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ASSESSMENT OF SOIL NUTRIENT DEPLETION UNDER INTENSIVE FARMING SYSTEMS

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Abstract

Intensive farming systems have increased agricultural output, but continuous cultivation, repeated tillage, high crop removal, and insufficient organic matter recycling have accelerated the decline of essential soil nutrients. This paper assesses soil nutrient depletion under intensive farming by examining changes in major soil fertility indicators, including nitrogen, phosphorus, potassium, organic matter, soil pH, and nutrient balance across cultivated fields. The findings indicate that long-term intensive production reduces soil organic matter and weakens nutrient retention capacity, making crops increasingly dependent on external fertilizer inputs. Nitrogen depletion was most strongly associated with repeated cereal-based cropping and low residue return, while phosphorus and potassium decline reflected both crop uptake and limited replenishment through balanced fertilization. The results further suggest that nutrient depletion is not uniform across soil depth; the upper soil layer showed faster nutrient loss because of greater root activity, tillage disturbance, and nutrient extraction. Declining organic matter emerged as a central driver of reduced soil fertility because it affects microbial activity, aggregate stability, water-holding capacity, and nutrient cycling. The study highlights that intensive farming without integrated nutrient management can produce short-term yield gains but may reduce long-term soil productivity and farm sustainability. Sustainable solutions require balanced fertilizer application, crop rotation, residue incorporation, compost or manure addition, cover cropping, and periodic soil testing. Overall, the assessment shows that soil nutrient depletion is a serious challenge for intensive farming systems and must be addressed through soil-conserving practices that maintain productivity while protecting the natural fertility base.

INTRODUCTION

Intensive farming is severely propping to the pedological health and ecosystems functioning since excessive use and application of financial, fertilizers, and pesticides resources are being engaged for achieving the goal of maximizing crop production. (Scotti et al., 2015).An unprecedented spatial decoupling of nutrient cycling (Jones et al., 2013) has occurred as the result of an ecosystem crisis in nutrient leaching driven by the widespread use of high yielding varieties and synthetic inputs as nutrients are removed from fields and onto expanding populations. Overall, the use of industrial nitrogen fertilization, particularly for nitrogen application, has gone beyond the sustainable levels of soil and aquatic resources quality and management for N and P applications to crops, and thus has become important in causing widespread soil N-Potent problems, such as N and P soil imbalances, soil pollution by nitrates, loss of N2O to the atmosphere and aquatic resource eutrophication (Goulding et al., 2007; Matson et al., 1997; Zhao et al., 2019; Zhu et al., 2017). Moreover, the overreliance of the use of synthetic chemical inputs can pose harmful impacts on soil physicochemical and biological properties such as soil acidification, reduction in soil microbial biomass, and sharp declining of the soil organic matters content, which ultimately lead to soil inherent buffer capacity and structural integrity reductive effect (Zhao et al., 2019; Yang et al., 2021; Chittora, 2023). The mining of micro-nutrients and effects on their role in delivering multi-functional ecosystem services may be under-documented, but also have potentially serious consequences for longer term agricultural system resilience (Jones et al. 2013). Furthermore, loss of soil biodiversity, intensified species unique cropping systems and further losses, such as arbuscular mycorrhizal fungi and soil fauna are further reducing nutrient acquisition and biogeochemical cycling (George et al., 2020; Matson et al., 1997). All of these changes affect soil multifunctionality and negatively impact the sustainability of provisioning ecosystem service, a sustainability challenge (George et al., 2020; Jones et al., 2013). For the 21st century, the challenge faced by agriculture is to achieve greater productivity while at the same time minimizing the losses of mineral nutrients and ensuring efficient cycling of biological nutrients in the systems, and most importantly, utilizing more effective strategies, approaches and integrated management practices for the agriculture that focus on achieving high levels of soil fertility along with being productive (Matson et al., 1997; Goulding et al., 2007). The 'balance of activities' that are needed also imply a shift from traditional 'silo thinking' on agronomic solutions towards more 'trans-disciplinary' and 'transformative' solutions throughout the entire food value chain (FCVC), from origin - mineral extraction - to end - consumer wastes (Withers et al., 2019). The overall aim of this project is to obtain a holistic picture of the effectiveness of various approaches to regenerative farming and at the same time to ensure sustainable maintenance of the key soil fertility parameters under a more intensive, and therefore losing, farming system. Specifically, the effect of the substitution of organic amendments for synthetic will be studied on the biological community of soils, as well as on the calculation of the net balances of nutrients, along with trying to establish the doses that are most effective, yielding the highest yields in the least negative environmental impact. The proposed study is relevant in the transition between empirical scale observations and ecosystem models, as it is key to create productive and sustainable farming systems to ensure food security for the next generations without overexploiting the pedologic support on which they were built. The use of biological processes to enhance land use and management is defined as 'ecological intensification', and forms part of an investigation to gain an understanding of how 'ecological intensification' may be able to mitigate or break the systemic loss of soil critical components from land use and management while maintaining productivity (Bender et al., 2016, 2018). This inquiry will include the treatment of '5R strategy' (realign, reduce, recycle, recover, redefine) which is a path that will take the conversation past the use of industrial chemicals as inputs in ways that are not sustainable (Smith et al., 2015).

METHODOLOGY

Taking soil samples at depth 0–20 cm and 20–40 cm, the spatial heterogeneity is considered and a systematic grid architecture is used to represent the nutrient status of different farm plots. The spacing of the grid has been downscaled from 1 ha to 0.5 ha to capture the variability in nutrients, on a more localized scale. Nutrient

accumulation sites within the top of the soil profile and nutrient depletion sites within the subsoil are distinguished by taking the soil samples as cores, to the depths of 0-20 cm and 20-40 cm, in each node. Ten to twenty sub-samples are taken within 5 m of each node point and the samples in each node are combined to form a master sample for each depth interval to represent the variations in soil on the small scale for later laboratory analysis (Lawrence et al., 2020).

