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Sustainable pathways toward reimagining India's agricultural systems

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India's Green Revolution made the country a world leader in rice and wheat production, but it has taken its toll on people and the environment. In an era of climate change and population growth, agriculture must be made sustainable. Pathways to this ambitious goal require new approaches to agricultural policy and research.

During the 1960s and 1970s, India's Green Revolution brought about a remarkable agricultural transformation. Over the course of two decades, the country turned from one of the world's largest net importers of food grains into a leading exporter of rice and wheat and established its prominence in the global food market. However, the requirements for energy, water and fertilizers to sustain the production of new varieties of rice and wheat were substantial, and they had detrimental consequences. Green Revolution-based agriculture has led to the loss of soil nutrients[1], depletion of water resources[2], reduction in agrobiodiversity[3] and increases in greenhouse gas emissions[4]. Impacts on public health and the recurrent financial investments needed for seeds and chemical inputs helped create debt traps for many farming families, compounding the environmental impacts[5].

Transformative changes in India's agriculture are needed to reduce greenhouse gas emissions while maintaining production levels and sustaining ecosystem services. India needs to improve management of soils, water and crop residues, reduce food waste, augment biodiversity in and around farms, and ramp up carbon sequestration.

Pathways to Reducing Agricultural Greenhouse Gas Emissions

There are alternatives to the intensive rice-wheat production promoted under the Green Revolution.- These include natural, regenerative, organic, and no-tillage farming based on agroecological principles[6–8]. But critically, it remains unclear whether these systems can maintain high levels of productivity and how they would respond to changing climatic conditions.

We identify five main pathways to reducing net greenhouse gas emissions from the agriculture sector and increasing carbon sequestration in soils and biomass. Each pathway faces considerable implementation challenges, not only technical but also around knowledge and institutions.

Build soil fertility with less synthetic fertilizer. Many alternative agricultural systems emphasize a reduction in soil tillage and use of organic inputs to maintain a healthy sub-surface ecosystem while reducing greenhouse gas emissions. Such approaches have been used in India[9–11], but with little overall analysis of outcomes. Because at least 40 to 55% of India's soils today are severely deficient in nitrogen, phosphorus, potassium and organic carbon[12], synthetic fertilizers may seem virtually indispensable. But fertilizers are currently used inefficiently and in skewed proportions[13], partly because government subsidies have kept prices of nitrogenous

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fertilizers excessively low, leading to imbalanced use of phosphorus and potassium[14]. Crop residues and weed biomass can be put to targeted use instead of being burned. Integration of agriculture with livestock industries can provide dung and manure. Supplies of seaweed, aquatic weed biomass as well as aquaculture waste from fisheries can overcome the shortage of organic inputs. All these measures can create markets for waste products from other sectors.

Integrated nutrient management approaches[15] and pesticide-free farming methods (https://www.safeharvest.co.in/), which permit limited synthetic fertilizers but restrict other chemical inputs, may avoid some destructive outcomes while upholding productivity levels—but they require systematic trials. The national Soil Health Card program—a governmental scheme implemented to help farmers monitor the status of their soils—should be reinforced and expanded. Understanding soil health and correct fertilizer use will reduce the need for perverse fertilizer subsidies and increase farmers' ability to use fertilizers sustainably.

Above all, large-scale systematic testing is needed to establish the relative productivity of diverse place-based agricultural approaches over time. The diversity of India's soils, hydrology, regional climate regimes and cultural characteristics means that one-size-fits-all programs are bound to fail. This was a core problem with the Green Revolution.

Improve water management and crop diversity. Paddy rice production is associated with intensive water consumption, and rice is therefore an ecologically inappropriate crop choice where water is scarce. Nevertheless, rice is currently cultivated in semi-arid regions, such as parts of Punjab[16]. This results in unsustainable rates of groundwater extraction. In addition, in hypoxic conditions inundated rice fields emit methane, a short-lived but potent greenhouse gas whose emissions must be reduced urgently[17]. Both water consumption and methane emissions can be reduced through improved water management.

Before the Green Revolution, traditional cropping choices emphasized pulses, beans, and a variety of nutritious drought-resistant crops such as millets and sorghum. Re-establishing greater crop diversity, especially in dry areas, can help address current challenges in meeting food security while adapting to climate change. However, moving toward crop diversity will require comprehensive reconsideration of agricultural land uses at the landscape scale, along with heavy investments in agricultural extension services.

Reuse crop residue as raw material. In India each year, between 92 and 122 million tons of residue from rice, wheat and sugarcane are burned in the fields. These fires emit particulate matter and greenhouse gases[18]. The residues are burned because in the Green Revolution-based rice-wheat system, there is a very short interval between the end of the rice harvest and the start of sowing wheat. The slow decomposition of crop residues inhibits their use in situ, while hiring machinery to quickly break down crop residues and assist with decomposition is expensive. Yet crop residues and weed biomass could also be useful in other sectors. Fueling biomass power plants, these residues could generate 120 Terawatt hours of electricity – nearly 10% of India's current total energy production[19]. A functioning market for recycling crop wastes as soil amendments would also benefit farmers by providing them both with extra income and a reliable supply of organic biomass.

Expense and transport challenges hinder the development of such markets. One solution is to provide financial support to farmer cooperatives and small agribusinesses for processing crop waste with other biomass for reuse in agriculture and other industries.

Reduce greenhouse gas emissions from livestock. India is currently home to over 535 million head of livestock[20] that produce greenhouse gases equivalent to 467.5 million tons of carbon dioxide per year. Three strategies have been proposed to mitigate these emissions[21]. Cattle can be fed with methane-inhibiting feed additives such as seaweed; they can be vaccinated against rumen methanogens with methanogen vaccines to control their methane emissions; and regular and time-controlled breeding can also contribute to reducing emissions.

However, all three strategies face considerable cultural and practical challenges. At the large scale, each would be expensive and administratively complex. Without a subsidized distribution system for feed additives, the benefits of reduced methane emissions would accrue to the global community whereas the costs for the additives would fall on the smallholder. Even raising the average quality of cattle feed would reduce methane emissions rates but would be prohibitively costly for smallholders. Since cattle are widely associated with sacred values, manipulating them through vaccines and breeding systems would not sit well with much of the population.

Promote agroforestry for carbon sequestration with co-benefits. In India, where many smallholders have little access to forest areas, agroforestry services may be essential for a viable agricultural system[22]. Agroforestry in mixed-use, multifunctional landscapes (e.g., Fig. 1) provides key ecosystem goods and services such as fuel wood, fruits, fodder, and fibers. Agroforestry's green infrastructure helps constrain erosion, stabilize fragile soils and steep slopes, and can sequester some carbon. Protection of late-successional forests in situ, termed proforestation[23], is far more effective in storing carbon than growing new trees through afforestation. Again, the role of trees and forests needs to be considered at the landscape scale.

Policy frameworks needed to generate the pathways

These pathways cannot be implemented at the necessary scale without explicit participation and commitment of government

Fig. 1 Mixed-use and multifunctional landscapes are common in India. Smallholder agricultural systems in mountain villages, such as this one in the Darjeeling Himalaya mid-montane, depend on close integration of crops, livestock, and forest resources. The bluish haze is from wood-burning household stoves. (*R. Seidler photo*).

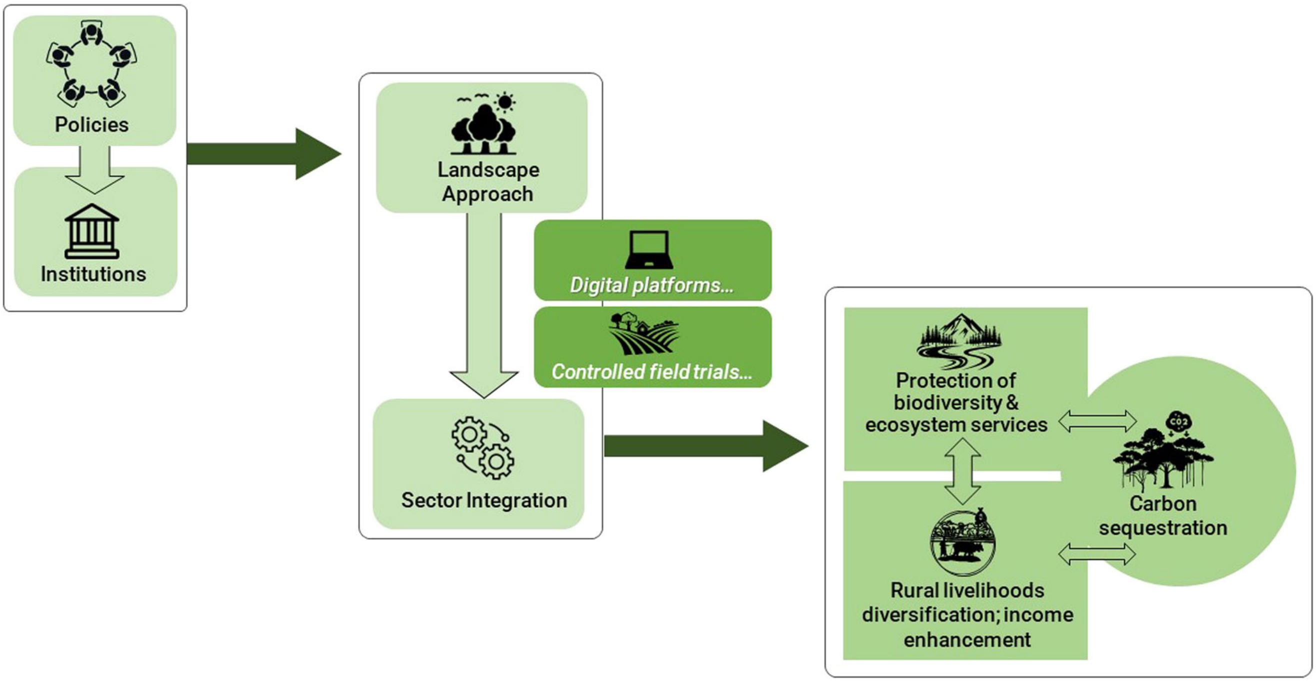

Fig. 2 A simplified, schematic transformation pathway for Indian agricultural systems. The diagram outlines the flows of information and influence needed to generate large-scale outcomes incorporating biodiversity protection, livelihoods support and climate mitigation.

agencies and research institutions. Scattershot approaches will not suffice. Here we describe the steps depicted in Fig. 2.

(i) New policy frameworks are urgently needed to reshape institutional networks and increase their capacity to adopt and implement landscape-systems approaches to agricultural research and resource management. Key agencies such as Indian Council of Agricultural Research and government think-tank NITI-Aayog must implement programs promoting sustainability, climate resilience, biodiversity maintenance, and ecosystem services – not focusing exclusively on agroecosystems but also incorporating nearby ecosystems such as forests, wetlands, abandoned fields, urbanizing areas.

(ii) Landscape approaches should be implemented using available technologies such as controlled field trials across multiple agroecosystems and digital platforms to generate knowledge commons. These can help improve communications and facilitate interdisciplinary collaboration, promoting sectoral integration.

(iii) Field trials are needed to evaluate performance not only in terms of productivity but also of synthetic or organic soil amendments and pesticide inputs, greenhouse gas emissions, and resilience to climate extremes. Field trials can fill gaps in knowledge, enabling widespread application of agroecological principles and locally appropriate natural and organic methods. Such trials require significant changes in research paradigms to incorporate multiple actors beyond the agricultural scientists focused on agronomy, gene editing and breeding. Close participation of farmers, local non-governmental organizations and agencies is critical for collecting large-scale farm-level data. Currently, public sector extension agencies and universities rarely explore synergies or cooperation[24].

(iv) Emerging technologies, especially digital platforms, can help create a national movement for the spread of new paradigms and action at the grassroots level. Several government initiatives are underway (e.g., KisanMitr (https://kisanmitr.gov.in)), mKisan Portal (http://www.mkisan.gov.in/aboutmkisan.aspx). Civil society organizations such as Digital Green (https://www.digitalgreen.org/) and e-Kisaan (http://www.ekisaan.com/) already demonstrate potential to reach thousands of farmers[25] and provide transformative information and services from the start of the crop cycle to product marketing (https://agrevolution.in/company).

Globally, and nationally in India, a radical shift in thinking about food systems and sustainability is underway. Steps toward agricultural sustainability in India must generate a multidimensional food system that continues producing enough food calories while sequestering carbon, protecting biodiversity and ecosystem services, and supporting rural livelihoods. Many practices will need to change to meet these goals simultaneously. A holistic lands-based approach to agricultural research can help meet the requirements of food systems in the era of climate change, while helping the country realize its ambitious Nationally Determined Contributions – thereby honoring the state's social contract with its own people as well as with the international community.

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