Soil Phosphorus Distribution across Diverse Land Use Systems: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. Author ANN conducted the literature searches, analyzed the data, wrote the manuscript, communicated and collaborated the study with guide. Author RKM provided guidance, supervision and editorial feedback. All authors read and approved the final manuscript.

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ABSTRACT

Phosphorus (P) is a crucial nutrient necessary for healthy plant growth. While soils typically contain a sufficient total amount of P (200-300 mg P kg⁻¹), less than 1% of it is readily available to plants. In India, despite an adequate total P content, approximately 42% of soils are deficient in plant-

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available P_2O_5 and 38% have medium availability. The dynamics of phosphorus in soil are influenced by various processes, including dissolution-precipitation, sorption-desorption, and mineralization-immobilization reactions. These dynamics are highly responsive to agricultural practices and land-use patterns, which play a significant role in shaping the P distribution of P in the soil. One major factor that affects the distribution and availability of phosphorus in the soil is a change in land use. When natural ecosystems are transformed into plantations or croplands, it substantially alters the physical, chemical and biological properties of the soil. This transformation impacts soil fertility and can lead to significant changes in the distribution of P within different chemically defined pools. Consequently, this affects the availability and stability of P in the soil. Soil P fractionation, a method used to assess P availability, solubility and dynamics, is a suitable tool to understand how P behaves under different land-use systems. However, the specific effects of land-use changes on P fractions are not well-documented. To gain a better understanding of how land-use changes impact the distribution and availability of different P fractions in the soil, research studies have been conducted.

1. INTRODUCTION

"Phosphorus (P) is a crucial nutrient for plant growth and its availability in soil is essential for sustaining soil fertility and agricultural productivity. Despite the presence of sufficient total P in most soils worldwide, only a small fraction of it, about 1%, is readily available to plants. This limited availability is due to the physicochemical properties of P and its interactions at the soil mineral interface" [1]. In India, as an example, a paradoxical situation exists where there is an adequate amount of total P in soils, yet a significant percentage of them (42%) are deficient in plant-available P and 38% have medium availability. This discrepancy between total P content and plant-available P underscores the importance of understanding P dynamics in soils [2]. "Phosphorus in soil exists in both organic and inorganic forms and it is relatively immobile. When P is applied to the soil through fertilizers or other sources, it can either be taken up by crops or become physically/chemically adsorbed onto soil minerals such as calcium, aluminium and iron. It can also be incorporated into organic P compounds. The behaviour of P in soil is influenced by various complex processes, including dissolution-precipitation, sorption-desorption and mineralization-immobilization reactions. These processes respond to agricultural management practices and changes in land use" [3].

"Land-use change and the intensification of cultivation have become dominant global trends in response to the increasing global demand for food, feed, fibre and biofuel production driven by population growth" [4]. "Phosphorus is a key nutrient that requires particular attention in the context of land-use changes because it is often the most limiting nutrient for plant productivity, especially in tropical regions. Land-use changes can lead to increased P losses from the soil through processes like erosion, leaching and runoff, reducing the overall P content in the soil" [5]. Changes in land use can transform plant-available P into more recalcitrant P pools [6]. "This means that P becomes less soluble and less accessible to plants, affecting their ability to acquire this essential nutrient. These changes in P dynamics in response to land-use alterations can have significant effects on the distribution of P within chemically defined pools in the soil" [7]. "This, in turn, affects the availability and stability of P for plant uptake. While the impact of land-use changes on soil organic carbon (SOC) is relatively well-documented, its effect on soil P fractions is less studied. Research has shown a strong and positive correlation between P fractions and the carbon content in soil, particularly with the organic fractions. This suggests that soil organic matter (SOM) plays a crucial role in maintaining P availability" [8]. "The presence of SOM can enhance the availability of P by preventing it from becoming too tightly bound to soil minerals, making it more accessible to plants" [9]. Therefore, maintaining and enhancing soil organic matter can be a key strategy for sustaining P reserves and ensuring its availability for crops in changing land-use scenarios.