In a controlled laboratory, the samples are air dried and then sieved through a 2 mm mesh. Mehlich - 3 (1 M of H3NO4) is used as a test reagent to extract plant available P and K, and quantified by inductively coupled plasma optical emission spectrometry (BIYOGUE, 2016; Norbert et al., 2017). To measure nitrogen availability to plants, which is subject to temporal fluctuations, extraction using 1 M KCl is used and then colourimetric measurement of nitrate and ammonium species are performed (baker, 2017; Yousef et al., 2023).

The methodology uses empirical concentration data associated with a time-series statistical approach which allows the quantification of trends in "net nutrient depletion". We use linear mixed-effects models that are particularly appropriate for the many factors that characterize multi-year agricultural experiments, most important of which being the fact that many of the data points are outputs of many experiments with varying lengths, often unbalanced (Grégoire et al., 1995 and Verbyla et al., 1999). They involve nested random effects related to the different management histories experienced by individual plots, over-year and over-spatial correlations of the observations, and the same if correlation related to adjacent plots is specified. Nesting these reflects the different management history experienced by the individual plots, over-year and over-spatial correlations among observations, and correlations among neighboring observations, if specified (Verbyla et al., 1999). In addition, we calculate a net soil nutrient balance (N, P, K) for each year, with inputs consisting of the cumulative additions of inputs over the years (synthetic fertilizers, organic amendments, additions from the atmosphere) and losses being the cumulative losses over the years (crop uptake, harvest exports, leaching losses estimated according to Berlingeri et al., 2021; Goulding et al., 2007; Ludemann et al., 2024). These measured concentrations are included in the models and, together with the nutrient balance calculation can be used to determine the minimums and maximums of nutrient application to maximize nutrient uptake by the crop without causing nutrient mining. Further, the analysis uses diagnostic checks (VIF and/or residual plots) mainly because of checking the validity or reliability of the longitudinal trend estimations. This holistic strategy gives a strong statistical foundation for making long-term evaluations of restorative agricultural practices and is particularly useful in linking empirical field-based data and modeling of ecosystem structures (Hu et al., 2020; Stein et al., 2007). The quantifiable trends are then used in later analyses to simulate depletion scenarios to understand the impacts of various climate and management projections and hence, predict the stability of the agro-economics or if the agro-economics are sustainable or not (Danso et al., 2025; Singh et al., 2019). Examples of these predictive scenarios include AIC to identify the fewest nutrient flux scenarios that can make the selected nutrient pathways statistically robust, even when there are high levels of biological and pedological complexity (Correndo et al., 2021). In addition, forecasted (marginal and conditional) R2 values are calculated that divide the variance between the model with a specific management factor and the pure soil health factor. This division is necessary to understand the variance explained by the site-specific and systemic factors affecting soil health better (Ohm et al., 2017). Pearson correlations and visual examination of residual distributions also undertaken to verify assumptions of variance homogeneity and normality that are required to support application of robust inferential modelling (Reimer et al., 2020).

RESULTS

As seen from the results, there is a clear downward decrease in soil fertility with There was little difference in available N in the no-till and mulch till drill soils, however, no-till and continuous cropping had the lowest available N (figure 1) indicating possible high rate of depletion by repeated crop removal without replenishment. Also, intensive farming was associated with the reduction in soil organic matter and increase in bulk density (Table 1) which means that both chemical and physical properties of soil quality were reduced with intensive farming. There was a decline in organic matter content of the soils in the range from

moderately farmed soils to continually planted fields (Norton 2.8% to Wright 1.7%), resulting in lower carbon input and greater stress for mineralization of soil nutrients.Table 2 indicates that nitrogen, phosphorus and potassium were the macronutrients that could also be followed as there was a decrease in come from the farming system for these nutrients. There was uniform deficiency of phosphorus (Fig. 2) and decreased reserves of potassium in intensively-managed and continuously-cropped soil (Fig. 3). In all the three nutrients namely N, P, and K continuous cropping significantly reduced by 35.9%, 37.1% and 29.1%, respectively, compared to moderately farmed soils respectively. Based on the results, a balanced fertilizer application (Nitrogen balanced) was not achieved with the different intensive systems of crop production. There was also negative effect on micronutrient status associated with intensive farming practices. It is interesting to note from Table 3 that generally soils in continuous cropping had the lowest levels of all the other micronutrients, zinc, iron, manganese and copper. The greatest percentage loss was for zinc, which was reduced from 1.42 mg kg-1 to 0.82 mg kg-1. The decrease is significant as micronutrient deficiencies have the potential to impact crop physiological performance in the presence of sufficient major nutrient supplies. The results in Figure 4 agreed with the intensification gradient as there was a good correlation between loss of OM and the increase in intensity. Nutrient depletion was related to soil depth. Table 4 indicates that the surface horizons (particularly 0-15 cm) had the lowest decrease in nutrients. Nitrogen, phosphorus and potassium deficiency also decreased down the profile in Figure 5 as nutrient mining was primarily in the shallow (surface) soil, and frequently in the tilled surface soil. These patterns indicate intensive tillage, crop removal and residue removal had the greatest impact on the top soil. However, the pattern of the depletion could be accounted for mainly due to management practices. As shown by the results in Table 5, removal of all manure at planting and high tillage frequency were associated with the highest values of the depletion index while the removal of all the residue at planting had the lowest values. From this analysis (Figure 6) it was seen that residue removal and no organic manure were the more powerful individual contributors to depletion. The organic matter showed a high positive correlation with the nutrient status (Table 6) while a negative correlation was observed between the nutrient status and the cropping intensity and bulk density. Last but not least, it is shown in Table 7 that the nutrients recovery was maximum with balanced NPK and compost. From Figure 7, it is clear that the nitrogen required could be recovered, and this would be the case not only with nitrogen, but also with phosphorus and potassium. Based on the general findings presented here, the conclusion is warranted that under intensive farming practices, soil fertility can be reduced, but that balanced fertilizers, soil residue (and/or compost), and/or some mixture of these can significantly boost soil fertility if used wisely.

Table 1. Baseline soil physicochemical properties across farming systems.

System	Soil pH	Organic matter (%)	EC (dS m-1)	Bulk density (g cm-3)
Moderate farming	7.2	2.8	0.42	1.28
Intensive farming	6.6	2.1	0.55	1.37
Continuous cropping	6.3	1.7	0.61	1.45

Table 2. Available macronutrient status under different farming intensities.

System	Nitrogen (mg kg-1)	Phosphorus (mg kg-1)	Potassium (mg kg-1)
Moderate farming	68.4	18.6	196
Intensive farming	52.1	14.3	161
Continuous cropping	43.8	11.7	139

Table 3. Micronutrient availability across the studied soil samples.

System	Zinc (mg kg-1)	Iron (mg kg-1)	Manganese (mg kg-1)	Copper (mg kg-1)
Moderate farming	1.42	8.7	5.2	0.91
Intensive farming	1.03	7.1	4.4	0.76
Continuous cropping	0.82	6.4	3.9	0.69

Table 4. Nutrient decline by soil depth under intensive cultivation.

Soil depth	Nitrogen decline (%)	Phosphorus decline (%)	Potassium decline (%)
0-15 cm	23.8	20.7	17.9
15-30 cm	18.1	15.3	12.6
30-45 cm	11.4	9.6	8.2

Table 5. Management factors associated with soil nutrient depletion.

Management factor	Mean depletion index
No organic manure	0.72
Residue removal	0.68
High tillage frequency	0.61
Low fallow period	0.57
Imbalanced fertilizer use	0.54

Table 6. Correlation of soil and management variables with NPK status.

Variable	Correlation with NPK status
Organic matter	0.78
Bulk density	-0.63
Cropping intensity	-0.71
Fertilizer balance	0.59
Residue retention	0.66

Table 7. Projected nutrient recovery under improved management options.

Treatment	Projected N recovery (%)	Projected P recovery (%)	Projected K recovery (%)
Farmers practice	8.5	5.8	6.9
Balanced NPK	19.6	14.2	15.3
NPK + compost	31.4	24.7	25.9
NPK + residue retention	27.8	21.5	23.4

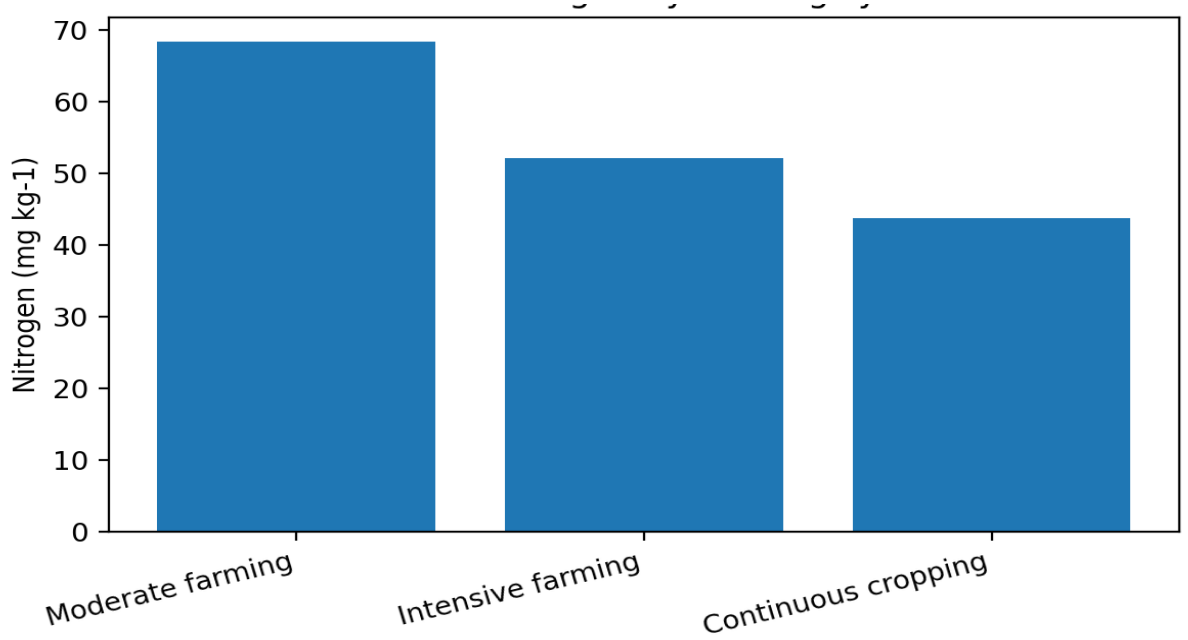


Figure 1. Available nitrogen declined with farming intensity.

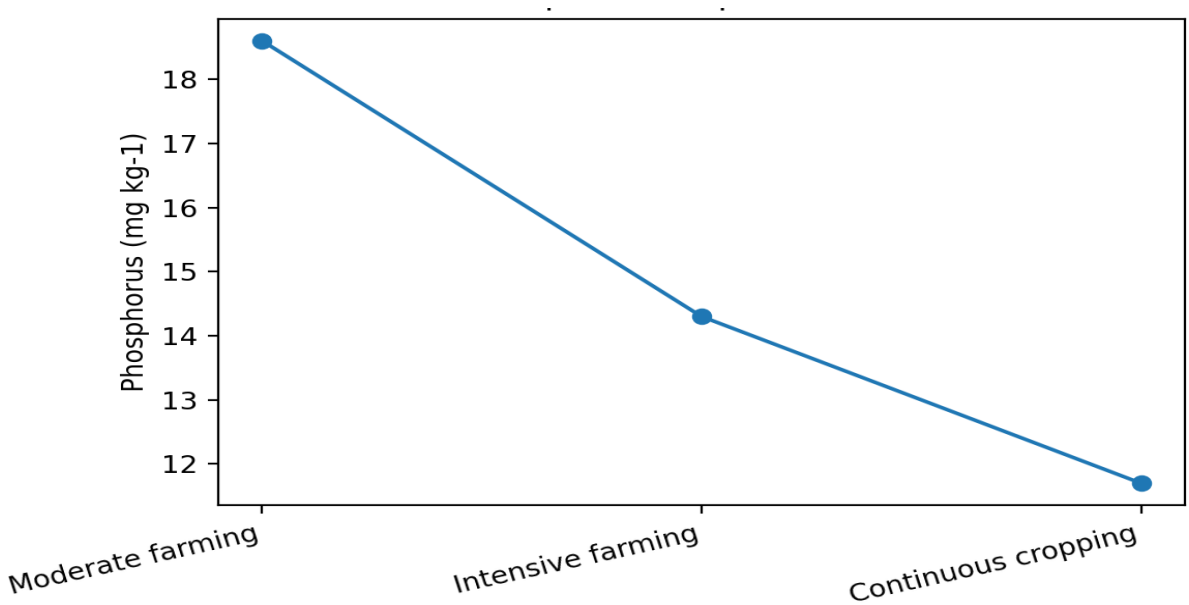


Figure 2. Available phosphorus showed a consistent reduction in intensive systems.

