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Future crop breeding needs to consider future soils

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Modern crop breeding and seed certification agencies ignore the known spatial heterogeneity of soils and develop cultivars to thrive in a 'one-size-fits-all' soil environment. Neglecting the evolving dynamics of soils substantially undermines the capacity of new genotypes to deliver optimal yield and stress resilience, and requires urgent consideration in future plant breeding programmes.

Innovations in plant breeding have played a major part in raising global food production, mainly through the introduction of high-yielding traits, and have enhanced protection against the evolving challenges of diseases, pests, abiotic stresses, nutritional deficiencies and post-harvest issues. Plant breeding has major challenges ahead to feed 25% more people over the next 30 years, which will require increasing food production by 50–60% (ref. 1). Achieving the challenge of food security in a changing climate with a 2-°C-warmer world relies on crop breeding advances to produce ever more efficient and resilient cultivars.

Achieving consistently higher crop yields depends not only on plant breeding but also on agronomy and soils, which provide the crucial resources that plants require (such as water, nutrients, microbiota and anchorage). Intensive agricultural practices and weather extremes (precipitation, warming and drought) have caused unprecedented damage to the world's soils. Extensive use of machinery in field operations, ranging from sowing to harvesting, and frequent tillage at the same depth causes compaction and the formation of hardpans that restrict root penetration. Tillage breaks large aggregates into finer particles, which makes soil more susceptible to erosion by wind and water. Erosion carries away 20–37 billion tonnes of nutrient-rich topsoil annually, which causes an estimated cereal production loss of 7.6 million tonnes[2]. Tillage practices have also caused widespread losses of soil structure, organic matter, water retention capacity and nutrient availability. Overall, soil degradation is increasing globally and 35% (1,660 million ha) of agricultural land is affected, which jeopardizes our ability to meet future food security goals[2].

Future agricultural intensification to meet growing food demands will increase soil damage and compaction. Elevated temperatures, altered precipitation patterns and an increased frequency of extreme weather events due to climate change will further exacerbate soil stresses. To protect soils, future management must prioritize soil conservation, primarily through the adoption of sustainable agricultural practices. The adoption of reduced or no tillage, cover cropping, and residue retention will lead to future soils that are more heterogenous in structure because many of the processes involved are biologically driven. The dynamic nature of key soil properties and their potential effect on plant yield raises several important questions for crop breeders and soil scientists, including whether modern cultivars are capable of achieving potential yields under changing soil conditions (such as reduced tillage); whether plant breeding research should pivot to test genotypes under a wider range of contrasting soil conditions (including those observed under sustainable agriculture management); and whether seed certification agencies need to test genotypes under variable soil conditions (such as reduced or no tillage) before certification.

The disconnect between crop breeding and soil science

We conducted an extensive bibliometric analysis to compare global research on plant breeding and its proportional focus specifically on soils and their physical properties (that is, those soil properties that relate directly to soil texture and structure) (Supplementary Information). The evidence, based on more than 650,000 published papers, suggests that plant breeding has not considered the effect of soils in 90% of plant breeding-related research (Fig. 1). The ratio is even lower when it comes to testing plant genotypes under variable soil physical properties, as only about 1% papers tested cultivars under contrasting soil physical properties (for example, bulk density or soil texture). The disconnect between breeding activities and soil science extends to seed certification agencies. To get certified, new genotypes undergo mandatory statutory testing processes to ensure their distinctiveness, uniformity and stability. However, none of the seed certification agencies worldwide have any defined protocols to test the performance of new varieties under variable soil conditions. In fact, breeding trials are mainly conducted on high-yielding soils and prioritize traits such as yield and disease resistance. Consequently, breeding lines become varieties on the basis of tests on a limited range of soil types, and there is a strong bias towards varieties with high-yield potential.

The longstanding disconnect between soil science and plant breeding arises from a combination of historical, institutional and practical factors that have hindered collaborative efforts. Crop breeding research usually prioritizes testing traits under controlled conditions, and avoiding the complexity and heterogeneity of soil properties. Separate academic and research institutions can limit opportunities for cross-disciplinary knowledge sharing. Additionally, research funding mechanisms often prioritize specialized research within individual disciplines. Limited cross-disciplinary understandings of the fundamental mechanisms and spatiotemporal dynamics present considerable challenges to effective collaboration and communication between soil scientists and plant breeders. Consequently, this disconnect between plant breeding and soil science leaves open major questions about whether modern cultivars can achieve potential yields under contrasting future soil physical or tillage conditions.

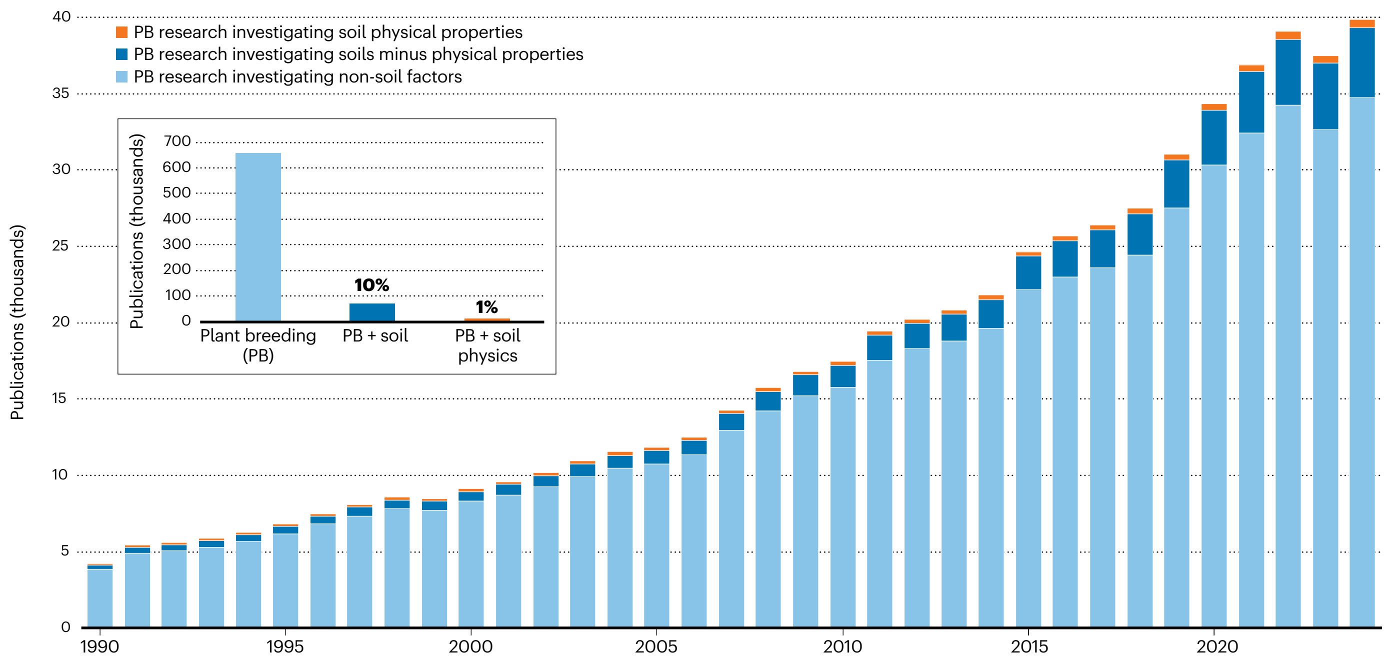

Fig. 1 | Annual research productivity of plant breeding and its proportional focus on soils and soil physical properties. Known published research on plant breeding started in 1900; the first papers with a focus on soils and soil physical properties were published in 1924 and 1926, respectively. The vertical bars represent annual plant breeding publications: light blue, plant breeding research focusing on non-soil factors; dark blue, share of plant breeding research focusing on soils but not soil physical properties; and orange, plant breeding research that considered on soil physical properties. The subfigure within the panel shows the total publication trends for the three categories.

The dynamic nature of soil texture and structure

The limited number of publications that examine new cultivar growth under different soil conditions might be based on the false assumption that soil physical properties such as texture and structure are not dynamic. Additionally, nutrient deficiencies — particularly of nitrogen, phosphorus and potassium — are often overly prioritized and considered easily manageable through fertilization. Therefore, crop cultivars are developed for 'one-for-all' soil types, which neglects the effect of temporal variability in soil physical properties on plant growth. However, soil physical properties such as porosity can change substantially over the course of a growing season[3], and even more so over longer periods of time. Loss of soil structure increases resistance to root penetration, and affects nutrient and gaseous exchanges and water fluxes, which impairs soil biodiversity and soil functions. Recent studies have also highlighted that soil structure can have a greater effect on root growth than genotypic variability or nitrogen fertilization[4].

Variations in parent material, topography and climate lead to diverse soil textures across both space and depth. Textural differences influence soil functions, including water-holding capacity, nutrient retention and root development, which leads to variable yield. Root growth in spring barley was more affected by soil texture than nutrient availability, mainly owing to texture-related differences that affect water availability[5]. Recent work[6] has highlighted the critical role of soil texture in regulating plant responses to water stress by influencing the onset of ecosystem water limitations; sandy soils exhibit greater sensitivity to soil drying owing to steeper hydraulic conductivity curves, whereas clayey soils are more sensitive to vapour pressure deficits. Unlike nutrient deficiencies, which can be remedied by adding fertilizers, it is difficult to remediate impaired soil physical properties, especially over short timescales.

Conservation agriculture and climate change driving future soil heterogeneity

Conservation agriculture (also referred to as regenerative) practices such as reduced or no tillage are gaining considerable popularity worldwide for delivering wider benefits for economic gains, soil health and, in some cases, carbon sequestration. However, no tillage imposes risks for seed germination (early seedling establishment) and root growth because of increases in bulk density during initial years. The effect of no tillage on crop yield remains debated: some studies suggest reductions or no change in yield, whereas others report improvements (particularly over extended periods)[7]. This variability in yield response might be due to existing varieties not being suited to the harder soil conditions under no tillage, especially in initial years. If the global area under no tillage increased from 12% to 50%, could this initially lead to notable yield loss owing to reduced seed germination and restricted root growth? No tillage also presents additional challenges, such as accelerating acidification and increasing residence times of heavy metals, pollutants and mycotoxins in soils. Hence, breeders urgently need to integrate no-tillage conditions into their selection pipelines.

In addition to management practices, climate change and extreme weather events can also generate substantial changes in soil physical properties. Warming, rainfall patterns, permafrost thawing, floods and storms have accelerated land degradation globally, and markedly transform soil physical properties. Soil warming accelerates the breakdown of macroaggregates into microaggregates, which results in loss of soil structural stability and water retention. Recent work[8] showed that long-term warming increased soil bulk density by 4.5% and decreased total porosity and non-capillary porosity by 3.4% and 5.0%, respectively. Rainfall patterns directly influence soil moisture levels and subsequently compaction and penetration resistance. Soils are more prone to compaction when the water content is high or near the optimal value for plant growth. This sensitivity highlights the crucial role of soil physical properties in determining plant water-use strategies and ecosystem responses to climate-induced drying conditions.

Integration of crop breeding and soil science

Traditionally, breeders have focused on traits that are directly related to yield, disease resistance and abiotic stress tolerance, and have overlooked the role of soil structure in mediating these traits. As a result, new varieties might perform suboptimally under diverse soil conditions, especially in soils with varying structural characteristics. It is crucial that the genotypes developed today are resilient and adaptable to the soils of tomorrow. Perennial and deep-rooted plants with strong soil penetration ability can help with soil structure recovery, which results in increased soil penetrability and aeration. Furthermore, selecting genotypes with beneficial root traits is crucial for increasing crop production. For example, acute root tip angles, high root hair density and roots with increased mucilage excretion can help plants to grow better in compacted soil[9]. As a result, deeper-rooting varieties will be better placed to facilitate water and nutrient uptake, which will be important under drier future conditions.

Beyond the immediate effect on crop yields, failing to consider soil physical properties in breeding programmes might lead to an increased reliance on agricultural inputs such as fertilizers and irrigation. To address this critical issue, breeders must integrate an understanding of soil physical constraints into their programmes, and ensure that genotypes are tested and selected under conditions that mirror real-world soil variability and future dynamics. Specifically, new crop varieties should be tested in soils with varying bulk density (that is, compaction) levels that represent the range of conditions typically encountered under both conventional and conservational tillage systems. Yield differences across these different bulk densities can inform breeders about the necessity of developing cultivars suited for denser soils, with a focus on root traits that facilitate penetration through compacted layers. The integration of soil science and crop breeding is particularly important in regions with severe soil degradation, such as sub-Saharan Africa, where 65% of the land area is degraded and cereal yields have stagnated at less than 1.5 t ha^{-1} (ref. 10). Continuously changing soil conditions in these areas necessitate the development of resilient crop varieties that are capable of thriving in such challenging environments.

Concurrently, soil scientists should use high-resolution soil mapping and monitoring systems to capture spatial variations in bulk density and soil texture. Given that soil texture influences water availability, these data can guide the development of genotypes tailored to specific soil types to ensure optimal yields across diverse environments. As root growth is often hidden, it can be difficult to pinpoint the causes of yield reduction, especially in high bulk density soils. High-throughput phenotyping technologies and imaging techniques such as X-ray computed tomography scanning offer non-destructive methods to monitor root growth and architecture in response to varying soil conditions. These insights can be directly integrated into breeding pipelines to select genotypes with desirable root traits for specific soil conditions, and ultimately improve crop resilience and yield under diverse soil environments.

We issue an urgent call to encourage greater collaboration between soil scientists and plant breeders. By combining expertise from both fields, a more comprehensive understanding of how soil physical properties influence crop performance can be gained. Integrating soil metrics as essential criteria for evaluating crop genotypes alongside promotion of education and awareness about the importance of soil physics among plant researchers, breeders, agronomists and farmers can reverse over one hundred years of neglect and help to engineer improved plant performance and resilience into our future cropping systems.

Data availability

The source data for Fig. 1 are provided in the Supplementary Information. Source data are provided with this paper.

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Competing interests

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Additional information

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