***Understanding vulnerability to phosphorus scarcity through bottom-up assessments of regional-scale opportunities***

**Highlights**

* Fresh insights into lowering vulnerability to phosphorus scarcity from bottom-up approach.
* Material flow analysis reveals losses and use inefficiencies of phosphorus.
* Targeted schemes can make a region less vulnerable to P scarcity.
* Nutrient management and investments in assets make farmers more resilient.
* Farmers are unaware of soil P levels and use excess of fertilizers.

ABSTRACT

A methodological framework using the bottom-up approach and substance flow analysis is illustrated to identify strategies for reducing regional vulnerabilities to phosphorus (P) scarcity, and methods of evaluating the impact of the identified strategies using P vulnerability index are outlined. The strategies were developed in consultation with two groups of stakeholders, namely those with greater influence and a higher stake, such as government officials, and those with less influence and a lower stake, such as farmers with small landholdings. The bottom-up approach gave fresh insights that were not identified in the top-down approach reported in the literature. The study region, namely Sonipat in Haryana, India, is highly vulnerable to disruptions in P supplies (vulnerability index of 38.73). Analysis of P flows showed that farmers in the region use predefined amounts of fertilizers without evaluating the fertility levels of soil. The region can reduce its P requirements by 11 574 tonnes annually (about 85% of the current requirements) through recovery and recycling of P from human wastes and by adjusting the fertilizer dose. Although crop diversification alone may not have a significant impact on the vulnerability index, its value can be increased to 60 and above, implying adequate security, if crop diversification is combined with recycling and recovery of P and better governance. Amongst all the indicators of P vulnerability, those with the highest impact on the index were soil fertility, farmers’ income, and access to institutional credit.

*Keywords*Bottom-up approach; Phosphorus flows; Phosphorus security; Vulnerability Index

**1. Introduction**

The nexus between water, food, and climate change and its implications for sustained supply of soil nutrients now attract increasing interest from researchers (Chowdhury et al., 2017). Among soil nutrients, phosphorus (P) is particularly important because its stocks are being rapidly depleted (Schroeder et al., 2010), because anthropogenic factors have accelerated its linear movement, and also because of its role in eutrophication of water bodies (Geissler et al., 2018). Scarcity of P will soon be a threat to food security unless adequate measures are taken (Steffen et al., 2015). The increasing scarcity of P coupled with its skewed geographical distribution mandates immediate attention by agrarian economies and also from those of Australia and Europe (Cordell and Neset, 2014). India, for instance, not only depends on imports to meet 85%–90% of its P requirements (Indian Bureau of Mines, 2018) but has also shown a steady decrease in its soil P over time (Dey et al., 2017). These two constraints can endanger India’s ambitious targets to achieve food security (Rao et al., 2015). Although loss of P is a global issue, concerted ground-level actions may be delayed on account of many barriers as was the case with actions to deal with climate change (Eisenack et al., 2014). More studies are therefore essential to illustrate the methods by which actions for P conservation and sustainability can be prioritized.

Yet only a few studies have been carried out related to vulnerability to inadequate supply of nutrients, particularly P, in agricultural soils; these studies have mainly used the *top-down* approaches to assess vulnerability and to identify strategies to address it (Basu et al., 2011; Cordell and Neset, 2014; Nanda et al., 2019; Paramasivam et al., 2017; Weikard, 2016). The policies related to vulnerability and the plans to implement those policies also mostly follow the top-down approach (DeLeon and DeLeon, 2002) and seldom involve stakeholders at the grass-roots level. The objectives and expected outcomes envisaged in the policymaking process at the federal level are not always realized after those policies are implemented (Huesoa and Bellb, 2013; Keohane and Victor, 2015). The importance of the *bottom-up* approach for policy and planning was recognized in the 1980s (Sabatier, 1986) but the approach has not been used widely although it is particularly relevant to devising strategies to reduce vulnerability to water scarcity (Sen et al., 2018), energy scarcity (Rosenowa and Eyre, 2016), and impacts of climate change (Andresen, 2015; Rayner, 2010). The bottom-up approach to planning has also proved useful in watershed management (Koontz and Newig, 2014), soil conservation (Chellappan and Sudha, 2015) and community management of forests (Rout, 2018). In other words, grassroots-level information is a useful input for making policy decisions (Fraser et al., 2006).

It is against this background that the present study analyses, by establishing the right context through interactions at grass-roots level, the working of various programmes that can influence P security. Using the bottom-up approach to vulnerability assessment, the study compares its results with those obtained from using the top-down approach (Nanda et al., 2019). Specifically, the study focuses on the coherence and divergence of policies and schemes designed at the national (federal) level and their outcomes at grass-roots level to highlight key issues that can improve resilience and help in identifying priorities for policymaking. Objective and measurable evidence is essential for effective policymaking, and the present study provides just such evidence – in the form of indicators, a phosphorus vulnerability index (PVI) (Nanda et al, 2019), and assessment of P flows – for policies aimed at dealing with vulnerability to P scarcity and for identifying critical intervention points (Venkatesh and Kansal, 2018).

Substance flow analysis (SFA) has been shown by several researchers as a useful tool in investigating P flows and stocks for decision-making (Brunner, 2010; Venkatesh and Kansal, 2018). In France, for instance, P flows were studied for 16 years, from 1990 to 2006: the studies showed that P balance was positive for the country as a whole (Senthilkumar et al., 2012). In their efforts to control eutrophication in the Baltic Sea, researchers in Finland identified aquaculture and effluents as the primary causes of the loss of nutrients from the system (Asmala and Saikku, 2010). In China, a stock and flow model with time series data for 1984 to 2008 estimated that 80.5% of the extracted P was lost to natural water bodies and to soil (Ma et al., 2012). In Japan, slag from the iron and steel industry was identified as a potential source of P recovery (Matsubae-Yokoyama et al., 2009). In the UK, SFA identified discharge from wastewater treatment plants, animal manure, food waste, and sewage sludge as potential sources of P recovery (Cooper and Carliell-Marquet, 2013).

The present study extends the work of Nanda et al. (2019) to a subregional level by identifying priority indicators through stakeholder engagement at grass-roots level supplemented with analysis of P flows in the region to identify strategies for making the subregion less vulnerable to P scarcity. The key objectives of the study were as follows: 1) to understand the perceptions of farmers related to future P scarcity and their methods of coping with it; 2) to estimate the PVI for the subregion; 3) to compare vulnerability indicators from earlier top-down studies with the indicators from the present bottom-up study; and 4) to identify strategies to achieve P security (soil fertility) and to evaluate the impact of those strategies in terms of the PVI.

**2. Methodology**

The steps used in this study, using the bottom-up approach, to identify strategies of achieving P security in a given region are shown in Fig. 1. As explained by Nanda et al. (2019), a P-secure region should have a PVI greater than 60. In the present study, strategies to increase the PVI were devised based on 1) actions that increase the value of indicators with a high weighting, 2) flows of P in the subregion to regulate the demand and supply of P, and 3) perceptions of stakeholders. Stakeholders (SH) in this study came from two main categories: those with greater influence and a higher stake (SH1), such as government officials, and those with less influence and a lower stake (SH2), such as farmers with small landholdings. For each strategy, the PVI was estimated by identifying the indicators that are likely to be influenced by the proposed strategies. Details of each step are explained in the following sections.

Identifying significant indicators

Phosphorus flow diagram

• Stakeholder consultations

— SH1

— SH2

Estimating PVI

PVI as a result of each identified strategy or a combination of strategies

Is the revised PVI > 60?

Yes

No

Collecting data for identified indicators

Strategies for P security

**Fig. 1.** Steps to identify strategies using bottom-up approach for achieving phosphorus security.

*2.1. Identifying indicators of vulnerability to phosphorus scarcity*

Vulnerability studies have often used an indicator-based approach (Alam et al., 2017; IGES, 2013; Sharma et al., 2017). In bottom-up studies, communities that are affected by the scarcity of a given resource, that is communities vulnerable to such scarcity, are consulted in selecting the appropriate indicators. The starting point for the present study was the list of indicators given by Nanda et al. (2019), who had assessed India’s vulnerability to P scarcity using a top-down approach. The list was supplemented by adding the indicators given in studies that had used the bottom-up approach, namely those that computed a global adaptation index (IGES, 2013) and a climate vulnerability monitor and climate change vulnerability index (AEA, 2012). The final selection of indicators was based on the relevance of the indicators to a) phosphorus vulnerability assessment (PVA), b) geographical scale of the study, and c) the chosen study area. Any repetitions across the studies were eliminated and similar indicators were merged into single indicators. Experience gained during field visits and stakeholder consultations proved particularly useful in making the final selection. The chosen indicators were screened based on their likely impact, which was estimated from the weights assigned to them by the stakeholder to each indicator (the weight, wi, was 0, 1, or 2: the higher the weight, the greater the potential impact)

Stakeholder consultations were undertaken using semi-structured interviews and group discussions. Semi-structured interviews were used for the SH1 group whereas both the methods were used to elicit responses from members of the SH2 group. Respondents for SH2 were identified with inputs and help from respondents from SH1. Finally, significant indicators were chosen for calculating the PVI. These indicators were those that had either secured a weight of greater than 2 when the weights assigned by both the groups were added or those that had been assigned a weight of 2 by at least one of the two groups (SH1 or SH2). Data for each indicator were collected from published reports of government departments, records archived in the departments in the region, and consultation with key informants.

*2.2. Calculating phosphorus vulnerability index*

The phosphorus vulnerability index was calculated using the method given by Nanda et al. (2019. The method comprises standardizing indicator values (eq. 1), normalizing the weights (eq. 2), and finally calculating the PVI (eq. 3).

 (1)

where Ii,std is the standardized value of the ith indicator, Ii is the observed value of the ith indicator, and Ii,max is the maximum threshold value of the ith indicator.

(2)

 wi,std =

where wi,std is the standardized weight of the ith indicator, n is the number of indicators, and wi is the weight assigned to the ith indicator.

(3)

The value of PVI can range from 1 to 100, with 1 representing very high vulnerability and 100 representing no vulnerability. The catergorization of PVI in descending order of vulnerability to P scarcity is as follows: very high vulnerability (PVI <20), high (20.1–40), moderate, (40.1–60), low (60.1–80), and very low (>80). The confidence interval (CI) of the values is set at a significance level (α) of 10% by applying *t*-statistics to the weights given by the stakeholders.

*2.3. Phosphorus flows*

To identify the most suitable points of intervention for devising the strategies for P supply or demand, P flows in the region were examined with agriculture as the core sector. The framework for P flows was conceptualized from the work of Senthilkumar et al. (2012) and Mishima et al. (2010) and is shown in Fig. 2. With the administrative region serving as the system boundary, P flows across various system components, which include people, crops, industries, livestock, and soil. Inflows to the region are associated with such natural geogenic processes as leaching of natural rock P or atmospheric deposition, which may be augmented by run-off from surrounding regions. The same geogenic factors also drive the outflows from the region. Besides these factors, inflows are also from anthropogenic sources such as import of chemical fertilizers and food. Outflows from the system are in the form of finished goods, farm produce (including that from livestock), and waste. Interactions among these components are further influenced by many other factors.

The present study used various methods of estimating P flows depending on available data. For instance, P flows from livestock were estimated from its dietary requirements for P and apportioning them between the different inflow and outflow channels from this node. For the node representing people, P flows were estimated based on regional food production and consumption. Flows in the form of human wastes were estimated using P concentration per capita in solid and liquid waste as reported for the population and those in the form of livestock waste were estimated using excretion rates as reported in literature. It may be noted that data on natural resources in the developing countries are not monitored regularly and, at times, are shrouded in secrecy with limited or no peer review. The method of accounting for P flows proposed here is therefore suitable for other developing countries and can be refined for countries where comprehensive and more reliable data are available: given the low reliability of data and various assumptions, the mass balance for each node is indicative—no claim is made of a comprehensive SFA for P, and the study focuses only on those flows that are linked to strategies identified by grassroots-level stakeholders. Accordingly, P flows are estimated only for some components, as shown in Fig. 2. The methodology for each of these components is explained in the following sections.

*2.3.1. Uptake of phosphorus from soil by crops (F1)*

F1was calculated using eq. 4:

(4)

where F1 is P taken up by crops from soil (tonnes per year); Qm is the yield (tonnes per year) of or area (acres per year) under the mth crop; xm is the rate of uptake of P from soil by the mth crop during its life (in kilograms per tonne or per acre); and k is number of different crops produced in the region.

*2.3.2.* *Dietary requirements of livestock for phosphorus (F2)*

Livestock receive their dietary P requirements either fromlocally grown fodder (F2a) or from fodder or feed sourced from nearby regions (F2b). F2 was calculated using eq. 5:

(5)

where F2 is P present in fodder (tonnes per year); Ly is the no. of yth livestock;

py is the P required to maintain the body weight of the yth livestock (in grams per day per animal) ;; t is number of livestock species in the region; and y is the given species of livestock.

F2a can be estimated using eq. 4, assuming that P taken by a crop from soil remains as part of the fodder consumed by livestock. A part of the fodder in a region could be supplemented with crop residues (the amount of P in the residues can be calculated using eq. 10).

F2b was estimated using eq. 5a.

(5a)

F2b = F2 – F2a.

*2.3.3. Dietary requirements of people (F3)*

Phosphorus in people’s diet comesfrom locally grown farm produce (F3a), from livestock in the form of milk and meat (F3b), and farm produce from non-local sources (F3c).

F3a and F3c were calculated using eq. 6.

where F3ais the P consumed by people through locally grown farm produce in the region (tonnes per year); PCc is P content of the cth crop produced and consumed (in grams per kilogram of produce); Cc is the quantity of the cth crop produced locally (or sourced from outside the region for F3c) and consumed (in kilograms of produce per year); and z is the number of different crops produced and consumed in the region.

(6)

F3b was calculated using eq. 7.

(7)

where F3b is P consumed by people in the form of livestock produce (tonnes per year); t is the number of livestock; b is the number of different kinds of livestock produce; y is the given species of livestock; j is the given category of livestock produce; sy,j is P concentration in the jth produce from the yth livestock species (in milligrams of P per kilogram of produce); and Ly,j is the number of yth species of livestock producing jth variety of produce from the region.

*2.3.4. Phosphorus in waste generated by people (F4)*

F4was calculated using eq. 8.

(8)

where F4 is the quantity of P in the waste generated by people (tonnes per year); pww is P concentration in the waste, both solid and liquid (in grams per capita per day); and P is the population of the region. F4, in liquid form, could be discharged as open defecation directly into soil (F4a) or from sewage treatment plants (F4b) or directly discharged into open drains (F4c). Solid waste is either taken to landfills (F4d) or returned to soil (F4e) through dumping grounds, composting, or other means.

*2.3.5. Phosphorus in waste generated by livestock (F5)*

F5 was calculated using eq. 9.

(9)

Where F5 is the P in livestock excreta(tonnes per year); Ly is the number of yth livestock in the region; ey is the amount of P in the excreta of yth species of livestock (in kilograms per animal per year); and t is the number of livestock species. F5 could be used either as fuel for cooking (F5a) or as manure (F5b).

*2.3.6. Phosphorus in crop residues* (F6)

F6 was calculated using eq. 10.

(10)

where F6is the P present in crop residue in the region (tonnes per year); Rm is the quantity of residue produced from the mth crop (in kilograms per year); zm is the P concentration in residues from the mth crop (kilograms of P per kilogram of residue); and k is the number of different crops. Other flows, such as P lost to the region because of export of crops (F7) and animals (F8) from the region were estimated using eqs. 4 and 7, respectively, where Qm was replaced with Qexp,m (quantity of the mth crop exported) and Ly was replaced with Lexp,y,j (quantity of the jth animal product exported from yth animal). The quantity of P imported in the form fertilizer (F9) was calculated from the data published by relevant government agencies.

*2.4. Strategies to reduce vulnerability to phosphorus scarcity*

Different types of strategies are considered that could potentially impact the PVI of a region. The strategies are categorized into a) supply-side measures such as technological interventions to improve P recovery and recycling of P from human and animal wastes, thereby reducing the demand for P fertilizers; b) demand-side measures such as a shift in cropping pattern from P-intensive crops to crops that require less P; and c) institutional measures such as developing an enabling environment to address the challenges faced by farmers. For each of the strategies, the impact on indicators and their values were assessed. The revised value of each indicator as a result of the relevant strategies was worked out in consultation with experts and SH1 stakeholders and the PVI was then recalculated using eq. 3.

**3. Study area**

The study area was chosen based on such desired features as a farming-dominated economy, a literate farming community, and a significant proportion of farmers with small landholdings (less than 1 hectare). These features led to Sonipat district in the state of Haryana, India. Haryana is in northern India and shares its boundary with the national capital, New Delhi. Being traditionally an agrarian economy, agriculture in Haryana has been promoted actively since 1965 (Singh, 2000). Sonipat is part of the Yamuna river basin, which is a sub-basin of the Ganga river basin. The Gangetic Plains, often referred to as the food bowl of India, account for 48.5% of the country’s rice production and 75% of its wheat production (Koshal, 2014). Another relevant factor was the stagnation in Haryana’s agriculture production since 2000 and its declining soil fertility (Pathak, 2010) (Shukla et al., 2005), which point to the state’s potential vulnerability to P scarcity.

Sonipat has sandy and clayey loam soils (approximately 67% of the soils are sandy). The district’s economy is driven primarily by agriculture, which accounts for 63.1% of the district’s workforce (Directorate of Census Operations, Haryana, 2011). The rural literacy in the region is 66.7% (Directorate of Census Operations, Haryana, 2011), and 62.6% of the farmers have landholdings smaller than a hectare. Per capita income is nearly half of that recorded in the adjoining areas (ICAR-National Dairy Research Institute, 2018). The main challenges faced by farmers in Sonipat district are low soil fertility (State Agricultural Department, 2019), salinity, and water-logging (Choubey et al., 2009).

**4. Results**

The stakeholders that make up the category SH1 were officials serving in office of the Deputy Director, Agriculture, in Sonipat, those working in the local agricultural extension centre (known as KVK, short for *Krishi Vigyan Kendra*, an extension service centre for farmers), soil-testing officers in the Agriculture and Farmers’ Welfare Department in Sonipat, members of the agriculture produce marketing committee (APMC), and fertilizer wholesalers. Their inputs helped in identifying suitable stakeholders under the category SH2, which comprised local farmers. In addition, we had the opportunity to talk to a group of 50 farmers who happened to be attending a training programme at the KVK in September 2018. Nineteen farmers were selected for in-depth interviews. The interviews were transcribed and analysed with the help of open coding to arrive at core codes or categories (Corbin and Strauss, 2008).

The more important items of information that emerged from the interactions with stakeholder groups were the willingness of farmers to switch to a different crop and their ignorance of the nutrient levels of their soils and of the government schemes related to agriculture. These findings are important because a change in cropping pattern may impact the vulnerability to P scarcity in future, and ignorance of the nutrient status leads to indiscriminate application of fertilizers; in fact, monitoring by government authorities has highlighted low soil fertility in the region (State Agricultural Department, 2019) whereas farmers believe that their lands are fertile and that the greater the quantity of fertilizers they apply, the greater will be the yield. This knowledge gap can be a starting point for policymakers to engage actively with farmers in choosing crops that match the soil’s nutrient status. Alternatively, the state can bring about the desired behavioural change through such fiscal methods as mandating a minimum support price for each crop at the regional level, offering subsidies or tax concessions to reward judicious application of fertilizers, and encouraging crop diversification and organic manures through suitable incentives. The interaction with farmers (SH2) also highlighted their lack of confidence in the ability of the government machinery to implement the relevant schemes and their perception that the officials are slow to respond and tend to favour the more prosperous and influential farmers in the region.

*4.1. Indicators of vulnerability to scarcity of phosphorus*

Of the total 91 indicators collected from the literature, 25 were repetitive or similar, 15 were irrelevant to P-related studies, 10 were irrelevant to studies at the sub-regional scale, and 6 were irrelevant to the chosen study area owing to differences in local conditions. The remaining 35 indicators were used in stakeholder consultations. Table S1 gives brief narratives and the weights assigned by the two categories of stakeholders to each of these indicators. Finally, 21 significant indicators (Table 1) were identified for calculating the PVI as explained in Section 2.1, and Table S2 gives more details of the given Ii and Ii,max values.

**Table 1**

Significant indicators for calculating phosphorus vulnerability index of Sonipat, India.

| Indicator (i) | wi  | Ii,max | Ii | Data source |
| --- | --- | --- | --- | --- |
| 1. Farmers’ purchasing power (US dollars per year)
 | 4 | 7000 | 2405 | ICAR-National Dairy Research Institute, 2018; Institute for Development and Communication, 2014 |
| 1. Proportion of farm income spent on fertilizers (%)
 | 4 | 100 | 16.5 | National Sample Survey Office, 2014 |
| 1. Soil fertility levels (percentage of soil samples with P content greater than 20 mg/kg)
 | 4 | 100 | 0.08 | State Agricultural Department, 2019 |
| 1. Proportion of marginal farmers with access to credit (%)
 | 4 | 100 | 24.5 | Kumar and Kumar, 2018 |
| 1. Heads of cattle per cultivator
 | 4 | 8 | 3 | Directorate of Census Operations, Haryana, 2011 |
| 1. Potential to access alternative sources of P
 | 4 | 100 | - | Information not available  |
| 1. Effectiveness of governance
 | 4 | 1 | 0.25 | Consultation with SH2 stakeholders |
| 1. Proportion of landholdings smaller than 1 hectare (%)
 | 4 | 100 | 62.6 | Directorate of Census Operations, Haryana, 2011 |
| 1. Rural literacy (%)
 | 4 | 100 | 66.7 | Directorate of Census Operations, Haryana, 2011 |
| 1. Increase in use of organic fertilizer over previous years (%)
 | 4 | 100 | 33.5 | Annual Reports, National Centre of Organic Farming |
| 1. Yield of cereals (t/ha)
 | 4 | 5.1 | 3.55 | Agriculture Informatics Division, 2019 |
| 1. Net annual investment in productive assets (in USD per capita)
 | 4 | 7000 | −516(debt) | National Sample Survey Office, 2014 |
| 1. Markets for agricultural produce per 100 000 households
 | 3 | 25 | 10 | Ministry of Food Processing Industries, 2017 |
| 1. Proportion of area under bio-farming to net sown area (%)
 | 3 | 100 | 0.11 | National Centre of Organic Farming, 2017 |
| 1. Crop diversity
 | 3 | 1 | 0.45 | Kumar and Kumar, 2018 |
| 1. Proportion of agricultural workforce to total workforce (%)
 | 3 | 100 | 41.4 | Directorate of Census Operations Haryana, 2011 |
| 1. Share of non-agricultural sources of income of farmers (%)
 | 3 | 100 | 40 | ICAR-National Dairy Research Institute, 2018 |
| 1. Implementation of P-related policies (qualitative)
 | 2 | 1 | 0 | Primary survey and secondary data (policy documents) |
| 1. Imperviousness of soil to water (%)
 | 2 | 100 | 60 | Asian Development Bank, 2010 |
| 1. Proportion of households with access to improved sanitation facilities (%)
 | 2 | 100 | 90 | International Institute for Population Sciences, 2017 |
| 1. Proportion of net sown area to total geographical area (%)
 | 2 | 100 | 67.2 | Department of Economic and Statistical Analysis, 2019 |

Table 2 compares significant indicators from the top-down approach (Nanda et al., 2019) with those found using the bottom-up approach in the present study.

**Table 2**

Comparison of significant indicators from studies using top-down and bottom-up approaches.

|  |  |  |  |
| --- | --- | --- | --- |
| Indicator | Indicators common to both approaches | Indicators unique to bottom-up approach | Indicators unique to top-down approach |
| Economic | Farmer’s purchasing power, proportion of marginal farmers with access to credit, proportion of farm income spent on fertilizers | Share of non-agricultural sources of income, markets for agricultural produce per 100 000 households, net investment in productive assets | GDP per capita (PPP), level of urbanization, P GDP elasticity, disguised employment |
| Social  | Proportion of landholdings smaller than 1 ha, rural literacy, heads of cattle per cultivator, proportion of net sown area to total geographical area | Crop diversity, yields of cereal crops, proportion of agricultural workforce to total workforce, proportion of households with access to improved sanitation facilities | Growth of rural population, proportion of non-poor in rural population, proportion of households owning telephones, proportion of area under cereal crops |
| Environmental | Proportion of area under bio-farming, soil fertility level, potential to access alternative sources of P, increase in use of organic manure | Imperviousness of soil to water | Proportion of area irrigated with groundwater, import dependence, national importance of P |
| Governance | Implementation of P-related policies, effectiveness of governance |  |  |

Of all significant indicators, nearly half were unique to the chosen (bottom-up) approach, confirming its merits as a channel to seek policy inputs. Hence, policies identified using the top-down approach should be supplemented with those identified using the bottom-up approach. Further, bottom-up studies help in realizing the challenges encountered while implementing a given policy and in identifying strategic intervention areas. For example, information on new policies and scientific information reached only a few farmers – those attending any of the training programmes organized by the KVK – whereas most members of the farming community remained ignorant of policies beneficial to them and of relevant technical advances in farming. This points to the need to strengthen the training and communication strategy. Similarly, financial institutions, which play a critical role in making farmers less vulnerable by extending credit and offering insurance cover to them, have not reached out effectively to small and marginal farmers.

Some indicators identified using the top-down approach are significantly linked to other indicators found in the present study. For instance, a government scheme targeted at doubling farmers’ income includes livelihood diversification and cultivating cash crops. Farmers in Sonipat were experimenting with such diversification, and any support from the federal government would improve P security at the regional level. Although reducing vulnerability on the national scale is important, it is imperative to meet the needs of the vulnerable groups at the local level to build their capacity to adapt.

*4.2. Vulnerability assessment of the region*

Of the 21 significant indicators, data for one indicator, namely the potential to access alternative sources of P, were not available for the region. Hence the remaining 20 indicators were used to calculate the PVI. Data for the indicators were converted where required to make them unidirectional (by subtracting the value from 100; Nanda et al., 2019) so that the higher the value of a given indicator, the lower the vulnerability. The overall PVI for Sonipat was 38.73, which marks the district as highly vulnerable to P scarcity. At 10% level of significance, uncertainty analysis for the weights assigned to the indicators led to a PVI in the range of 30.4–40.8. Indicators responsible for the low PVI of the region were less fertile soils, low purchasing power of farmers, limited access to institutional credit, a large proportion of farmers with small landholdings, fewer heads of cattle per cultivator, limited use of organic manures, and excessive use of chemical fertilizers. Since these indicators also figure in the top-down vulnerability assessment studies, it can be assumed that federal government schemes may help in making the region less vulnerable in future. However, several measures are required at grass-roots level to maximize the benefits from such schemes and to address other indicators that influence the PVI. These measures include increasing crop yields, crop diversification, and enabling farmers to obtain P from alternative sources such as recycling or reusing waste. Supplementing the existing schemes with policies specifically targeted at P can make the region more resilient to P scarcity.

*4.3. Phosphorus flows*

Table 3 lists the data sources used for estimating P flows in the region. The actual data, collected for the year 2017/18, are given in Table S3. Data not available for the year were extrapolated from the values for the previous years. The more important data are given here.