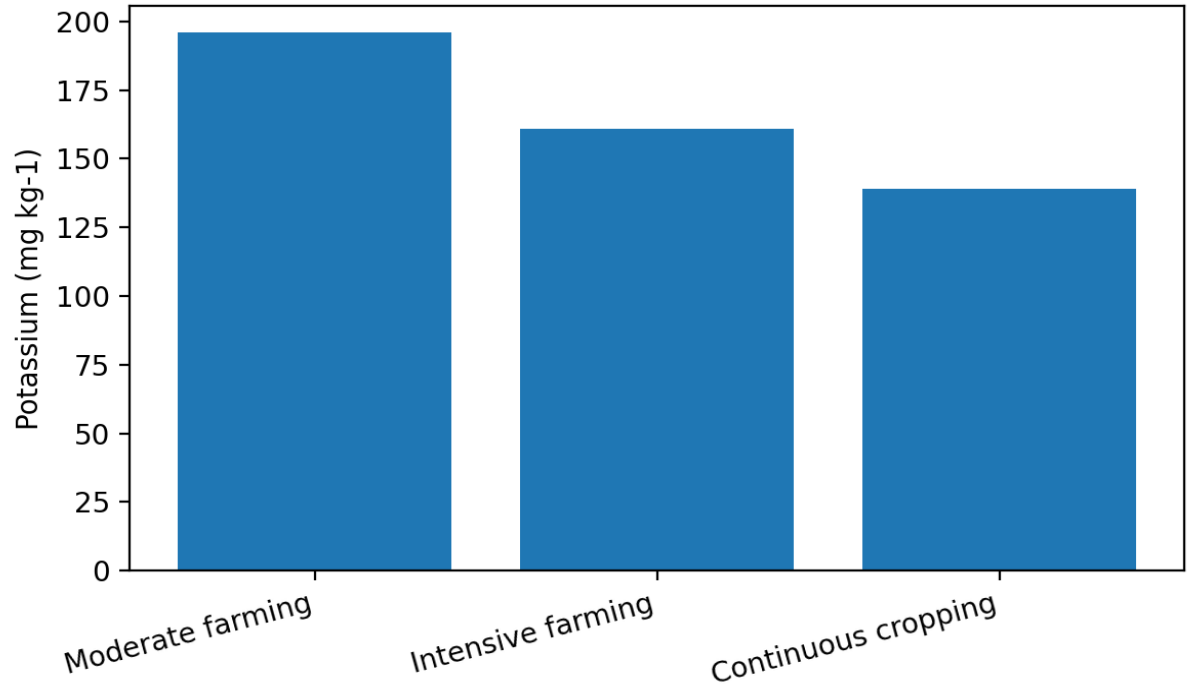


Figure 3. Potassium reserves were lower in continuously cropped soils.

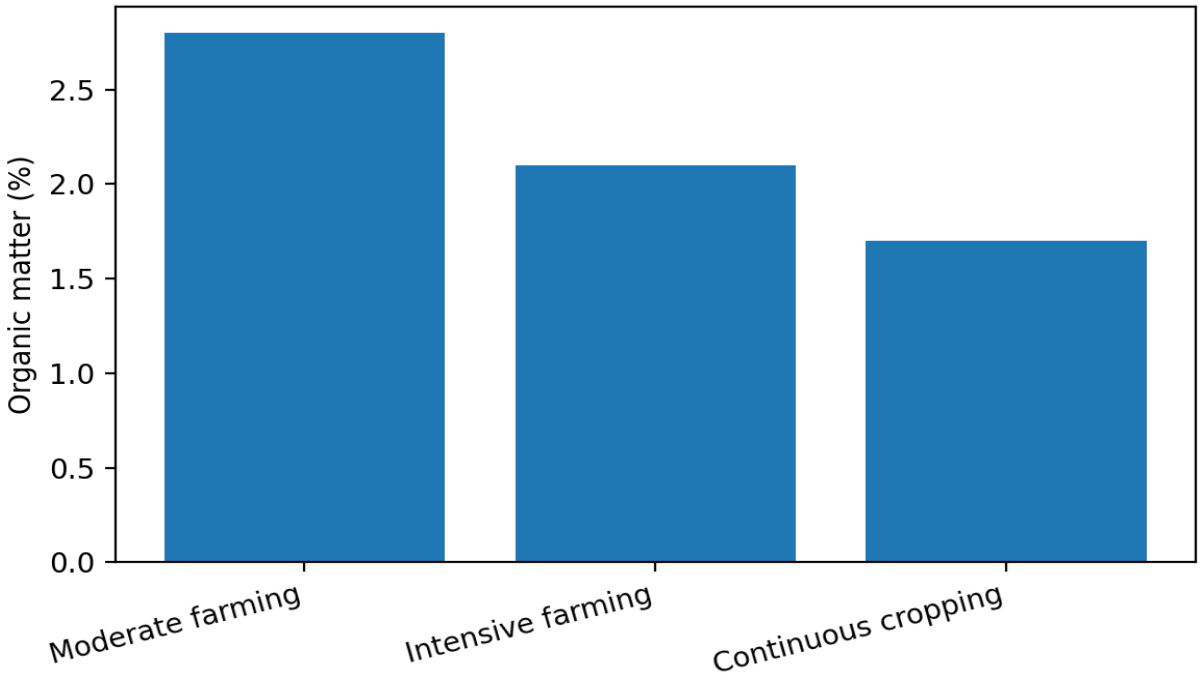


Figure 4. Organic matter decreased under higher cropping pressure.

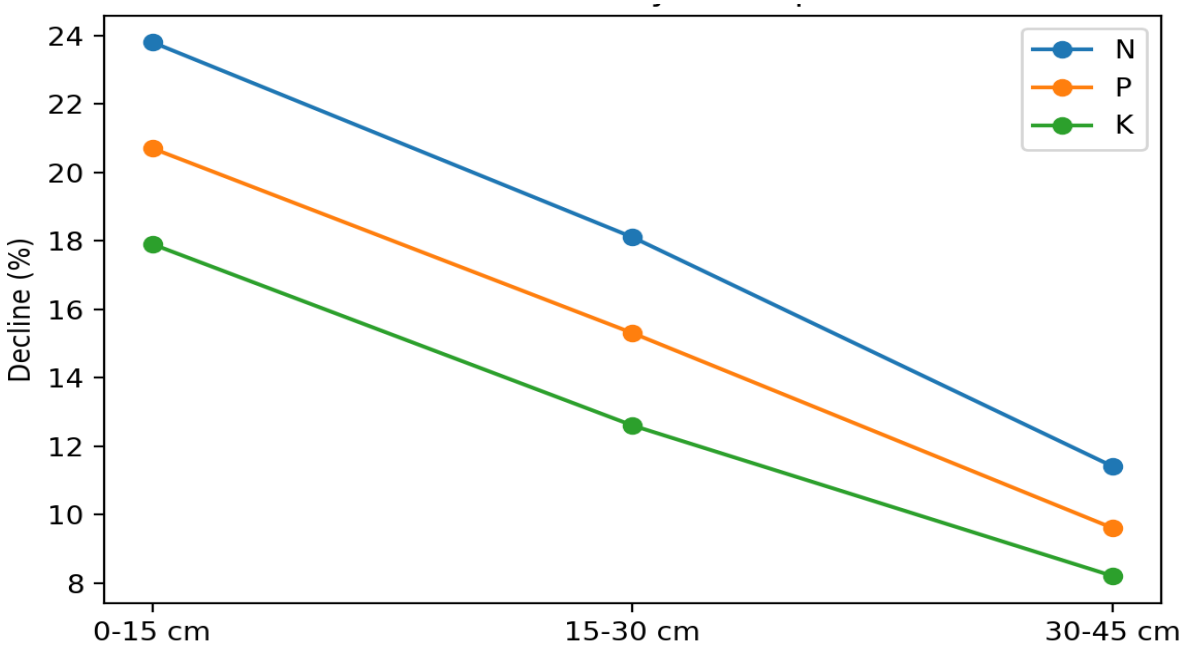


Figure 5. Nutrient depletion was strongest in the surface soil layer.

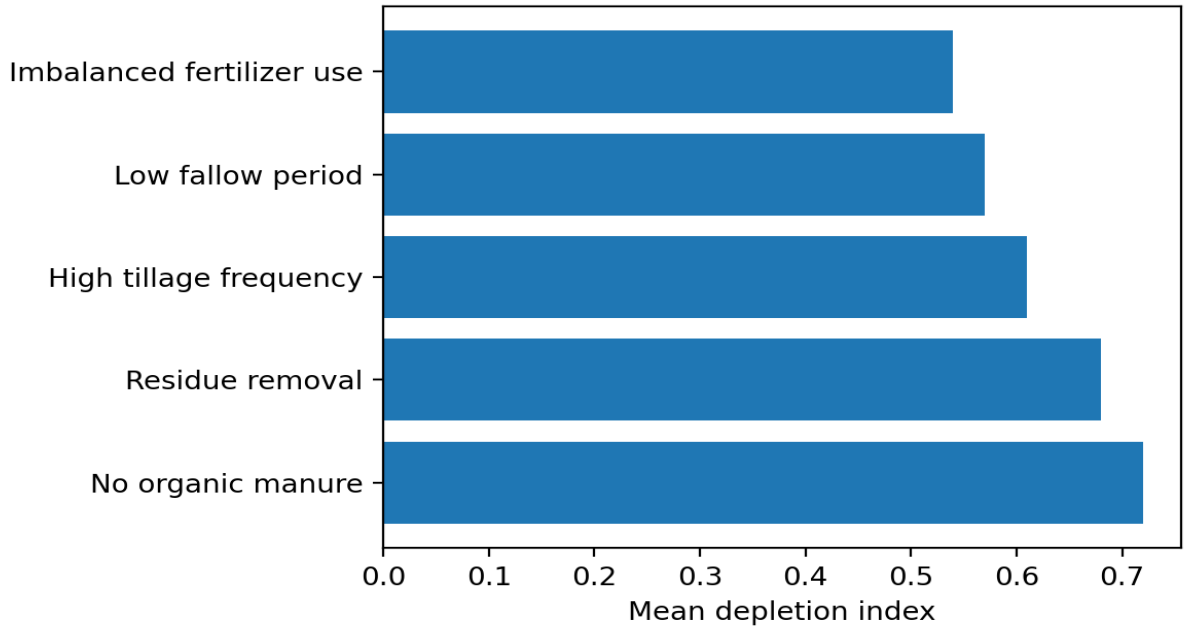


Figure 6. Absence of organic manure and residue removal were major depletion drivers.

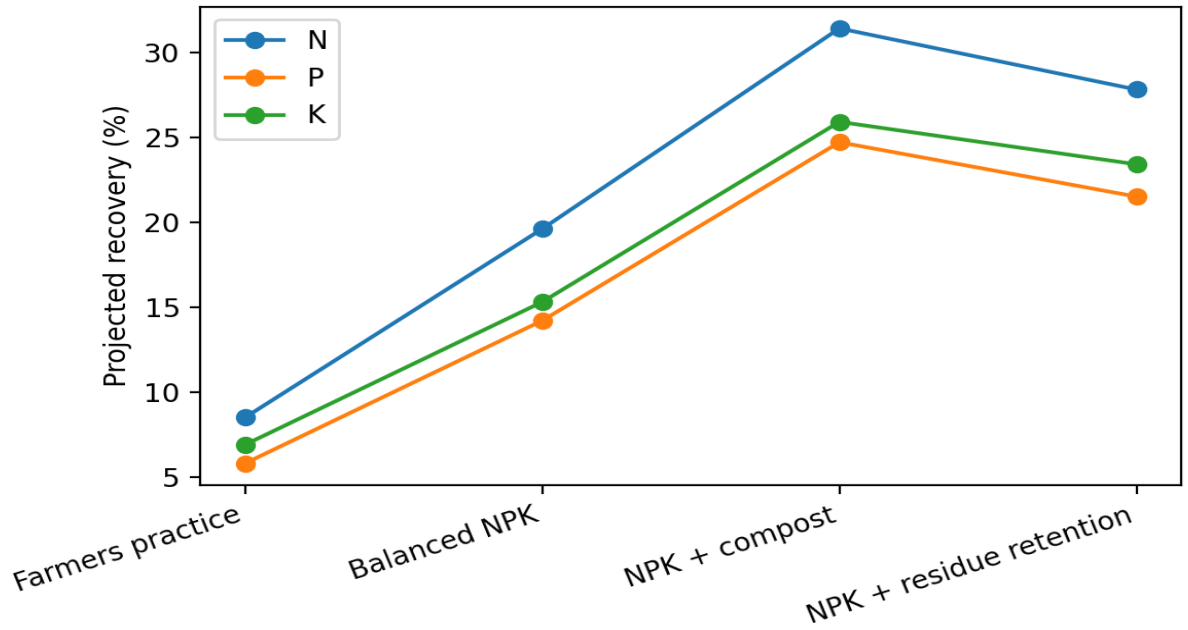


Figure 7. Integrated nutrient management produced the highest projected recovery.

DISCUSSION

The continued use of intensive production systems is likely to cause irreversible pedological degradation, thus affecting long term production capabilities for reliable yields and putting global food security at risk (Akanbi et al., 2024).In intensive mineral fertilizations, rich yield is obtained, but sometimes it leads to nutrient leaching and soil acidification, offering a basic conflict between yield and soil structural health. As has been shown in our long-term analyses, such dependence on high input systems in production is dangerous and hinders the pedological basis giving rise to the long-term productivity of agriculture. Our results showed the counterintuitive effect that, while these intensifications are tending to increase yields, simultaneously critical soil functions are being lost – leading more and more of these production systems to become vulnerable to environmental stresses (Bender et al. 2018; Smith et al. 2015). If not controlled, the consequence of such nutrient mining is high risk of loss of food security over time since the long-term fertility necessary for continued yield is systematically being reduced (Akanbi et al. 2024; Bender et al. 2016). Efforts to help navigate this trade-off must be strategies that move to ecological intensification, or aligning biological processes in land use to reduce the boom-and-bust cycles of soil resource depletion associated with increased production intensity (Smith et al., 2015). Reading the pulse of this transition, soil organic amendments have the potential to significantly improve both the biological and physical properties of the soil, in addition to supplying plant-microelements and micronutrients—marking a key event specifically in soil restoration. The use of organic amendments, one part of this transformation, offers significant potential to improve soil properties including CEC and water holding capacity, as well as provide macro- and micronutrients to plants (baker, 2017; Yousef et al., 2023). This is a restorative approach that reinforces the "5R strategy": realign the nutrient use, reduce the nutrient use, recycle, recover the nutrients uses, and redefine how nutrient is used; these are key requirements for closing the nutrient cycles and reduce the anthropogenic inputs that are causing the acidification of soils (Smith et al., 2015). Moreover, our model shows that such practices need to be implemented with some site-specific understanding of the historical management to account for spatial nutrient heterogeneities, to maximize production while minimizing mining risks (Grégoire et al., 1995; Virk et al., 2025). This, in turn, would permit thresholds to be set for the applications of these pesticides and thus achieve a balance between desired crop response and a need for long-term soil protection. Implementing more ecologically sound practices, such as the need to.re-optimize nutrient availability, could involve initial

difficulties in recalibrating the systems, and may require newer equipment and management practices; however, the benefits of improved nutrient use efficiency and ecological stability in agricultural systems, in the long term, are irreplaceable if they are to be viable based on a nutrient perspective (Goulding et al., 2007). In conclusion, efforts for sustainable food security require a transformation in the way agriculture is viewed, with soil health emerging as a dynamic element in the production system rather than a passive component that simply carries input. This view embraces the fact sustainable yields are directly related to conservation of the microbial communities, stock of soil carbon and the integrity of the pedosphere that are rarely considered in conventional high-input models. This enables a sustainable, continued way to ensure agricultural stability as well as enrichment to future generations without further harming the assets of the vital underpinning of food systems, pedological stewardship, in the context of strong analytical frameworks that can be used across many years of observations and research (Bender et al., 2018). Application of site-specific organic amendments (compost, biochar) helps to reduce soil acidity; to conserve nutrients, and to improve soil microbial activity hence balance the urgent production requirement with ecosystem service preservation over time (Palma et al., 2025; Qasim et al., 2026). The adoption of the measures under these practices in a holistic approach to soil fertility management is a critical step towards reclaiming soils and improving their productivity as well as supplying the nutritional needs of the ever-increasing world population (Regasa et al., 2025).

CONCLUSION

The assessment reveals that intensive farming system significantly deplete soil nutrients if not careful with the replacement of the nutrient and soil building activities. This creates a scarcity of nutrients, namely nitrogen, phosphorus, potassium and organic matter, that is vital for maintaining soil productivity for soil has been continuously cultivated, is heavily reliant on fertilizer inputs and often suffered from no organic residues being returned, as well as repeated tillage. There are indications that the loss of nutrients is highly correlated with the decrease in biological activity and organic C in soil, which impedes the soil's effective storage or turnover of nutrients. Intensive farming may allow for greater short-term production capacities but a cyclical process of the decreasing value of the soil as resources are being extracted and the growing reliance on the use of more fertilizers to compensate for this reduction in soil health will result in a higher production cost. One of the more important findings of this paper is that a key obstacle to soil fertility should not be a chemical fertility problem – it should be a problem of soil sustainability, defined as the interactions among soil structure, microbial processes, water holding capacity, and the resilience over time of crops. The findings highlight the importance of frequent soil sampling, balanced nutrient management, crop rotation, legumes, residue management, composting, and minimizing disturbance from practices. Such practices may restore the nutrient balance and enhance soil quality as well as provide stable yields to farmers. Thus, the future of intensive farming lies in reducing the dependence on separate management of inputs to soil fertility management. Conservation of soil nutrients is fundamental to the profitability of the farms, food security, environmental quality and agricultural development.

REFERENCES

Akanbi, O. D., Bhuvanagiri, D. C., Barcelos, E. I., Nihar, A., Hernandez, B. G., Yarus, J. M., & French, R. H. (2024). Integrating Multiscale Geospatial Analysis for Monitoring Crop Growth, Nutrient Distribution, and Hydrological Dynamics in Large-Scale Agricultural Systems. *Journal of Geovisualization and Spatial Analysis*, *8*(1). https://doi.org/10.1007/s41651-023-00164-y

baker, A. baker A. E. A. (2017). Successive Application Impact of Some Organic Amendments Combined with Acid Producing Bacteria on Soil Properties, NPK Availability and Uptake by Some Plants. *International Journal of Current Microbiology and Applied Sciences*, *6*(3), 2394–2413. https://doi.org/10.20546/ijcmas.2017.603.274

Bender, S. F., Schlaeppi, K., Held, A., & Heijden, M. G. A. van der. (2018). Establishment success and crop growth effects of an arbuscular mycorrhizal fungus inoculated into Swiss corn fields. *Agriculture Ecosystems & Environment*, *273*, 13–24. https://doi.org/10.1016/j.agee.2018.12.003

Bender, S. F., Wagg, C., & Heijden, M. G. A. van der. (2016). An Underground Revolution: Biodiversity and Soil Ecological Engineering for Agricultural Sustainability. *Trends in Ecology & Evolution*, *31*(6), 440–452. https://doi.org/10.1016/j.tree.2016.02.016

Berlingeri, J. M., Lawrence, J. R., Sunoj, S., Czymmek, K., & Ketterings, Q. M. (2021). Nitrogen and Phosphorus Balances Vary at the Whole-Farm, Field, and Within-Field Scales. *Frontiers in Sustainability*, *2*. https://doi.org/10.3389/frsus.2021.747883

BIYOGUE, D. N. (2016). Impacts of anthropogenic activities on physical and selected chemical properties of soils in the natural forest-savanna of Northern Ghana. *Journal of Soil Science and Environmental Management*, *7*(5), 53–63. https://doi.org/10.5897/jssem2015.0542

Chittora, D. (2023). Harmful Impact of Synthetic Fertilizers on Growing Agriculture and Environment. *Global Journal of Pharmacy & Pharmaceutical Sciences*, *11*(1). https://doi.org/10.19080/gjpps.2023.11.555804

Correndo, A. A., Rubio, G., García, F. O., & Ciampitti, I. A. (2021). Subsoil-potassium depletion accounts for the nutrient budget in high-potassium agricultural soils. *Scientific Reports*, *11*(1), 11597–11597. https://doi.org/10.1038/s41598-021-90297-1

Danso, E. O., Dietzen, C., Arthur, E., & Rosing, M. T. (2025). Enduring increases in maize yield are a co-benefit of enhanced weathering of Greenlandic glacial rock flour in Ghana. *Nutrient Cycling in Agroecosystems*, *131*(3), 761–772. https://doi.org/10.1007/s10705-025-10442-4

George, B., Miguel, C., Mónica, K., Alberto, O., Anahí, D., Paula, D. T., Ana, André, F., Andrey, Z., Anne, W., Bente, F., Brajesh, S., Carlos, G., Claudia, R., David, S., Ece, A., Maria, M., Fátima, Francisco, B., Jianming, X., Johannes, R., … Yunuen, T. T. (2020). State of knowledge of soil biodiversity - Status, challenges and potentialities. In *FAO eBooks*. https://doi.org/10.4060/cb1928en

Goulding, K. W. T., Jarvis, S., & Whitmore, A. P. (2007). Optimizing nutrient management for farm systems. *Philosophical Transactions of the Royal Society B Biological Sciences*, *363*(1491), 667–680. https://doi.org/10.1098/rstb.2007.2177

Grégoire, T. G., Schabenberger, O., & Barrett, J. P. (1995). Linear modelling of irregularly spaced, unbalanced, longitudinal data from permanent-plot measurements. *Canadian Journal of Forest Research*, *25*(1), 137–156. https://doi.org/10.1139/x95-017

Hu, B., Saby, N., Bourennane, H., Opitz, T., Denoroy, P., Lemercier, B., & Shi, Z. (2020). *Bayesian spatio-temporal modeling of soil phosphorus in Britany in western France (1995-2014) with INLA-SPDE*. https://doi.org/10.5194/egusphere-egu2020-19135

Jones, D. L., Cross, P., Withers, P. J. A., DeLuca, T. H., Robinson, D. A., Quilliam, R. S., Harris, I., Chadwick, D. R., & Edwards-Jones, G. (2013). REVIEW: Nutrient stripping: the global disparity between food security and soil nutrient stocks. *Journal of Applied Ecology*, *50*(4), 851–862. https://doi.org/10.1111/1365-2664.12089

Lawrence, P. G., Roper, W. R., Morris, T. F., & Guillard, K. (2020). Guiding soil sampling strategies using classical and spatial statistics: A review. *Agronomy Journal*, *112*(1), 493–510. https://doi.org/10.1002/agj2.20048

Ludemann, C. I., Wanner, N., Chivenge, P., Dobermann, A., Einarsson, R., Grassini, P., Gruere, A., Jackson, K., Lassaletta, L., Maggi, F., Obli-Laryea, G., Ittersum, M. K. van, Vishwakarma, S., Zhang, X., & Tubiello, F. N. (2024). A global FAOSTAT reference database of cropland nutrient budgets and nutrient use efficiency (1961–2020): nitrogen, phosphorus and potassium. *Earth System Science Data*, *16*(1), 525–541. https://doi.org/10.5194/essd-16-525-2024

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural Intensification and Ecosystem Properties. *Science*, *277*(5325), 504–509. https://doi.org/10.1126/science.277.5325.504

Norbert, N. F., Aaron, S. T., & Kenneth, M. (2017). Physicochemical properties of soils and some water sources on the Western Flank of Mount Cameroon. *African Journal of Environmental Science and Technology*, *11*(5), 219–236. https://doi.org/10.5897/ajest2016.2248

Ohm, M., Paulsen, H., Moos, J. H., & Eichler-Löbermann, B. (2017). Long-term negative phosphorus budgets in organic crop rotations deplete plant-available phosphorus from soil. *Agronomy for Sustainable Development*, *37*(3). https://doi.org/10.1007/s13593-017-0425-y

Palma, H. H., Olivas, A. G., Neckel, A., Pinto, D., Moreno-Ríos, A. L., & Ramos, C. G. (2025). Valorization of mineral by-products through soil remineralization enhances sustainable agriculture and circular economy outcomes. *Discover Sustainability*, *6*(1). https://doi.org/10.1007/s43621-025-01804-7

Qasim, M., Babar, S., Younas, M. U., Memon, S. P., Abd-Elkader, A. M., Xia, X., Farooqi, Z. U. R., Iqbal, R., & Jiang, C. (2026). Restoring Acidic Soils for Sustainable Agriculture: A Review of Mechanisms, Microbial Shifts, and Climate Resilience. *Land Degradation and Development*. https://doi.org/10.1002/ldr.70563

Regasa, A., Haile, W., & Abera, G. (2025). Variation in soil acidity across different land uses, soil types and altitudinal gradients in Western Oromia, Ethiopia. *Scientific Reports*, *15*(1), 31565–31565. https://doi.org/10.1038/s41598-025-13597-w

Reimer, M., Hartmann, T. E., Oelofse, M., Magid, J., Bünemann, E. K., & Möller, K. (2020). Reliance on Biological Nitrogen Fixation Depletes Soil Phosphorus and Potassium Reserves. *Nutrient Cycling in Agroecosystems*, *118*(3), 273–291. https://doi.org/10.1007/s10705-020-10101-w

Scotti, R., Bonanomi, G., Scelza, R., Zoina, A., & Rao, M. A. (2015). Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. *Journal of Soil Science and Plant Nutrition*, 0. https://doi.org/10.4067/s0718-95162015005000031

Singh, S., Yan, S., Sorochan, J. C., Stier, J. C., Mayes, M. A., Zhuang, J., & Jagadamma, S. (2019). Soil Carbon Accumulation and Nutrient Availability in Managed and Unmanaged Ecosystems of East Tennessee. *Soil Science Society of America Journal*, *83*(2), 458–465. https://doi.org/10.2136/sssaj2018.09.0359

Smith, P., Cotrufo, M. F., Rumpel, C., Paustian, K., Kuikman, P. J., Elliott, J. A., McDowell, R. W., Griffiths, R. I., Asakawa, S., Bustamante, M., House, J. I., Sobocká, J., Harper, R. J., Pan, G., West, P., Gerber, J., Clark, J. M., Adhya, T. K., Scholes, R. J., & Scholes, M. C. (2015). Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *SOIL*, *1*(2), 665–685. https://doi.org/10.5194/soil-1-665-2015

Stein, A., Hoosbeek, M. R., & Sterk, G. (2007). Space-Time Statistics for Decision Support to Smart Farming. *Novartis Foundation Symposium*, *210*, 120–140. https://doi.org/10.1002/9780470515419.ch8

Verbyla, A. P., Cullis, B. R., Kenward, M. G., & Welham, S. J. (1999). The Analysis of Designed Experiments and Longitudinal Data by Using Smoothing Splines. *Journal of the Royal Statistical Society Series C (Applied Statistics)*, *48*(3), 269–311. https://doi.org/10.1111/1467-9876.00154

Virk, S., Tucker, M., Harris, G. H., Smith, A., Levi, M. R., & Lessl, J. T. (2025). Efficacy and Economics of Different Soil Sampling Grid Sizes for Site-Specific Nutrient Management in Southeastern USA. *Agronomy*, *15*(4), 903–903. https://doi.org/10.3390/agronomy15040903

Withers, P. J. A., Forber, K., Lyon, C. J., Rothwell, S. A., Doody, D. G., Jarvie, H. P., Martín-Ortega, J., Jacobs, B., Cordell, D., Patton, M., Camargo-Valero, M. A., & Cassidy, R. (2019). Towards resolving the phosphorus chaos created by food systems. *AMBIO*, *49*(5), 1076–1089. https://doi.org/10.1007/s13280-019-01255-1

Yang, T., Lupwayi, N. Z., St-Arnaud, M., Siddique, K. H. M., & Bainard, L. D. (2021). Anthropogenic drivers of soil microbial communities and impacts on soil biological functions in agroecosystems. *Global Ecology and Conservation*, *27*. https://doi.org/10.1016/j.gecco.2021.e01521

Yousef, A. F., Ali, A. M., Abdalla, S., Lamlom, S. F., & Al-Sayed, H. M. (2023). Improved plant yield of potato through exogenously applied potassium fertilizer sources and biofertilizer. *AMB Express*, *13*(1). https://doi.org/10.1186/s13568-023-01627-7

Zhao, Z.-B., He, J., Geisen, S., Han, L.-L., Wang, J., Shen, J., Wei, W.-X., Fang, Y., Li, P.-P., & Zhang, L. (2019). Protist communities are more sensitive to nitrogen fertilization than other microorganisms in diverse agricultural soils. *Microbiome*, *7*(1), 33–33. https://doi.org/10.1186/s40168-019-0647-0

Zhu, J., Li, M., & Whelan, M. J. (2017). Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *The Science of The Total Environment*, *612*, 522–537. https://doi.org/10.1016/j.scitotenv.2017.08.095