2. FORMS OF PHOSPHORUS IN SOIL

Soil phosphorus, a vital nutrient for plant growth, exists in two primary forms: organic and

inorganic. These two forms collectively constitute the total phosphorus content in the soil. However, a significant portion of soil phosphorus, approximately 80%, is considered immobile and not readily available for plant uptake [10]. Understanding the distribution of these phosphorus forms is essential for effective soil management [11]. Organic phosphorus accounts for about 30% to 65% of the total soil phosphorus. It originates from decaying organic matter, including plant residues, roots and microbial biomass. Unfortunately, organic phosphorus, in its native form, is not directly accessible to plants due to its limited solubility and mobility in the soil [12]. Within the organic fraction, there are labile forms, specifically orthophosphate monoesters and orthophosphate diesters, which are more susceptible to transformation. Microorganisms, such as bacteria and fungi play a pivotal role in this process [13]. They excrete enzymes that break down these organic phosphorus compounds, converting them into orthophosphate ions, which are the primary inorganic forms that plants can readily absorb. This conversion, known as phosphorus mineralization, is vital for making phosphorus available to plants [14]. It's a biological process that unlocks the essential nutrient from its organic reservoir, ensuring plants can access the phosphorus they require for growth. Thus, understanding the dynamics of organic and inorganic phosphorus and their interactions with soil microorganisms is crucial for optimizing nutrient availability in agricultural and ecological systems [15].

The inorganic phosphorus forms can be classified to exist in three different pools:

1) Plant-available (soil solution) phosphorus: The pool is comprised of inorganic phosphorus dissolved in water/ soil solution that is readily available for plant uptake.
2) Sorbed phosphorus: This phosphorus pool is comprised of inorganic P attached to clay surfaces, iron, aluminium and calcium oxides in soil. The P in this pool is released slowly for plant uptake.
3) Mineral phosphorus: This phosphorus pool is comprised of primary and secondary phosphate minerals present in soil. The secondary phosphorus minerals include calcium, iron and aluminium phosphates.

The release of phosphorus from this pool is extremely slow and occurs when the mineral weathers and dissolves in soil water. Once the phosphorus enters the soil through chemical fertilizers, manure, biosolids or dead plant or animal debris, it cycles between several soil pools via processes such as mineralization, immobilization, adsorption, precipitation, desorption, weathering and dissolution [16].

3. SEQUENTIAL PHOSPHORUS FRACTIONATION METHODS

Soil P fractionation is a suitable procedure to assess the availability, solubility and dynamics of soil P under different land-use managements [15]. The following method is followed for sequential fractionation of Phosphorus.

Chang and Jackson [17] endorsed that **"Saloid-P was extracted from 0.5 g of soil with 25 mL of 1N NH_4Cl with half-an-hour shaking and centrifugation at 7000 rpm for 10 minutes. Aluminium-P was extracted from the residual soil with 25 mL of 0.5N of NH_4F (pH 8.2) by shaking the suspension for one hour and centrifuged. Iron-P was extracted from the residual soil by shaking with 25mL of 0.1N NaOH for seventeen hours and centrifuged at 2000 rpm for 5 minutes. The residual soil was then suspended in 25 mL of 0.3M sodium citrate solution and shaken for 15 minutes with 1 g sodium dithionate. Excess of citrate and dithionate was oxidized by adding 1.5 mL of 0.25M $KMnO_4$ solution and Reductant soluble-P (RS-P) was estimated. The soil residue left after the estimation of RS-P was added with 50 mL of 0.1M NaOH and shaken for one hour and centrifuged to get clear filtrate for estimation of Occluded-P (Occluded-P). Finally, Ca-P was extracted by shaking the residual soil with 25 mL of 0.5N H_2SO_4 for one hour and centrifuged. The concentration of P in the respective extracts obtained after shaking with each of the extractant was estimated by the ascorbic acid method"**.

The total-P was estimated by using vanadomolybdophosphoric acid reagent and the intensity of yellow colour was read at 470 nm in spectrophotometer. Organic-P was calculated by subtracting the sum of total inorganic or mineral P from total-P. The experimental data obtained was subjected to statistical analysis adopting Fisher's method of analysis of variance. Testing of significance was done by SPSS 16.0 version and values are given at 5 per cent and 1 per cent level of significance.

A 0.5 g sample of soil is placed in a 40 mL centrifuge tube and sequentially extracted with the following extractants and shaken horizontally for 2 hours, followed by centrifugation at 3500 rpm for 15 min and then filtered using filter paper and extract contains the following P forms, respectively.

4. DISTRIBUTION OF P FRACTIONS AS AFFECTED BY DIFFERENT LAND-USE SYSTEMS

Prakash et al. [1] conducted "a study to investigate the effect of poplar-based agroforestry, rice–wheat, maize–wheat and cotton–wheat cropping systems on soil P fractions and P availability in Indo-Gangetic alluvial soils". He reported that among the different land-use systems, the available-P was found to be significantly low under agroforestry system (Table 1.) reason being the low application of inorganic fertilizers in this system whereas, the SOC was found to be significantly high under agroforestry system due to high biomass return to the land, followed by rice-wheat due to high application of FYM and biomass return.

Flow chart 1. Sequential phosphorus fractionation method by Chang and Jackson [17]

P Fraction	Extractant	Soil(g): Solution(mL)	Condition
Saloid-P	1N NH₄Cl	1:25	Shake for 30 min & centrifugation
Al-P	0.5N NH₄F (pH 8.2)	1:25	Shake for 60 min & centrifugation.
Fe-P	0.1N NaOH	1:25	Shake for 17 hour & centrifugation.
Reductant soluble-P	0.3 M sodium citrate + 1g sodium dithionate.	1:25	Suspension was heated on water bath at 80º C for 10 min & centrifugation.
Occluded-P	0.1M NaOH	1:50	Shake for 60 min & centrifugation.
Ca-P	0.5 N H₂SO₄	1:25	Shake for 60 min and centrifugation.
Residual P/ Organic P	Total Phosphorus - sum of all fractions of Phosphorus		

Hedley et al. [18]

Flow chart 2. Sequential phosphorus fractionation method by Hedley et al., [18]

Extractant	P fraction	P form
0.5M NaHCO₃	Water extractable and exchangeable P	Labile-P
0.1M NaOH	Al/Fe-P	Moderately labile-P
1M HCl	Ca/Mg-P	Relatively insoluble-P
Conc.H₂SO₄ + H₂O₂	Organic-P/Residual-P	Residual-P
sum of the first four fractions		Total-P

Table 1. The Soil properties of the surface (0–15 cm) soils under different land use in Punjab, India

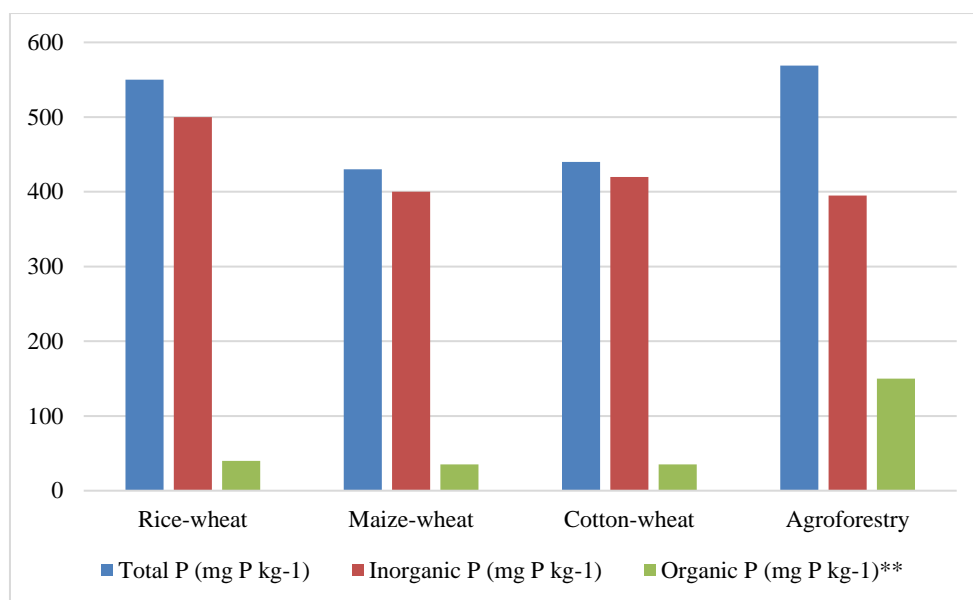| Property	Rice-wheat	Maize-wheat	Cotton-wheat	Agroforestry
pH	7.76	7.73	7.72	7.29
Electrical conductivity (dS m⁻¹)	0.31	0.34	0.28	0.33
Sand (%)	60.0	63.0	63.3	64.6
Silt (%)	25.1	23.1	23.3	21.8
Clay (%)	14.1	13.1	13.5	13.6
SOC (g kg⁻¹)	4.74	3.98	3.94	5.78
Available P (mg kg⁻¹)	16.0	14.1	14.9	9.8
Available K (mg kg⁻¹)	87	87	83	100
CaCO₃ (g kg⁻¹)	1.41	2.53	1.22	1.73

Prakash et al. [1]

Fig. 1. Distribution of organic, inorganic and total P pools in surface (0–15 cm) soils under different cropping system
Prakash et al. [1]

Table 2. The Concentration (% of total P) of organic, inorganic P pools in surface (0–15 cm) soils under different land uses in Punjab, India.

Property	Land-use			
	Rice–wheat	Maize–wheat	Cotton–wheat	Agroforestry
H$_2$O-Pi'	0.20^c (0.005)	0.18^b (0.003)	0.12^a (0.003)	0.19^b (0.002)
Ca-EDTA-Pi[†]	13.13^b (0.051)	15.34^c (0.058)	15.42^c (0.043)	12.80^a (0.044)
Na-EDTA-Pi[}]	68.92^b (0.072)	69.79^c (0.086)	71.10^d (0.049)	53.57^a (0.111)
NaOH-Pi'	9.97^d (0.052)	8.80^c (0.050)	7.92^b (0.042)	6.45^a (0.050)
TPi'	92.23^c (0.058)	94.11^c (0.053)	94.56^d (0.051)	73.01^a (0.111)
H$_2$O-Po'	0.18^b (0.002)	0.16^a (0.002)	0.16^a (0.002)	0.19^c (0.002)
Ca-EDTA-Po[†]	0.51^c (0.002)	0.43^b (0.002)	0.32^a (0.002)	1.01^d (0.003)
Na-EDTA-Po[}]	1.39^c (0.013)	1.01^b (0.008)	0.73^a (0.009)	4.68^d (0.021)
H$_2$SO$_4$-Po[‡]	0.74^c (0.002)	0.62^a (0.003)	0.72^b (0.002)	2.58^d (0.007)
$_c$TCA-Po^m	0.76^c (0.002)	0.63^b (0.003)	0.56^a (0.004)	3.14^d (0.006)
$_H$TCA-Po.	0.45^b (0.002)	0.51^c (0.003)	0.43^a (0.002)	0.74^d (0.002)
NaOH-Po'	3.31^b (0.061)	2.13^a (0.051)	2.07^a (0.043)	14.21^c (0.135)
TPo^y	7.34^c (0.057)	5.49^b (0.052)	4.98^a (0.045)	26.55^d (0.113)
Res-P^b	0.43^{ab} (0.011)	0.40^a (0.011)	0.46^b (0.011)	0.44^b (0.007)

'H$_2$O-Pi/Po is the water soluble inorganic and organic P, [†] Ca-EDTA-Pi/Po is iron associated inorganic and organic P,[}] Na-EDTA- Pi/Po is calcium–aluminium associated inorganic and organic P, [‡] H$_2$SO$_4$-Po is acid soluble organic P, ^{m} $_c$TCA-Po is sugar bound organic P, . $_H$TCA-Po is nucleic acid organic P and polyphosphate, ' NaOH-Pi/Po is humic bound inorganic and organic P, ^{b} Res-P is residual P, ^{y} TPo is organic P, ' TPi is inorganic P
Prakash et al. [1]

The author described with a graph the changes in the distribution of different P fractions as affected by land-use system.

The graph shows that total P concentration was significantly higher in soils under agroforestry (569 mg P kg^{-1}) than the other land uses. Among the sole cropping systems, rice–wheat exhibited significantly greater total P concentration than maize–wheat and cotton–wheat cropping systems (Fig. 1). Under sole cropping systems, inorganic P was the dominant fraction that represented 92.2, 94.1 and 94.6% of total P in soils under rice–wheat, maize–wheat and cotton–wheat systems, respectively. However, soils under agroforestry had a

relatively lower proportion (73%) of inorganic P and a greater proportion of organic P (27%) compared to other land uses. Significantly lower proportion of inorganic P in soils under agroforestry may be ascribed to relatively lower fertilizer P application than the other land uses, higher uptake of P by poplar trees and wide C: P ratio of soil or could be immobilization of P by microorganisms in their structural development to mineralize the organic residues added into the soil. The author in the following table represented the distribution of inorganic and organic P fractions.

Water soluble inorganic P concentration was significantly lower in soils under cotton–wheat, whereas, Water soluble organic P was significantly higher in soils under agroforestry. The concentration of calcium–aluminium associated inorganic P was significantly higher in soils under sole cropping systems compared to agroforestry this could be attributed to the formation of insoluble Ca–P compounds in these soils having a calcareous nature as Ca^{2+} activity in the liquid phase is mainly responsible for the formation of insoluble Ca-phosphate mineral in calcareous soil.

A relatively lower proportion of calcium–aluminium-associated inorganic P in soils under agroforestry may be attributed to the effect of organic matter returned to the soil through litter fall and root biomass that can solubilize the native soil P [1].

5. FORMS AND DISTRIBUTION OF PHOSPHORUS AND THEIR CORRELATION WITH DIFFERENT SOIL PROPERTIES UNDER DIFFERENT LAND USE SYSTEMS

Majumdar et al. [19] conducted "an experiment in Northern Transition Zone of Karnataka to study the forms and distribution of phosphorus and their correlation with different soil properties under different land use systems of the Singhanhalli-Bogur micro-watershed. The results showed that the Reductant Soluble-P was the dominant fraction in all the land use systems except non-paddy land use where Ca-P was the dominant fraction. Soil pH had a negative and significant correlation with Al-P in most of the land use. Fe-P had a significant and positive correlation with organic carbon and clay in paddy and forest land use systems. Reductant Soluble-P showed a negatively significant correlation with

pH. Ca-P and Occluded-P recorded a significantly positive correlation with organic carbon in all the land use systems".

The Table 4. shows the per cent contribution of Saloid-P to the total P in surface samples varied from 0.27 per cent (forest land use) to 0.82 per cent (non-paddy land use). This might be due to the high P-fixation capacity of these soils and also due to transformation of soluble forms of P into relatively less soluble forms with the progress of time. The conversion of soluble P to various forms of P varying in their solubility depends on soil reaction, content of sesquioxides, free $CaCO_3$, soil texture and organic carbon content.

The mean content of Al-P varied between 23.10 mg kg^{-1} (non-paddy land use) to 72.50 mg kg^{-1} (forest land use). The Al-P content was highest under forest land use system which could be attributed to the low pH prevailing in the system. the ratio of Fe-P to total-P depicted that this fraction of P forms a dominant portion of mineral P (second highest) under paddy land use system.

The mean value of Fe-P varied from 15.47 mg kg^{-1} (non-paddy land use) to 47.89 mg kg^{-1} (paddy land use) in surface soil samples. The higher Fe-P content in surface soils of paddy land, non-paddy land and forest land use might be attributed to the presence of more organic carbon which provides organic acids which leads to solubilization of iron to ferrous form along with phosphates resulting in precipitation of ferrous phosphate.

The variation of reductant soluble P of surface soil samples under different land use system ranged between 26.70 to 164.20 mg kg^{-1}. The contribution of Red. Sol. P to total P was observed the highest under forest land use system. However, the ratio of Occluded-P to total P in different soil under different land use system varied within a narrow limit of 4.20 to 9.25 per cent.

The mean value of Ca-P content ranged between 8.45 mg kg^{-1} (forest land use) to 65.29 mg kg^{-1} (non-paddy land use). The high Ca-P content of surface soil under non-paddy land use could be attributed to high $CaCO_3$ content. The mean content of total-P and organic-P varied between 348.55 to 496.90 mg kg^{-1} and 191.69 to 240.11 mg kg^{-1}, respectively, in different land use systems.

Table 3. The physical and chemical properties of soils under different land use system

| Sl. No.	Land use system		pH (1:2.5)	EC (1:2.5) (dSm^{-1})	OC (g kg^{-1})	CaCO$_3$ (g kg^{-1})	Textural class
1	Agriculture						
a)	Paddy land	Range	5.8-8.4	0.03-0.88	5.1-5.9	2.5-52.5	Clay
		Mean	6.6	0.17	9.8	14.2	
b)	Non-paddy land	Range	6.6-8.2	0.05-0.25	4.2-15.3	12.5- 72.5	Sandy loam
		Mean	7.8	0.13	7.0	30.2	
2	Horticulture (mango orchard)	Range	6.0-8.1	0.03-0.38	6.0-13.2	5.0-52.5	Clay loam
		Mean	6.8	0.12	9.2	14.8	
3	Reserved forest	Range	6.0-7.1	0.03-0.11	8.4-23.7	7.5-32.5	Clay
		Mean	6.3	0.06	15.9	17.2	

Majumdar et al. [19]
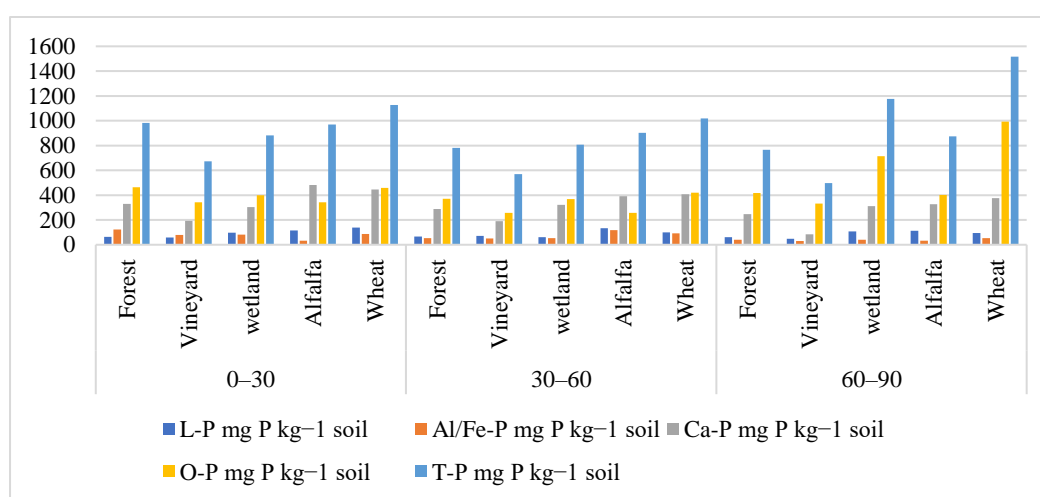
Fig. 2. Distribution of phosphorus form: L-P labile (water extractable and exchangeable) bound P, Al/Fe-P, Ca-P, O-P, T-P in the soil
M Sheklabadi et al. [26]

6. CORRELATION BETWEEN DIFFERENT P FORMS AND SOIL PROPERTIES UNDER DIFFERENT LAND USE SYSTEMS

"The negatively significant correlation of pH with saloid-P of surface samples under different land use may be due to the conversion of easily available surface adsorbed saloid-P into a less soluble form of P. Saloid P also showed a significant negative relationship with clay. Since saloid-P is the most soluble form of P, it reacts with clay and gets fixed into an insoluble form" [15]. "Soil pH had a negative and significant correlation with Al-P in almost all the land uses. This may be due to low aluminium activity at higher p^H, thus P is not precipitated as Al-P in larger quantities. A correlation study revealed that Al-P showed a significant positive correlation with organic carbon and clay. A significant positive correlation with organic carbon might be due to the mineralization of organic P and conversion into Al-P fraction due to high biological activity" [20]. "The relation with clay is because the content of aluminium in clay is much higher than that of iron or calcium. Therefore, added soluble phosphate is most likely to be fixed as Al-P. Al-P showed a significant negative relation with pH which showed an increase in pH is associated with a decrease in Al-P content" [21]

Fe-P had a significant and positive correlation with organic carbon and clay in paddy and forest land use systems. This relationship with organic carbon may be due to the mineralization of organic-P and conversion into Fe-P. When soluble-P is added, it reacts with Fe and Al of soil clay minerals to form insoluble Fe and Al-P [22]. Fe-P showed a significant negative relation with

pH in non-paddy land use which showed an increase in pH is associated with a decrease in P content [23]. There was a significant negative correlation (r = -0.443**) observed between free $CaCO_3$ and Fe-P in non-paddy land use. A high amount of Ca-P was found at high pH at which Fe-activity is usually less to precipitate P into Fe-P. Reductant soluble P showed a significant and negative correlation with pH which indicated that with an increase in pH reductant soluble P will decrease. Reductant soluble P showed a significant positive correlation with organic carbon in paddy and forest land use systems. Reductant soluble P showed a significant negative relationship (r = -0.570**) with clay content in the horticulture land use system [24].

"Ca-P exhibited a significant positive correlation with pH, clay and organic carbon in almost all the land use systems. A significant positive correlation with pH indicates an increase in Ca-P with an increase in $p^{H"}$ [15]. The correlation coefficient (r = 0.376**) between CaCO3 and Ca-P was highly significant in the case of non-paddy land use system. The high CaCO3 content of surface samples in this land use system might have reacted with P resulting in higher Ca-P."

"Total-P also showed a significant and positive correlation with organic carbon and clay content. Organic carbon also exhibited a significant and positive correlation with organic P in all the land uses. The phosphorus in the surface soils might have complexed with the organic acids as organic carbon was in greater amount in surface soils" [25].

7. DISTRIBUTION OF P FRACTIONS AT DIFFERENT DEPTHS

In another study by M Sheklabadi et al. [26-27] the following observations were made for P fractions at three different depths.

Within the surface layer, there were significant differences in L-P among forest, vineyard and cultivated lands (alfalfa and wheat). There were no differences observed between cultivated lands and wetland. High amounts of L-P in cultivated lands surrounding the lake lead to P directly entering wetland ecosystem. Distribution of P fraction by depth demonstrated that L-P in the surface layer of wheat was higher (43%) than in the second and third layers. As the inorganic

fertilizers were applied on the surface. In contrast, Al/Fe-P fraction in 30–60 cm depth of alfalfa systems was greater. In this system, the lowest amounts of Al/Fe-P in 0–30 cm depth may be attributed to leaching and translocation of secondary minerals in the soil profile through preferential paths, a result of the root system of alfalfa. As alfalfa and wheat systems were located at the margin of the lake, partial saturation of 30–60cm depth in the soil profile may cause more P in the form of Al/Fe to be bounded in this layer. Of all the fractions, Ca-P was the most affected by land-use change. The highest amounts of this fraction were observed in vineyards and cultivated lands, respectively. The highest amount of Ca-P fraction was found in 30–60 and 60–90 cm depths of wheat cultivation soil (376.21 mg P kg^{-1}). It might be because farming practices increased P sequestration in the Ca-P fraction under cultivated land compared with native land. In general, 35.25% of total Ca-P in all land uses was sequestrated in the surface layer. The change from a wetland to a cultivated system led to an increase of 4% Ca-P in the surface layer. The amount of O-P sequestrated in the subsurface layer in all land-use treatments was higher than in the upper layers. Mineralization of organic matter in deeper layers in all treatments was lower. On average, 40.8% of the total high recalcitrance of P was observed in the subsurface in all treatments, whereas 30.6% of this fraction was sequestrated in the surface layer[28].

8. CORRELATION OF P FRACTIONS WITH SOIL ORGANIC CARBON (SOC)

Several studies were conducted to study the correlation between SOC with the inorganic and organic fractions of P, and how SOC sequestrated by SOM influences their availability, distribution and dynamics in soil. Prakash *et al.* [1] reported "a correlation matrix depicting the relationship among soil organic C and P pools. In all the land uses except for agroforestry, SOC, exhibited a highly significant positive correlation with soil P fractions, indicating the role of SOC in determining P dynamics in soils. The probable reason for relatively lower values of correlation coefficient (r) in soils under agroforestry is the entirely different soil management system, compared with the other cropping systems. Under agroforestry, soils are least disturbed because of restricted soil tillage, which affects the oxidative losses of SOC"[29].

Table 4. Phosphorus fractions (mg kg^{-1}) of surface soil samples under different land use systems

Sl. No.	Land use system	Saloid-P	Al-P	Fe-P	RS-P	Occl-P	Ca-P	Total- P	Organic- P
1	Agriculture								
	a) Paddy land								
	Range	1.40-1.72	24.46-42.24	34.60-54.65	40.80-68.40	13.00-28.88	9.40-62.50	404.22-442.25	222.59-264.98
	Mean	1.57	32.22	47.89	58.76	18.7	21.4	420.73	240.11
	SD	0.09	5.54	6.04	9.25	4.28	18.06	13.94	11.16
	a) Non-paddy land								
	Range	2.30-3.68	18.8-27.76	12.36-19.40	26.70-59.10	9.80-34.00	40.10-96.20	305.63-398.5	108.98-302.41
	Mean	2.89	23.10	15.47	36.74	20.01	65.29	348.55	191.69
	SD	0.47	3.02	1.80	8.85	7.15	14.50	28.74	39.60
2	Horticulture (mango orchard)								
	Range	1.44-2.70	30.31-68.10	25.10-30.41	44.50-61.24	9.44-22.47	7.54-62.80	275.77-421.10	109.18-255.18
	Mean	2.08	53.50	27.64	54.24	15.20	27.39	361.73	191.73
	SD	0.42	10.70	1.40	4.92	3.40	19.59	39.11	37.41
3	Reserved forest								
	Range	1.00-1.80	64.28-97.60	20.5-46.4	80.80-164.20	32.80-62.14	5.5-12.82	400.20-550.25	189.94-309.31
	Mean	1.40	72.50	35.70	104.63	46.69	8.45	496.9	235.69
	SD	0.22	9..93	7.66	22.82	8.61	2.01	62.68	30.02

Majumdar et al. [19]

Table 5. Correlation coefficient between the forms of phosphorus with soil properties under paddy, non-paddy, Horticulture and forest land use system

Soil Property	S-P	Al-P	Fe-P	RS-P	Occl-P	Ca-P
pH (Paddy)	-0.681**	-0.512**	-0.26	-0.510**	-0.445**	0.561**
OC (Paddy)	0.672*	0.823**	0.852**	0.432*	0.611**	0.533**
CaCO$_3$ (Paddy)	0.052	0.132	0.324	0.478*	0.363*	0.231
Clay (Paddy)	-0.561**	0.689**	0.722**	0.571*	-0.052	0.622**
pH (Non-Paddy)	-0.520**	-0.564**	-0.07	-0.395**	-0.333**	0.521*
OC (Non-Paddy)	0.301*	0.623**	0.21	0.462*	0.160*	-0.03
CaCO$_3$ (Non-Paddy)	0.062	0.561*	-0.443**	0.272*	0.245	0.376**
Clay (Non-Paddy)	-0.289*	0.273**	-0.073	-0.03	-0.142	0.340*
pH (Horticulture)	-0.614**	-0.532**	-0.454**	-0.540**	-0.585**	0.882**
OC (Horticulture)	0.685**	0.671**	0.756**	0.534**	0.599**	0.159
CaCO$_3$ (Horticulture)	0.123	0.446**	0.226	0.575**	-0.019	0.259**
Clay (Horticulture)	-0.952**	0.691**	0.374**	-0.570**	-0.169	-0.229
pH (Forest)	-0.464**	-0.564**	-0.224	-0.373**	-0.390**	0.501*
OC (Forest)	0.305*	0.613**	0.546**	0.496**	0.267*	0.090*
CaCO$_3$ (Forest)	0.065	0.281*	0.207	0.281*	0.148	0.377**

Majumdar et al. [19]

Table 6. Correlation matrix depicting the relationship among soil organic C and P pools

Soil organic carbon	Inorganic P				
	H_2O-Pi	Ca-EDTA-Pi	Na-EDTA-Pi	NaOH-Pi	TPi
Rice–wheat	0.74**	0.66**	0.68**	0.64**	0.68**
Maize–wheat	0.58**	0.67**	0.68**	0.68**	0.68**
Cotton–wheat	0.53**	0.62**	0.60**	0.62**	0.61**
Agroforestry	0.21	0.36	0.30	0.34	0.31

Soil organic carbon	Organic P									
	H_2O Po	Ca-EDTA-Po	Na-EDTA-Po	H_2SO_4 Po	cTCA Po	HTCA-Po	NaOH-Po	TPo	Res-P	Total P
Rice–wheat	0.64**	0.68**	0.60**	0.66**	0.67**	0.65**	0.74**	0.71**	0.68**	0.68**
Maize–wheat	0.57**	0.69**	0.68**	0.71**	0.67**	0.65**	0.61**	0.68**	0.71**	0.69**
Cotton–wheat	0.46*	0.58**	0.51*	0.59**	0.66**	0.55**	0.45*	0.53**	0.54**	0.61**
Agroforestry	0.38	0.32	0.35	0.33	0.33	0.33	0.32	0.33	0.26	0.32

H_2O-Pi/Po is the water soluble inorganic and organic P, † Ca-EDTA-Pi/Po is iron associated inorganic and organic P,) Na-EDTA- Pi/Po is calcium–aluminium associated inorganic and organic P, ‡ H_2SO_4-Po is acid soluble organic P, m cTCA-Po is sugar boundorganic P, . HTCA-Po is nucleic acid organic P and polyphosphate, ˙ NaOH-Pi/Po is humic bound inorganic and organic P, b Res-Pis Residual P, ʸ TPo is Organic P, ˙ TPi is Inorganic P

* Correlation is significant at p \ 0.05 level (2-tailed) ** Correlation is significant at p \ 0.01 level (2-tailed)

Prakash et al., [1]

9. CONCLUSION

Land-use changes affect P availability for plant uptake either by increasing P losses or by transforming it into more recalcitrant pools. Soil P was unsustainable due to the land-use change from native to arable lands. Native forests have greater Po (Organic P) and their conversion to sole cropping decreases this fraction which could provide P in the long term. Irrespective of the land use, the relative abundance of inorganic P fractions followed the order: Ca-Al associated iP > Fe-iP > Humic bound iP > Water soluble iP. Easily available Pi was the only fraction that increased after the intensification of cultivation. Soil P fractions showed a significant correlation with soil organic matter. Land-use change leads to an overall reduction of P stocks due to a strong decrease of SOC caused by erosion and yield export to trees. Mineralization from soil organic matter contributes to available P content highlighting the potential of SOM in maintaining P reserves. Inorganic phosphorus was found to be mainly composed of chemically more stable (NaOH Pi) and relatively insoluble phosphorus forms (HCl Pi and residual P) rather than available Pi in all land use types. Land use impacts are most apparent in terms of plant available forms.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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