Wheat and rice together account for 89% of the total crop production (Qm) in the region; nearly half of wheat production and almost all (95%) of rice production are exported (consultations with SH1 group). Sugarcane is the third main crop (6% share), used mostly by industries (above 95%) and by people living in Sonipat. Milk and meat are the two major animal products. Nearly 94% of the livestock consists of milch animals, mostly cows and buffalos, and any surplus is exported to nearby areas and to the dairy industry. Meat consumption in the region is low (50% of Ly) (Gandhi and Zhou, 2010). The primary P requirements of livestock are met through crop residues used as fodder. About 50% of maize is used for poultry feed, and the rest is imported. Sanitation coverage in the region increased from 80% in 2011 (Directorate of Census Operations, Haryana, 2011) to about 90% in 2017; however, many toilets constructed in rural areas are not connected to the drains or sewers lines. The proportion of wastes going directly to soil was estimated at 10% by SH1 group of stakeholders. The region has only one sewage treatment plant, which has the capacity to treat 3 million litres of sewage a day, is non-functional (Central Pollution Control Board, 2013). The solid waste generated by inhabitants is mostly taken to landfills, and nearly 70% of organic waste is converted into compost. Livestock excreta was earlier used as fuel for cooking (in the form of dung cakes) but not any longer, because all households now have access to liquified petroleum gas, and all waste is now returned to the soil either directly or after anaerobic digestion. Unutilized crop residues are spread out on the soil surface and burnt, which also returns P to soil.

**Table 3**

Data sources for phosphorus flows.

|  |  |
| --- | --- |
| Flow | Sources of data |
| F1 | Qm: (Department of Economic and Statistical Analysis, 2019); Office of Deputy Director, Agriculture, for Sonipat district, Haryana) xm: (Aishwath and Malhotra, 2013; Buresh et al., 2010; Malhotra and Srivastava, 2015; Mitra and Mandal, 2012; Pathak et al., 2003; Pierzynski and Logan, 1993; Vennila et al., 2017) |
| F2 | Ly: (Department of Animal Husbandry, 2014) py: (Singh et al., 2018) for cattle; (Reddy et al., 1980) and (Department of Animal Husbandry, Dairying and Fisheries, 2018) for poultryFor F2a, the region uses 66% of crop residues as fodder (Chauhan, 2010) and 50% of maize is consumed as poultry feed |
| F3 | Cc: (Department of Economic and Statistical Analysis, 2019), Office of Deputy Director, Agriculture, for Sonipat district, Haryana) PCc and sy,j: FAOSTAT database for India and Singh et al., 2002 Ly,j: (Department of Animal Husbandry, 2014); j: milk and meat |
| F4 | pww: (Central Public Health and Environmental Engineering Organization, 2013); (Central Public Health and Environmental Engineering Organisation, 2016)P: Government of Haryana: Sonipat district website  |
| F5 | Ly: (Department of Animal Husbandry, 2014)ey: (Directorate of Census Operations, Haryana, 2011; Gerber et al., 2005; Ramesh et al., 2009) |
| F6 | zm: (Baggiel et al., 2004)Rm: (Chauhan, 2010); extrapolated from 2003 data |
| F7 | Qexp,m: (Department of Economic and Statistical Analysis, 2019), Office of Deputy Director, Agriculture, for Sonipat district, Haryana)xm: FAOSTAT database; (Keil et al., 2018) |
| F8 | Lexp,y,j: (Department of Economic and Statistical Analysis, 2019); Office of Deputy Director, Agriculture, for Sonipat district, Haryana) |
| F9 | (Department of Economic and Statistical Analysis, 2019) |

Flows of P for the region are shown in Fig. 2. The region imports 14 126 tonnes of P in the form of fertilizer (13 538 tonnes a year) and livestock feed (588 tonnes a year) and exports 3804 tonnes of P the form of farm produce (2147 tonnes a year), waste (1268 tonnes a year), and animal products (419 tonnes a year). Some P flows such as those associated with industrial goods, geogenic causes, and several other minor flows have not been accounted for (it is assumed that their inflows and outflows offset each other). Further, the data are not highly reliable because the monitoring of parameters is limited; as mentioned earlier, the mass balance at each node is only indicative. The region imports 10 323 tonnes of P annually. Despite being a net importer of P, soil fertility has been declining (State Agricultural Department, 2019). This indicates that the region may be accumulating P in the form of residual P that is not available to crops because it is locked within soils (Linquist et al., 1996; Sattari et al., 2012). This locked P is not monitored in soil nutrient surveys.

Mining is not carried out in the region. Hence, the major source of P consumption in the region is agriculture. Of the total P required by crops (5827 tonnes a year), nearly 45% (2625 tonnes a year) is contributed by wastes generated in the region, against the total potential (ignoring industrial flows) of 66.3% (3863 tonnes a year). About 2565 tonnes P is exported annually in the form of food grains and animal products. Import of P as animal feed is 588 tonnes a year. Hence, the net P balance to maintain the population and livestock is positive, as the region has extensive agriculture and animal husbandry. The net annual additional requirement of P in soil (from crop uptake and replenishment from wastes) is only 3202 tonnes. This can be further reduced to 1964 tonnes a year if P lost in wastewater and solid waste is recovered and used. Hence, 11 574 tonnes a year (about 85%) of imported fertilizer can be avoided by using it judiciously and by recycling waste.

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**Fig. 2.** Annual phosphorus flows (tonnes) in Sonipat, Haryana, India.

The flow of P in the region shows three plausible ways of reducing P flux, namely recycling and reusing P from waste from the existing levels to the full potential, avoiding excessive use of fertilizers, and switching to less P-intensive crops.

*4.4. Strategies to address vulnerability to phosphorus scarcity*

Strategies to make the region less vulnerable to P scarcity were identified as explained in Section 2.4. These strategies are not mutually exclusive and may have overlapping influence on the indicators directly or indirectly. Each of the following sections (4.4.1 to 4.4.3) explains one strategy and its influence on the indicators of PVI and on the index itself.

*4.4.1. Strategy 1:* *recovering and reusing phosphorus from waste*

Nearly 88% of human waste (1238 tonnes of P annually) leaves the region untapped, but can be a potential source of P. People of Sonipat district generate 1409 tonnes of P in their waste annually, of which 171 tonnes currently enrich the soils of the district. Considering a conservative value of 50% P recovery, the district can get 627 tonnes of P annually from this source. To implement this strategy, the agricultural department of the district could work together with the water works and municipal departments for waste collection and P recovery (Diaz-Elsayed et al., 2019). Coordination and a shared vision among the various departments at the regional and federal levels are needed to source funds from existing programmes of the government. For instance, such schemes can be tied up with the river cleaning initiative. Table 4 shows the indicators influenced by this strategy and the PVI.

**Table 4**

Impact of recovering and reusing phosphorus from waste (Strategy 1) on phosphorus vulnerability index.

|  |  |  |  |
| --- | --- | --- | --- |
| Indicator | Nature of impact | Revised Ii | Index (confidence interval)  |
| Farmer’s purchasing power (USD per year)  | Indirect | 2600  | 39.84(31.1–42.0):highly vulnerable |
| Proportion of farm income spent on fertilizer (%)  | Indirect | 13 |
| Increase in use of organic manure compared to previous years (%) | Direct | 40 |
| Net investment in productive assets (USD per year)  | Indirect | −475 |
| Proportion of area under bio-farming to net sown area (%)  | Direct | 0.5 |
| Proportion of households with access to improved sanitation facilities (%)  | Direct | 100 |

*4.4.2. Strategy 2:* *Reducing phosphorus demand through crop choice and fertilizer dose*

The amounts of fertilizers applied to different crops in India (Chanda, 2014) indicate that the requirements are low for sorghum (22 kg/ha), pearl millet or bajra (4.5 kg/ha), maize (23.7 kg/ha), chickpea (21.6 kg/ha), and other pulses (17.5 kg/ha) and high for sugarcane (56.4 kg/ha), potato (110.8 kg/ha), and vegetables (87.1 kg/ha). At the same time, the choice of the crop is also governed by other considerations; for instance, rice, at 29.8 kg/ha, ranks low in terms of fertilizers but is a water-intensive crop, which is worse for water security of the region (Davis et al., 2018), which shows evidence of overexploitation of groundwater (Central Ground Water Board, 2013). This is a classic case of trade-offs in sectoral policies with respect to the cropping pattern: whereas a concern for water shortages demands that the area under rice be decreased, a concern for P security demands that more area be brought under rice or wheat than that under vegetable or potatoes. For the present study, we considered replacing the area under rice and wheat with less P-intensive crops suitable for the region, namely pulses, pearl millet, sorghum, maize, and chickpea so that P requirements are reduced to 70% of the current requirements. To implement this strategy, farmers should be encouraged to make more informed choices and given adequate resources (seeds), training, and crop insurance. Flows of P in the district indicate that 85% of the fertilizer currently applied to crops is in excess of the amount required by crops. It is possible to reduce this excess by training the farmers and setting up demonstration plots. The agriculture department and the KVK can undertake such initiatives. Demand-management strategies have the potential to lower the imports of P fertilizers to about 80% of the current levels. Demand management alone can make the district less vulnerable and place it in the medium category in terms of the PVI (Table 5).

**Table 5**

Impact of reducing phosphorus demand through crop choice and fertilizer dose (Strategy 2) on phosphorus vulnerability index.

|  |  |  |  |
| --- | --- | --- | --- |
| Indicator | Nature of impact | Revised Ii | Index (confidence interval)  |
| Farmer’s purchasing power (USD per year)  | Indirect | 4000  | 44.88(42.9–45.4)Moderately vulnerable |
| Proportion of farm income spent on fertilizers (%)  | Direct | 5 |
| Soil fertility levels (proportion of soil samples with P content greater than 20 mg/kg) | Direct | 50 |
| Yield or cereal crops (t/ha) | Direct | 4 |
| Net annual investment in productive assets (USD per capita) | Indirect | −250 |
| Crop diversity  | Direct | 0.25 |

*4.4.3. Strategy 3:* *improving governance and devising targeted policy measures*

The success of the above two strategies would depend on cooperation from the relevant institutions, good governance, related policies and their effective implementation. Governance and targeted policies could influence most of the indicators indirectly; however, 6 of the 21 significant indicators are directly influenced by better governance (Table 6) and were used for evaluating the effectiveness of the strategy (expressed in terms of a change in PVI). For example, doubling farmers’ income by 2022 is a federal government scheme encompassing other existing schemes related to irrigation, finance, marketing of agricultural produce, sustainable agriculture, and a few other sectors (Department of Agriculture Cooperation and Farmers Welfare, 2018). These schemes are aimed at lowering input costs as well as improving the existing infrastructure to boost farm productivity, offering insurance cover to farmers, and mandating a higher selling price.

Implementation of these policies at grass-roots level needs a closer look. For example, village-level institutions need to be strengthened (Centre for the Study of Developing Societies (CSDS), 2014) if the schemes are to be implemented effectively. On similar lines, improving access to soft loans to poorer farmers could support poverty reduction and a shift towards more scientific agriculture. Organizing small farmers into joint liability groups is a proven mechanism to ensure repayment of loans as well as community ownership and accountability and is thus an effective measure to persuade financial institutions to extend loans to farmers (Mukherjee, 2019). Non-governmental and voluntary organizations can help in such initiatives and can strengthen stakeholder networks in collaboration with a national-level task force (Sen et al., 2018). Panchayats (local government) can seek technical inputs from the KVK or development officers to ensure that latest technologies are deployed at grassroots level. These measures would also help in winning the trust of farmers and in improving agriculture-related governance.

**Table 6**

Impact of improving governance and devising targeted policy measures (Strategy 3) on phosphorus vulnerability index.
*Note*: all the indicators have a direct impact on the index.

|  |  |  |  |
| --- | --- | --- | --- |
| Indicator | Nature of impact | Revised Ii | Index(confidence interval) |
| Effectiveness of governance  | Direct | 0.75 | 48.06(33.2–51.8)Moderately vulnerable |
| Implementation of P-related policies (qualitative) | Direct | 0.75 |
| Proportion of marginal farmers with access to credit (%) | Direct | 50 |
| Markets for agricultural produce per 100 000 households | Direct | 3 |
| Share of non-agricultural sources in farmers’ income (%)  | Direct | 60 |
| Rural literacy (%)  | Direct | 80 |

*4.4.4. Impact of multiple strategies on PVI score*

Table 7 gives the impact of combining the strategies. In calculating the PVI, higher values were taken for those indicators that are influenced by multiple strategies.

**Table 7**

Impact of combinations of strategies on phosphorus vulnerability index.

|  |  |  |
| --- | --- | --- |
| Combination | PVI(confidence interval) | Vulnerability |
| Strategies 1 and 2  | 46.11 (43.9–46.6) | Moderate |
| Strategies 1 and 3  | 49.8 (35.5–53.4) | Moderate |
| Strategies 2 and 3  | 55.42 (48.7–57.1) | Moderate |
| All 3 strategies  | 61.17 (60.99–61.22) | Low |

None of the strategies by itself could markedly lower the vulnerability to P scarcity whereas any two strategies, when implemented in combination, could lower the vulnerability of Sonipat to take it from highly vulnerable to moderately vulnerable—and all the three strategies if implemented together will lead to a PVI greater than 60, taking the district to the secure category.

**5. Conclusion**

Importance of the bottom-up approach – the present study was the first to use it to assess the vulnerability of a region to scarcity of a soil nutrient – is evident when the top-down study conducted by Nanda et al. (2019) is compared with the present study: whereas the strategies identified by the former can at best raise the PVI for India from 36.62 to 49.35, the corresponding figures for the latter are 38.73 to 61.17. The present study thus supports the contention that policy planning should use both the approaches. If the measures suggested by the study are implemented, the chosen study region, namely Sonipat, an agrarian district in Haryana, India, will no longer be vulnerable to P scarcity. What is more, the region will be not only less vulnerable but also secure from such scarcity if all the 35 indicators identified in the present study are considered instead of only the 21 significant indicators considered in the present study.

Undertaken in a developing country constrained by sparse and unreliable data, the study had its limitations; however, it does demonstrate a systematic and quantitative approach to evaluating the impact of various schemes launched by the state for the benefit of farmers.

Participation of stakeholders from government departments as well as from vulnerable groups (mainly farmers) revealed the differences in their perspectives of resource management. For example, for farmers, the key concerns were low income, inadequate access to credit, less fertile soils, and lack of transparency in government schemes whereas state officials, perhaps predictably, did not perceive local governance as a challenge. More specifically, the many recommendations related to good farming practices found in policy briefs (National Academy of Agricultural Sciences, 2014) and research publications (Rao et al., 2015) are being ignored by the relevant agencies in the region—a serious lapse in resource management. The assessment of P flows showed the region to be a net P importer, primarily because of excessive use of fertilizers well beyond the recommended doses: judicious application can lower this consumption by 85%. Augmenting P resources through recycling and recovery and lowering the demand by raising less P-intensive crops are the measures that can take the region from being highly vulnerable to moderately vulnerable to P scarcity.

Strategies that could increase the region’s PVI substantially, that is, make the region less vulnerable, are a combination of demand-side, supply-side, and institutional measure to provide an enabling environment for implementation of targeted policies. Legislation specifically aimed at P (the P platform) adopted by such developed countries as Denmark, Germany, and the Netherlands highlights the growing importance of the nutrient (Barreau et al., 2018). However, technology alone cannot do much to make a region less vulnerable to P scarcity: we need a mix of policies, institutional support, and awareness building in addition to technology to achieve that end. Collaboration within different agencies of the government and across various stakeholder groups is essential to address the multidisciplinary nature of agriculture, which needs inputs also from such sectors as waste management, trade, and manufacturing (fertilizer industry) to find appropriate solutions and to implement them. Implementing the measures for P security also provides such co-benefits as controlling eutrophication of water bodies and recycling critical nutrients back into the system. Finally, the study illustrates how other countries with similar context and background could take up such studies on a regional scale, identify suitable strategies, and evaluate them objectively.

**Acknowledgements**

The authors would like to acknowledge the support from and the information shared by experts in the region, including officials from the office of the Deputy Director, Agriculture, Sonipat district and those from the KVK and soil-testing laboratories. A special acknowledgement is due of the contribution of the nineteen farmers in Sonipat through their in-depth interviews and of the fifty who expressed their views, thereby highlighting how they cope with the existing challenges to their livelihoods.

This research forms part of a doctoral thesis and did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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