at a rate of about 0.00002 yr^{-1} [13], so for simplicity this is assumed to be negligible and the rate is set to 0.

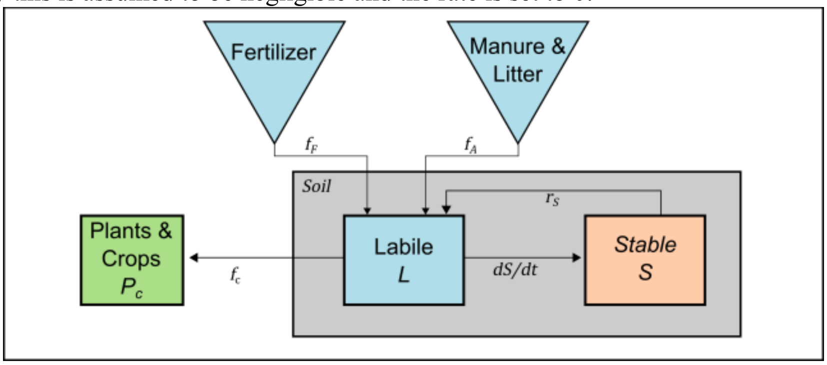

Figure 2 Schematic showing the simplified GDPPS model used for this study

2.2 Model

The transfer between the labile and stable pools is controlled using the van der Zee transfer model (Eq. 1) [11].

$$S = k \cdot M \cdot ln(a \cdot L \cdot t) \quad (1)$$

Where S is the size of the stable pool when controlled entirely by the geochemical relationship with the labile pool, L (kg/Ha), t is time (yr), a is a rate constant (kg.yr/Ha), M is the concentration of oxalate iron and aluminium combined (kg/Ha), and k is reactivity constant. The stable pool will change as the labile pool changes (Eq. 2 & 3).

$$\frac{dS}{dL} = \frac{k \cdot M}{L} \quad (2)$$

$$\frac{dS}{dt} = \frac{dS}{dL} \cdot \frac{dL}{dt} = \frac{k \cdot M}{L} \cdot \frac{dL}{dt} \qquad (3)$$

The size of the labile pool will change due to input fluxes (kg/ha/yr) from fertilizer (f_F) and manure (f_A), output fluxes from crop uptake (f_c), and transfer to the stable phase (Eq. 4). This is solved by substituting equation 3 into it, forming equation 4.

$$\frac{dL}{dt} = f_F + f_A - f_c - \frac{dS}{dt} \qquad (4)$$

$$\frac{dL}{dt} = \frac{f_F + f_M - f_c}{1 + \frac{k \cdot M}{L}} \qquad (5)$$

2.3 Data and implementation

Gridded data for the years 1970 and 2000 for P plant uptake, fertilizer and manure input, and area of croplands farmed are provided from earlier published studies [1,3]. Estimates of labile soil P concentrations for pre-industrial agricultural soils were used as the baseline for this study [14]. A database of Fe & Al oxalate concentrations and other soil chemical parameters was compiled from studies conducted across Sub-Saharan Africa (the full database is provided online at http://personalpages.manchester.ac.uk/staff/vahid.niasar/projectdata.html). This database is coupled to a Geographical Information System (GIS) soil type map of Sub-Saharan Africa defined by USDA taxonomy, provided by the International Soil Reference and Information Centre (ISRIC, UN) via the SoilGrids project (http://www.soilgrids.org) under an Open Data Commons Open Database License (ODbL) [15] and forms oxalate Fe and Al maps of the region. The value of k is set from initial labile and stable P concentrations and the oxalate Fe and Al Maps.

The model is run for individual countries assuming aggregated soil conditions across the country. Countries were selected to have contrasting soil chemistries and either positive or negative P balances (inputs – uptake). Historical P fertilizer and uptake data for individual countries is provided from the Food and Agriculture Organization (FAO, UN) databases [16], with published estimates of the ratio of fertilizer to manure for Africa for the years 1965 to 2002 used to calculate manure for individual countries [2]. P uptake was history-matched against the labile pool size; this approach tacitly considers non P factors on uptake, such as anthropogenic and climatic factors.

3. Results

3.1 Soil Chemistry

There are six dominant soil types across Sub-Saharan Africa as defined by USDA soil taxonomy. The mid latitudes and southern West Africa are dominated by Ultisols, north of these are Alfisols and south are the Oxisols. Entisols dominate most desert areas north of 15 °, including the southern Sahara, Somalia, East Ethiopia and large areas of southern Africa. Vertisols are mostly restricted to South Sudan and Western Ethiopia (Ethiopian Highlands) (Figure 3A). The database of soil chemical parameters shows that the concentration of oxalate Fe and Al have model definable ranges. Whilst there is considerable overlap, there are variations in both the mean and errors: Fe concentrations are significantly higher than Al (Figure 3B & C).

