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Integrating carbon sequestration and yield optimization in Indian cropping systems

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ABSTRACT

Agriculture contributes significantly to greenhouse gas (GHG) emissions but also holds strong potential for mitigation – particularly through soil organic carbon (SOC) sequestration. This study evaluates the impact of integrated management practices—such as biochar application, optimized irrigation, and fertilizer management on yield improvement and SOC sequestration in semi-arid regions of Maharashtra, India. Using APSIM simulations across five districts and diverse cropping systems, it compares these practices with conventional farming. Results indicate that integrated practices consistently improve yields, SOC levels, and economic viability. For instance, maize yields under integrated practices increased by over 30 %, with substantial SOC gains. A cost-benefit analysis reveals high benefit-cost ratios, making these practices economically viable for smallholder farmers. This study highlights the transformative potential of integrated practices in addressing food security and environmental sustainability, especially in semi-arid regions. Policy recommendations include subsidizing biochar, promoting precision irrigation technologies, and integrating SOC sequestration strategies into national climate action plans. These findings provide actionable insights for scaling sustainable agricultural practices in resource-constrained settings.

1. Introduction

Agriculture is a major contributor to greenhouse gas (GHG) emissions, plays a crucial role in driving climate change. It was estimated that agriculture contributes >80 % of anthropogenic N_2O emissions and 70 % of anthropogenic NH_3 emissions, that are result of application of livestock manure and inorganic fertilizer, around 40 % anthropogenic CH_4, due to enteric fermentation [1]. Methane emissions arise primarily from rice cultivation, ruminants, and manure, while nitrous oxide stem from manure, legumes, and fertilizer use. CO2 emissions, on the other hand, are associated with fossil fuel usage, soil tillage, deforestation, biomass burning, and land degradation [2,3]. Given the significant impact of agriculture on GHG emissions, attention is growing around mitigation strategies that also support resilience—particularly in dryland systems. Soil Organic Carbon (SOC) sequestration is one such practice, offering dual benefits of enhancing soil health and fertility while serving as a carbon sink [4–6]. SOC sequestration in agricultural soils is a low-cost strategy for mitigating GHG emissions and improving environmental quality [5,7]. However, the capacity of soils to sequester carbon is influenced by several factors, including crop type, soil properties, climate, and management practices [8–10].

The determinants of SOC sequestration capacity are complex, encompassing both biophysical and economic factors. Crop systems, such as crop rotation, cover cropping, and crop diversity significantly affect the amount of organic matter returned to the soil, influencing SOC levels [11,12]. Management practices like reduced or no tillage, improved crop residue management, and organic amendments (e.g., compost, manure) play a crucial role in enhancing SOC stocks [3,13].

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Additionally, the recycling of organic wastes from domestic activities and urban areas as organic fertilizers presents an opportunity to transfer organic carbon in ways that enhance SOC storage and improve soil nutrient content [10,14]. Economic considerations are vital in farmers' adoption of carbon sequestration practices. A comprehensive cost-benefit analysis helps evaluate the financial feasibility of different management systems, assess trade-offs between productivity and sustainability, and inform policies that promote economically viable climate-smart agriculture [14–16].

Furthermore, precision agriculture, by optimizing input use, can also support GHG mitigation while improving productivity [17]. For instance, in the warm, semi-arid regions of India, long-term application of farmyard manure has been shown to enhance SOC sequestration, illustrating the potential of tailored agricultural practices in different climatic regions [18,19]. Recent assessments emphasize the urgent need for sustainable intensification and climate-smart approaches in agriculture, particularly in climate-vulnerable regions such as India's semi-arid zones. Studies such as Aryal et al. [20], and Lal [21] highlight the importance of integrating soil health, water efficiency, and carbon management to achieve productivity, sustainability, and climate resilience programs like the 4p1000 initiative, the Climate-Smart Village approach [22]. In this context, our aim is to explore the determinants of SOC sequestration capacity across different crop and management systems and conduct a comprehensive cost-benefit analysis of SOC sequestration under various agricultural management practices. This study responds to that need by analysing how integrated management practices, including biochar application, critical irrigation, and optimized fertilization, perform in terms of both productivity and resilience in semi-arid, risk-prone agroecosystems. We explore the determinants of SOC sequestration across crop and management systems and conduct a cost-benefit analysis to identify practices that maximize both carbon sequestration and economic returns.

This study significantly contributes to the literature by integrating economic and biophysical analyses to evaluate SOC sequestration practices in semi-arid regions like Maharashtra, India. By leveraging APSIM simulations tailored to local conditions, it provides region-specific insights into the efficacy of integrated management practices which consistently outperform conventional systems in enhancing yields, SOC levels, and economic returns. The research uniquely bridges the gap between environmental sustainability and economic feasibility through detailed cost-benefit analysis, offering actionable policy recommendations such as subsidies for biochar, carbon credit programs, and investments in precision irrigation technologies. Additionally, the study quantifies drivers of SOC sequestration, providing empirical evidence to guide scalable, sustainable agricultural interventions that align with global climate goals while addressing food security challenges.

Following this introduction, the Section 2 details the methodology and data sources employed in the research. This is followed by the presentation of the results. In the subsequent section, we discuss the findings followed by the policy implications section. Finally, the last section offers our conclusions.

2. Methodology and database

2.1. Study area

The study focuses on five districts in Maharashtra: Ahmednagar, Amravati, Dhule, Jalna, and Yavatmal. These districts were selected based on their inclusion in the Soil Protection and Rehabilitation of Degraded Soil for Food Security in India, An Economics of Land Degradation (ELD) study (ProSoil) ,[1] funded by GIZ. It previously implemented sustainable land management interventions in the region. The choice of these districts allows for a continuation and comparison of results from earlier research efforts.

2.2. Simulation model and input data

Agricultural Production Systems SIMulator (APSIM), a process-based model, was utilized to evaluate the long-term changes in the cropping systems, especially SOC and productivity. To model the cropping system realistically, actual farming practices (literature and through interaction with extension personnel) were used as basic input for the APSIM simulation model. The analysis leverages APSIM to simulate the output data for major cropping systems across different taluks (sub-districts) in Maharashtra including cotton-fallow (cotton crop in Kharif[2] followed by fallow in post-rainy season), soybean + pigeonpea intercrop (soybean, pigeonpea cultivated as intercrop in Kharif followed by fallow in post-rainy season), soybean-chickpea (soybean in Kharif followed by chickpea in post-rainy season), maize-sorghum (maize in Kharif followed by the sorghum in post-rainy), maize-chickpea (maize cultivated in Kharif followed by chickpea in post-rainy season). The APSIM model was employed to simulate the performance of various cropping systems under different management practices. Soil parameter values were drawn from the Soil Health Card portal [23], the Maharashtra Department of Agriculture [24], and ISRIC SoilGrids [25]. Daily weather data were obtained from the Indian Meteorological Department (IMD) database. Crop management practices were derived from published literature and consultations with local agricultural extension officers. The taluks in Maharashtra served as replications in the study, ensuring that variations in soil type and climatic conditions across the region were adequately represented. The model performance was evaluated by comparing the simulated (APSIM output) and observed [24] productivity of homogeneous clusters (soil and climate) of taluks based on coefficient of determination (R^2) and Root mean square error (RMSE).

The management practices simulated in APSIM included the following:

- **Conventional System**: This baseline system reflects traditional farming practices in the region. Farmers typically apply only 66 % of the recommended fertilizer, operate under rainfed conditions without supplemental irrigation, and perform tillage three times per cropping season (mid-summer tillage, primary tillage before sowing, and secondary tillage for manure/weeds incorporation).
- **Critical Irrigation Management**: Supplemental irrigation is applied when the soil moisture in the top 40 cm reaches 25 % of plant available water content during the kharif season. During the post-rainy and summer seasons, irrigation is applied shortly after sowing to improve germination and plant establishment. The maximum number of irrigations is limited to four in Kharif and two in post-rainy.
- **Fertilizer Management**: In this practice, farmers apply 100 % of the recommended fertilizer rate, in contrast to the 66 % used in conventional systems. Urea, which contains 46 % nitrogen, is used as the fertilizer in simulations. Prior to designing the main experiment, we conducted preliminary APSIM simulations to assess yield sensitivity to phosphorus application under representative soils and climatic conditions of the study districts. The results showed negligible yield response for maize, the central crop in our sequences, which aligns with soil test data from arid regions of Maharashtra indicating that phosphorus availability is not a primary constraint on yield. Consequently, nitrogen optimization—modeled through urea application—emerged as the dominant factor influencing yield and

[1] The present paper is based on the work conducted in Managing Agricultural Soils as Carbon Sinks through adoption of negative emission strategies (MASCS) project funded by GIZ

[2] *Kharif* refers to the monsoon cropping season in South Asia, typically extending from June/July to September/October. *Rabi* refers to the winter cropping season in South Asia, usually spanning from November to March.

economic returns. This focus is also consistent with APSIM's structure, as the SoilP module, while robust for certain cereals, is not equally developed or validated for all crops within the APSIM suite, and no module exists for potassium.

- **Tillage Management**: This practice involves a single tillage operation per cropping season, excluding the mid-summer tillage. This contrasts with the conventional practice of three tillage operations.
- **Biochar Management**: Biochar is applied at a rate of one tonne per hectare on a dry weight basis every alternate year. For cost estimation purposes, the cost of 500 kg of biochar applied annually was used.
- **Integrated Management**: This is a combination of fertilizer management, biochar management, and critical irrigation applied together.

2.3. Cost-Benefit analysis

The cost-benefit analysis in this study evaluates the economic viability of various agricultural management practices in comparison to conventional systems. This analysis is grounded in detailed cost data and simulated outputs, with a focus on understanding the additional costs and benefits associated with each management practice.

2.3.1. