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Integrating soil resource information for sustainable soil management and climate-resilient rainfed agriculture

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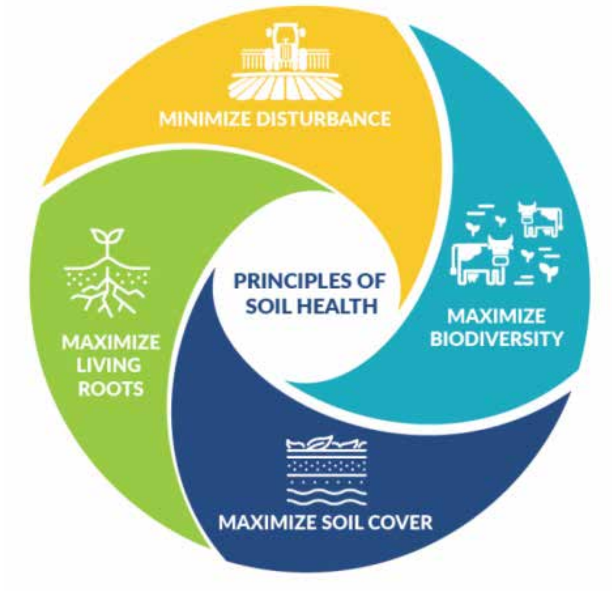
Rainfed agriculture plays a pivotal role in India's food security, covering nearly 52% of the country's net sown area and supporting the livelihood of millions of farmers. However, it is vulnerable to erratic rainfall patterns, soil degradation, and climate change impacts. Sustainable soil management in rainfed regions is essential for maintaining soil fertility, improving water-use efficiency, and ensuring food security. The role of soil resource information systems highlighting how soil resource information can be integrated in land-use plans and policies to promote climate-resilient agriculture is the need of the hour. By leveraging advanced tools and data products, farmers in rainfed systems can improve soil health and water-use efficiency, mitigate land degradation, increase resilience to climate change, and ensure sustainable livelihoods.

Keywords: Climate change, Digital soil mapping, Land use planning, Rainfed agriculture, Soil

RAINFED agriculture, reliant on monsoon, covers about 52% of the net sown area in India. It contributes to a large share of food grain production (40%) and supports two-thirds of livestock. However, it suffers from low productivity, land degradation, and climate variability. The primary challenges include lack of targeted development, poor market linkages, yield variability, soil degradation, and climate risks. Technological advancements have largely bypassed rainfed regions, focusing more on irrigated zones and climate change or climate variability. Rainfed agriculture, with yields roughly half that of irrigated agriculture, has emerged as a cornerstone of food security for the Global South, notably in the semi-arid tropics (SAT) of India. Climate change during the last two decades, coupled with insufficient adaptation measures have increased the vulnerability of agricultural production systems, thereby posing challenges to food security in the SAT. Crop yields in the SAT of India was projected to decline during the 2050s due to changing climate conditions. The low productivity of rainfed crops in SAT is generally attributed to the changing/uneven rainfall distribution pattern across the growing season, which adversely affects other facets of sustainable agricultural production through soil fertility degradation and acute soil moisture stress. Worse-still, the lack of effective adaptation measures threatens the resilience of rainfed agriculture to climate change and compounds the adverse impacts of rainfall fluctuations on crop yields. With nearly 37% of its land area under semi-arid ecosystems, India is highly vulnerable to drought and other impacts of climate change. Therefore, effective climate adaptation measures in response to climate change impacts on the agricultural sector needs to be assigned the highest priority.

The agriculture sector is grappling with production challenges, including land degradation, water scarcity, and the impacts of climate change. Agricultural production involves several interconnected and collaborative components—land resources, water resources, chemical fertilization, and climate—which are difficult to isolate from one another. Attempting to solve each problem separately, or focusing on any one specific problem, may not resolve the overall issue of sustainable crop production. Consequently, it is imperative to recognize the interconnectedness of the impacts of land and water resources alongside greenhouse gas (GHG) emissions through the land–water–energy–GHG nexus model. Nexus-thinking combines integrative systemic solutions to improve the usage of land and water resources besides efficient management of energy resources, while also considering social, economic, and environmental aspects. Sustainable resource management necessitates setting goals for using local resources to obtain long-term advantages while safeguarding natural resources and the environment. This approach plays a critical role



Principles of soil health

in enabling decision-makers to take actions that can effectively manage sustainable resource utilization to achieve maximum efficiency.