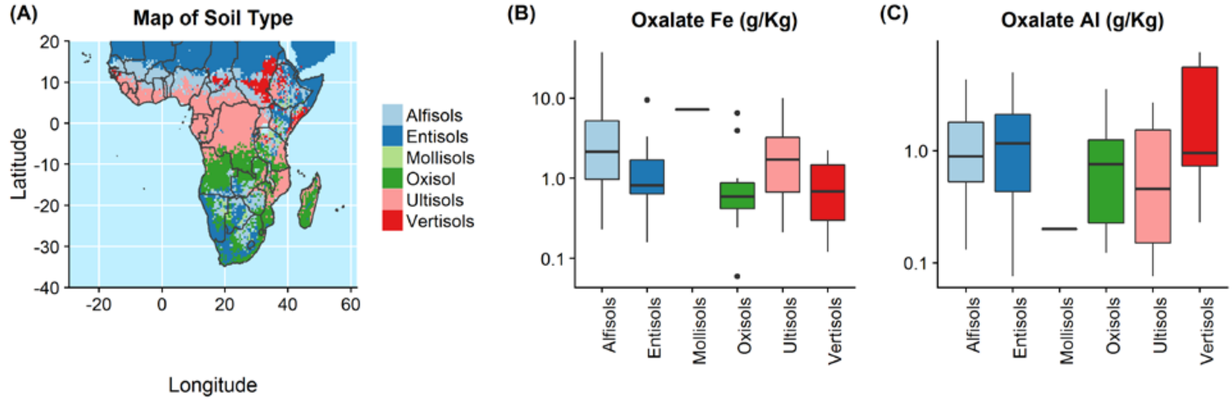

Figure 3 (A) Map of African soil types defined by the USDA taxonomy system [15]; (B) concentration of oxalate iron (g/kg) for soil types and (C) concentration of oxalate aluminium (g/kg) of soil types. B and C and defined using the database compiled for this study.

Fe and Al range from 0.06 to 37.2 g/kg and 0.07 to 8 g/kg respectively (Figure 3B & C). The highest Fe concentrations are across the tropical latitudes just north of the equator, whilst the lowest values are in the desert areas north of the tropics (Figure 4A). Al concentrations are highest in north east Sub-Saharan Africa (Figure 4B). Labile P concentrations have a median of 80 mg/kg and range from 10 to 530 mg/kg across Sub-Saharan Africa, with the lowest concentrations in the central latitudes (Figure 4C). The stable P concentrations are much higher ranging from 130 mg/kg to 4400 mg/kg. Both follow a similar distribution with notably lower concentrations on the equator at the north end of the Democratic Republic of Congo (D. R. Congo) and in the Central African Republic (Figure 4D).

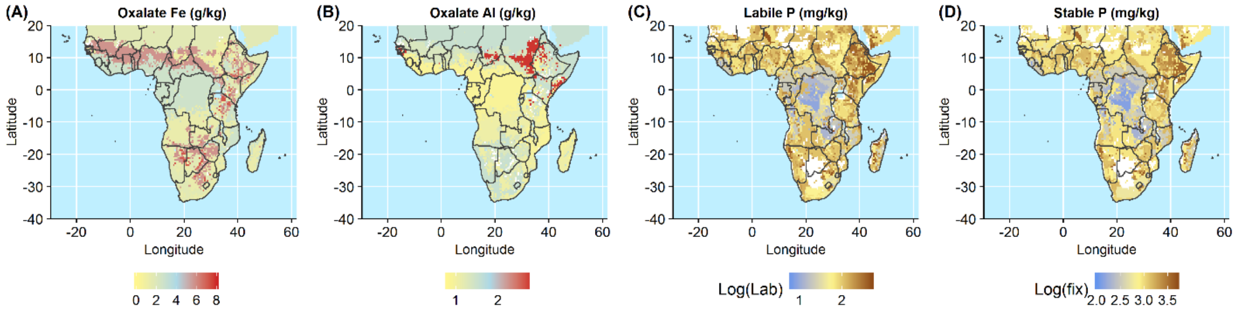

Figure 4 Distributions of concentrations of (A) Fe oxalate (g/kg), (B) Al oxalate (g/kg), (C) Labile P (mg/kg) [14], and (D) Stable P (mg/kg) across Sub-Saharan Africa [14].

3.2 Country Selection

Based on the P history and soil chemistry, the following countries were selected: Angola, Central African Republic, Ethiopia, Kenya, and Nigeria. Nigeria and Central African Republic were selected because both have significant proportions of tropical Ultisol soils; however Nigeria has had an increase in P uptake intensity whilst Central African Republic consistently had low P uptake. Central African Republic is located almost entirely on an area of low labile P, unlike the D. R. Congo which has a mixture of higher and low labile P (thus Central African Republic is selected to prevent non-representative results due to aggregation of non-Ultisol soils). Angola is selected because it has Oxisol soils, moderate labile P concentrations, and relatively stable P uptake. Ethiopia and Kenya are selected because both have had intensifications in P uptake, but they have very different soil types: Ethiopia has mixed soils whilst Kenya predominantly has Alfisols and Entisols.

3.3 Modelling

There is a good correlation between measured and modelled uptake of P (R^2 = 0.87 for all countries), however the detailed local variations are not reproduced by the model (e.g. Angola) (Figure 5B). There are variations between the different countries in P balance: for example whilst the P balance for all countries is negative in 1970, Kenya and Ethiopia have a positive P balance by 2000 but Angola and Nigeria remain P negative (Figure 5A). P balance is modelled very accurately (R^2 = 0.97); however the fit is strongly affected by the inputs and not just modelled outputs. Kenya and Ethiopia have both seen large increases in fertilizer application rates; however in Angola and Nigeria application rates remain low (<1 kg/ha) (Figure 5C). In all countries the labile pool is decreasing. In terms of percentage, the highest rates of labile P loss are in Kenya and Nigeria which have a modelled labile P loss of about 25 %; for comparison Angola has only had a loss of 10 % and Ethiopia has had a P loss of 6.6 % (Table 1).

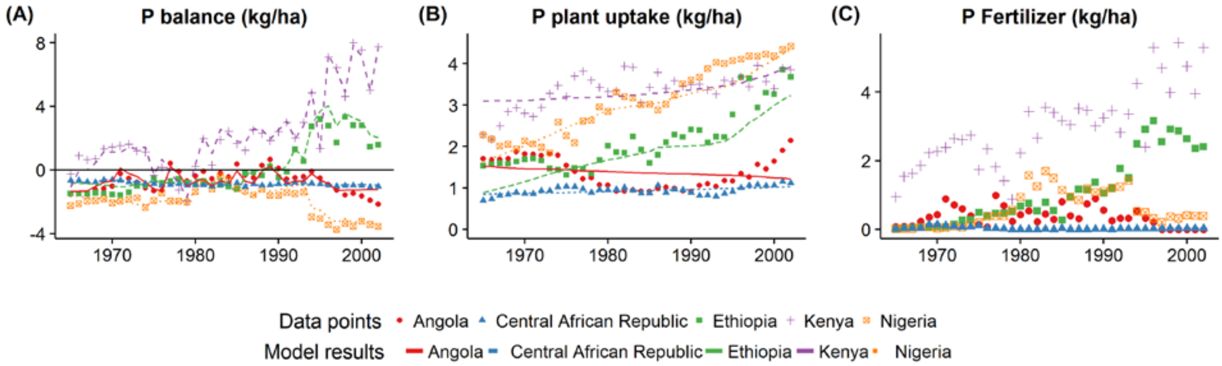

Figure 5 (A) P balance for labile pool (inputs – uptake, kg/ha) (B) plant uptake (kg/ha); (C) fertilizer application (kg/ha). Data is illustrated with points and modelled results with lines.

Table 1 Soil dominant types, starting labile P concentrations (1965), final modelled labile P concentrations (2002), total labile P loss, percentage labile P loss, and cumulative balance for individual countries.

Country	Soil Type	Labile P 1965	Labile P 2002	Labile P Loss	Labile P Loss	Cumulative P Balance
			kg/ha		%	kg/ha
Angola	Oxisol	95	84	9.4	10	-30
Central African Republic	Ultisol	65	55	8.7	14	-30
Ethiopia	Alfisol, Entisol, Ultisol, Vertisol	230	210	15	6.6	10
Kenya	Alfisol (south), Entisol (north)	155	120	34	23	85
Nigeria	Alfisol (north), Ultisol (south)	65	50	17	25	-70

4. Discussion

The effect P exerts on food production is shown most starkly in comparisons between the distribution of labile P in virgin (pre-industrial agricultural) African soils, the distribution of P uptake for the year 2000, and the distribution of farmed cropland in 2000 (Figure 1B & Figure 4C). Virgin soils in central Africa had a very low labile P concentration; this area is mostly in the north D. R. Congo and almost all of the Central African Republic. Concentrations in the low labile P region were a magnitude lower than anywhere else on the continent (Figure 4C). By 2000 P uptake on this low labile P area was far lower than any other region of Sub-Saharan Africa, despite it being farmed in 1970 (Figure 1A & B). This suggests that these low labile P soils cannot sustain high intensity agriculture required for the 21st century, and G-DPPS can be used to test this hypothesis.

The low labile P region is restricted to the Ultisol soil type (Figure 3A & Figure 4C), but there are other relationships between soil type and agricultural output that are less related to initial labile P concentrations. The relationship between soil type and farming intensity exists throughout the continent. For example, by 2000 Nigeria had some of the highest density agriculture on the continent, yet this was mostly restricted to the northern Alfisols rather than the southern Ultisols. Similarly in Kenya the highest agricultural intensity is on the southern Alfisols rather than the northern Entisols. The same pattern exists in Ethiopia where eastern Entisols have the lowest intensity and other soils (Alfisols and Vertisols) have much more intensive farming (Figure 1D & Figure 3A). These distributions demonstrate the influence that soil type and initial labile P concentrations have over agricultural distribution. However, in terms of P efficiency, the relationship between these soils and changing labile pools is critical; G-DPPS is used to assess this.

The P balance (the differences between inputs and uptake) shows great variation between countries, which is probably due to socio-economic factors; the values calculated by this study are consistent with another recent global study [17]. Highest fertilizer use is in Kenya and Ethiopia (Figure 5C), yet it is Nigeria that is noticeable for having a high rate of P uptake with relatively low P fertilizer application. G-DPPS assesses the effect that these forcings have on changes in labile pool size. Whilst there is a range of cumulative P balance for the period 1965 to 2002 with values from -70 to 85 kg/ha all soils have loss from the labile pool; for countries with a positive P balance this is due to the effect of the labile to stable transfer (Table 1).

Alfisols are arguably the most important soils for agriculture across the north of the continent, and are the dominant farmed soils in Kenya and Nigeria, countries with markedly different P histories (Figure 1D, Figure 3A & Figure 5C). Kenya and Nigeria have cumulative P balances between 1965 and 2002 of 70 and -85 kg/ha respectively, and initial labile P pool sizes of 154 and 65 respectively; yet both had a soil loss of about 25 %, which is largely due to transfer to stable pool (Table 1). Conversely Angola and Central African Republic had very similar P histories between 1965 and 2002: both had a cumulative P balance of 30 kg/ha loss, yet labile P was 10 % and 14 % respectively, and it is likely that these differences are due to the soil chemistries (Figure 5C, Table 1). The lowest labile P loss was in Ethiopia (6 %): this is despite it having a lower cumulative P balance (10 kg/ha) than neighboring Kenya (Table 1). Whilst the reason for this is likely to be related to soil chemistry, there may also be a “model effect” due to the aggregation of many soil types. Ethiopia’s aggregation includes Entisols, which do not produce a high van der Zee transfer as they are low in low oxalate Fe (Figure 2B).

Finally, Alfisols are the most important agricultural soils in Sub-Saharan Africa in terms of farmed cropland (Figure 2A and Figure 4D). However these soils are also highest in oxalate Fe and Al (Figure 2B & C): the van der Zee transfer model [11] states that because of the high oxalate Fe concentrations, these soils will have the highest rate of transfer of P from the labile pool to the stable pool when a stress is exerted on the system. Thus it appears that the soils most utilized for farming in Sub-Saharan Africa are also the soils most at risk of labile soil P loss due to internal and irreversible P transfer to stable pool. Thus they are least efficient in terms of fertilizer use.

The rates of loss reported here should not be considered representative of the “real” system, because the model is extremely simplified and does not consider any transfer from the stable pool to the labile pool, or runoff from either pool. Furthermore it has been calculated on aggregated country means rather than the more spatially accurate gridded approach [1,3]. However the approach does indicate the importance of considering geochemistry when conducting this type of modelling. More detail could be added in considering the Langmuir adsorption transfer between porewater and adsorbed pools. Most importantly it also highlights the risk of labile P loss in Alfisols, which warrants further research. G-DPPS could be particularly useful in forecasting future labile P pool sizes in areas like Nigeria that have low fertilizer use and high P uptake, which is leading to a fast rate of labile P loss further exacerbated by the internal P transfer to stable pool.

5. Conclusions

The results from this study show that the use of geochemical techniques to control the transfer of P between labile and stable pools of the G-DPPS model can provide good estimates of P uptake, even when greatly simplified and working on country averages. This article provides a methodology for defining soil chemistry by soil type, allowing easy global implementation when using GIS software coupled with the SoilGrids ODbL database. The model itself fits neatly into the existing DPPS model with only moderate changes.

The results from this study indicate that soil chemistry affects the rate of labile P loss causing differences in proportions of labile P loss between soil types, even where P histories are similar (e.g. Nigeria versus Angola). An important outcome of this research is that soils high in oxalate Fe and Al area are at high risk of labile P loss due to transfer to the stable phase. In Sub-Saharan Africa Alfisols have some of the highest oxalate Fe and Al concentrations, yet these are also the most agriculturally important soils in the region. Thus the most agriculturally important soils are at highest risk of labile P loss due to natural geochemical processes. We emphasize that these findings are in the early stages of research and no firm conclusions should be drawn, however the risk posed to these important soils warrants further research and full implementation of this model.

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