Soil management practices for climate resilient agriculture

Many proven soil management practices can help farmers adapt to the increasing weather variability and climate change while also reducing agricultural greenhouse gas emissions. Widespread adoption of these practices can significantly contribute to national food security and development goals. Climate change and variability can impact soil health and plant growth through reduced/erratic rainfall, severe droughts, intense weather events causing erosion, reduced groundwater recharge, and soil moisture stress. Higher soil temperatures hasten the breakdown of soil organic matter, reducing the soil's capacity to sequester carbon and retain water, and can also lead to soil salinization through higher evapotranspiration, as salts accumulate in surface layers, hindering plant growth and reducing yields. Proper management of irrigation and drainage systems is essential for growing salt-tolerant plants in such conditions.

Some soil properties, like texture, are more resistant to change, while others, such as organic matter, structure, base saturation, and pH, are more sensitive to environmental changes, including those driven by climate and land management practices. Soil carbon stocks are crucial for monitoring land degradation. Soil physical properties influence its response to climate change and guide the management practices needed to maintain key ecosystem services, such as water retention, nutrient supply, carbon sequestration, and reduced GHG emissions. Understanding these properties helps agricultural producers adapt to and mitigate the impacts of climate change.

Soil resources information systems

The foregoing discussions underline the direct relevance of systematically understanding the status and condition of soils, along with their properties to make informed decisions about climate-smart land use through sustainable soil management. The ICAR-National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), has played a pivotal role in generating detailed soil resource information for sustainable soil management in India, particularly in rainfed agricultural systems. Over the years, NBSS&LUP has undertaken several initiatives on land evaluation, soil fertility assessment and sustainable land-use planning. The Bureau uses a combination of conventional and digital data acquisition, survey and mapping tools to identify, demarcate, survey and map different soil types, terrains, vegetation, and agro-ecological zones. Land evaluation, including assessment of soils through acquisition of satellite data and on-site visual inspections and surveys, followed by laboratory analysis and digital soil mapping (DSM), is the first step towards generation of a soil resource information system. This is succeeded by the preparation of comprehensive land use plans and advisories for use by the farmers and other stakeholders. Steps generally followed in the preparation of land use plans/advisories based on soil information are discussed below.

Preparation of digital soil property maps serve as visual guidelines for the policy planners to prioritize areas for soil health management and resource conservation. The sub-steps for the preparation of maps are:

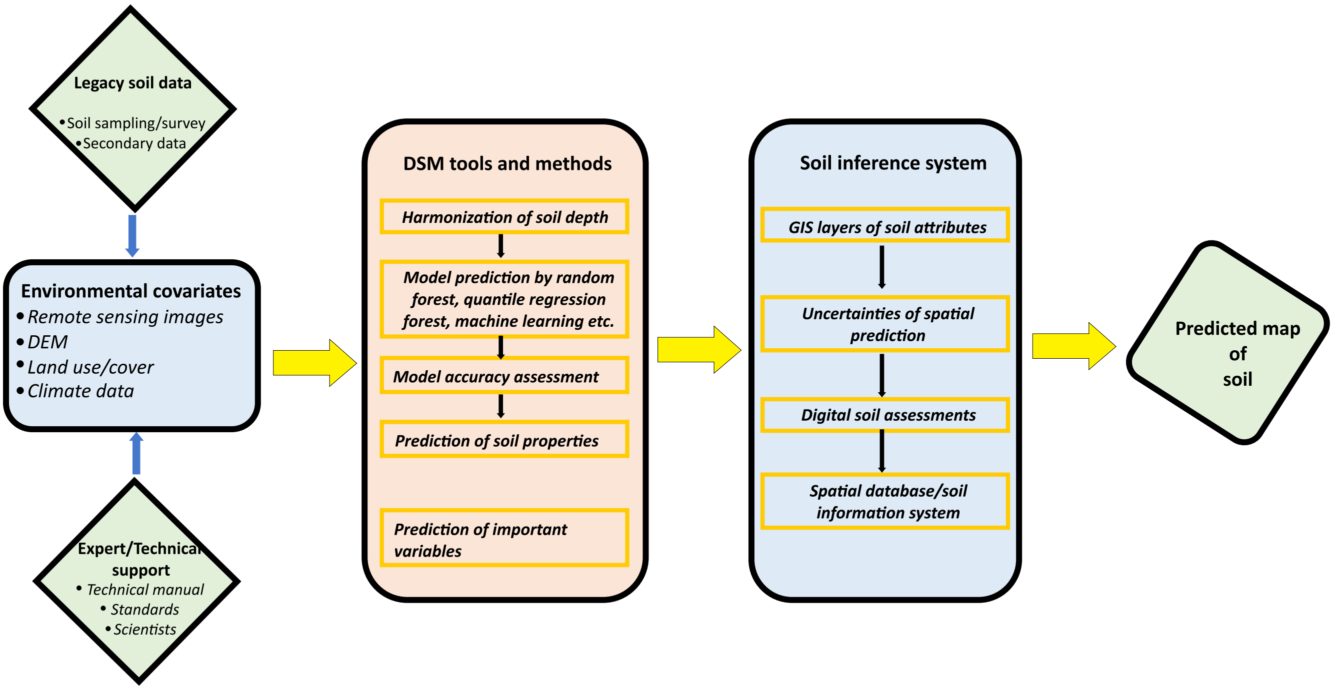
- Compilation of baseline information of the study area.
- Identification of sampling sites, conducting soil surveys, soil sample analysis, and characterizing soils followed by modelling and mapping of soil attributes (DSM).

Determination of site-specific crop suitability and preparation of block/district/region-wise climate-smart land-use plans and contingency plans at different administrative levels is the final step in the soil resource information system protocol. Land use plans typically involve soil conservation and water harvesting plans besides proposed alternate cropping/farming system plans. Usually, a multi-criterion is adopted for deciding the area-wise suitability for various crops. Areas under

Soil and Soil Health

Soil forms the foundation for plant growth and supports crop, forest, and livestock production by providing essential nutrients and water. It plays a critical role in the hydrological cycle and atmospheric gas exchange. Soil is also home to an incredible diversity of life, hosting more biological activity than any other land-based ecosystem.

Soil health is crucial for supporting plant growth and regulating nutrients, water, carbon, and gaseous cycles. Soil productivity depends on its physical, chemical, and biological properties, particularly its mineral composition, organic matter, biodiversity, and biological activity.



Digital soil map generation

S1 (highly suitable) and S2 (moderately suitable) categories of land are considered as qualifying criteria for including a particular crop for planning purpose. Recreational and other livelihood-based options are provided for non-arable lands. Similarly, various soil and water conservation measures and drainage line treatments are suggested to improve water resource and soil moisture of the block/district/region.

Case studies

Some examples and case studies where soil resource information by NBSS & LUP has contributed to sustainable management in rainfed regions are discussed below.

Climate-smart land use recommendations in Maharashtra

One of the notable contributions of the Bureau

गावातील प्रमुख माती

गावातील प्रमुख माती	सर्वे क्रमांक
हलकी मृदा (0-25 cm)	1
मध्यम मृदा (25-50)	1, 2, 5, 6, 7, 3, 137, 1, 2, 5,6, 7, 3, 137, 4, 8, 28, 138, 23, 24, 25, 18, 17, 9, 29, 26, 27, 30, 22, 31, 19, 32, 21, 33, 20, 17, 9, 29, 30, 31, 19, 32, 21, 16, 10, 33, 34, 20, 15, 11, 35, 14, 72, 69, 36, 73, 71, 12, 37, 13, 70, 78, 75, 76, 77, 74, 68, 79, 85, 82/A, 38, 67, 80, 81, 39, 40, 66, 82/B, 145, 84, 41, 86, 65, 42, 87, 43, 64, 97, 136, 60, 83, 44, 46, 63, 47, 96, 61, 48, 88, 91, 49, 90
उत्तम मृदा (50-75)	67, 84, 41, 42, 87, 43, 64, 97, 136, 60, 44, 46, 45, 63, 47, 96, 61, 59, 48, 88, 91, 98, 49, 58, 62, 90, 89, 57, 50, 92, 99, 122, 93, 56, 55, 51, 53, 54, 115, 121, 123, 94, 120, 117, 128, 52, 129, 124, 95, 119, 100, 101, 102, 116, 104, 103, 125, 118, 126, 106, 105, 114, 134, 131, 132, 130, 127, 113, 107, 108, 109, 133, 110, 111, 112
अन्य – क्षारयुक्त चोपन	--

पीक योग्यता

गावातील प्रमुख माती	पिके	सर्वे क्रमांक	
		सिंचना क्षेत्र	जिराइत क्षेत्र
हलकी मृदा	कपासी (देशी किंवा अमेरिकन), तुर, सोयाबिन, ज्वारी		
मध्यम मृदा	कपासी (देशी किंवा अमेरिकन), तुर, सोयाबिन, ज्वारी		
उत्तम मृदा	कपासी (देशी॰ अमेरिकन किंवा बि.टी.), तुर, सोयाबिन, ज्वारी॰ हरबरा॰ गहु		
अन्य – क्षारयुक्त चोपन			

Parcel-wise advisory containing the survey number-wise soil potentials/constraints along with crop options for the farmers in local language (*marathi*) involved is the formulation of parcel-level crop advisories, nutrient management plan and contingency plans for climate-smart agriculture. This is the first-of-its-kind exercise attempted for 5,000 villages covering 51 clusters spread across 16 districts of Maharashtra. The soils were classified based on their depth and moisture-holding capacity. For instance, in districts like Pune, Satara, and Ahmednagar, large areas exhibit shallow, coarse-textured soils with limited moisture retention, with underlying limitations of these soils for intensive cultivation. Parcel-level (survey number-wise) recommendations were made for crop selection, nutrient management and climate-smart measures such as crop diversification, conservation tillage and *in-situ* moisture conservation practices to mitigate the effects of erratic rainfall. Adoption of these techniques, would result in enhanced productivity for rainfed crops like sorghum, pulses, and oilseeds, which are well-suited to these soil and climatic conditions.

District contingency plans

The District Agriculture Contingency Plans (DACPs) for rainfed districts, developed by CRIDA in collaboration with NBSS&LUP and other ICAR institutes, SAUs, Krishi Vigyan Kendras (KVKs), State Agriculture Departments, focuses on enhancing resilience to climate variability and addressing the unique challenges of rainfed agriculture. The DACP integrates agro-climatic data, detailed soil information from NBSS&LUP, soil health and cropping patterns to suggest adaptive strategies. Vulnerable areas were identified based on soil properties such as poor water-holding capacity and fertility. Key components include alternative cropping systems, soil and water conservation practices, and real-time weather-based advisories. The plan promotes livelihood diversification, efficient water management, and soil health improvement. Livelihood diversification through horticulture and agroforestry, along with real-time weather advisories, help farmers make informed decisions leading to increased crop yields increase and income. It also emphasizes on the capacity building, extension services, and ICT tools for sustainable rainfed agriculture, ensuring food security amidst changing climatic conditions.

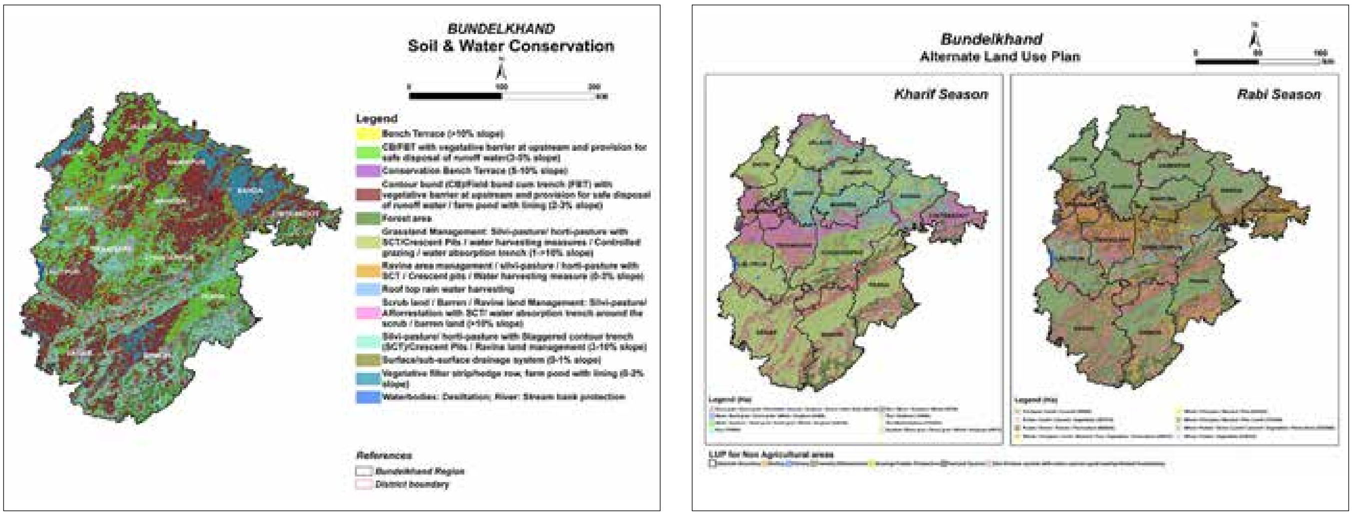
Land resource inventory of Bundelkhand region

The Bundelkhand region, spanning across seven districts each of Uttar Pradesh and Madhya Pradesh, is known for its extreme water scarcity and degraded soils, where agriculture is primarily rainfed. The Bureau classified soils in the region based on their depth, texture, organic carbon and water-holding capacity with the help of a hybrid standard operating protocol employing both traditional survey and digital soil mapping. Soils of the region are predominantly sandy loam with poor moisture retention, making them susceptible to erosion. The soil property maps were designed to help local authorities and farmers in selecting appropriate land use practices. For instance, in soils with shallow depth and low water-holding capacity, Bureau recommended cultivating short-duration crops rather than water-intensive crops.

Additionally, it guides farmers in adopting conservation practices like graded bunding and gully plugging to control soil erosion. The implementation of these measures based on Bureau's recommendations is expected to efficiently manage land and improve crop productivity, thereby offsetting the vulnerability of rainfed farming systems to erratic rainfall. Further, various soil and water conservation measures including check dams, contour bunding and vegetative barriers were recommended which fit well into the watershed management programmes, and are intended at improved soil moisture conditions, reduced runoff, and reduction in soil erosion.

Digital soil mapping in Vidarbha region, Maharashtra

The Vidarbha region of Maharashtra, another predominantly rainfed area, has faced recurring agricultural crises due to erratic rainfall and declining soil fertility. NBSS&LUP, for the first time, has introduced digital soil mapping (DSM) techniques for identifying soil fertility and suitability for various crops in the region. DSM was used to map the nutrient status and physical properties of soils, providing



Land resource inventory of Bundelkhand region for sustainable land-use planning
(*Source:* NBSS&LUP, Publ No.184)

critical insights for sustainable soil management. The soils of Vidarbha are generally deficient in nitrogen, phosphorus, and potassium, which limit crop yields. Based on soil information, the Bureau recommended integrated nutrient management (INM) practices integrating organic matter (such as farmyard manure and compost) with appropriate levels of chemical fertilizers. Soil fertility maps would enable the farmers in Amravati and Yavatmal districts to apply site-specific fertilizer doses for improved nutrient-use efficiency and reduced costs. As a result, rainfed cotton and soybean yields will increase significantly, contributing to the region's economic stability.

Climate-smart sustainable soil and land management in rainfed agriculture – Way forward

A multi-pronged approach is essential to overcome the barriers in adopting climate-smart sustainable soil and land management practices in rainfed systems, which is evident from the case studies. The adoption of climate-smart sustainable soil and land management practices in rainfed systems can be significantly enhanced using advanced tools like DSM, remote sensing, and Geographical Information System (GIS). DSM provides high-resolution data on soil properties, allowing farmers to make informed decisions regarding crop selection, irrigation, and precise nutrient management. Remote sensing and GIS technologies enable real-time monitoring of soil health, moisture content, and land-use changes, helping to identify erosion-prone areas and assess drought impacts. These technologies can be integrated into mobile-based advisory systems, offering farmers site-specific recommendations on sustainable practices. Capacity-building programs across various stakeholder levels should be developed to train farmers and extension workers on the use of DSM products, land use advisories, GIS, and precision agriculture techniques, while also ensuring access to affordable technology. Incentivizing the adoption of these tools through financial support, such as subsidies for soil testing and equipment, can encourage widespread use. Additionally, combining DSM data with climate models can create early warning systems for extreme weather events, allowing for proactive planning and risk mitigation in rainfed systems. Institutional support is vital to promote the integration of digital tools into national land management policies, fostering data sharing and standardization.

SUMMARY

Integrating soil resource information through advanced technologies like DSM and GIS is essential for achieving sustainable soil management and climate resilience in India's rainfed agricultural systems. These tools enable precise and informed decisions on land use, soil conservation and water management. As rainfall patterns continue to fluctuate due to climate change, the role of accurate soil resource information will remain indispensable in achieving sustainable agricultural practices. The Bureau has been empowering farmers and policymakers to make informed decisions on soil conservation, nutrient management, and crop selection by providing the necessary tools such as digital soil maps and climate-smart advisories, as evident from the regional case studies. By leveraging such data-driven approaches across different landscapes and at different scales, rainfed agriculture can become more productive, sustainable, and adaptive to future climate conditions. However, the success of the whole endeavor depends on continued investment in capacity building, institutional support, and the dissemination of these technologies to farmers. Policymakers must also focus on creating enabling environments that promote the use of soil resource information in land management strategies.

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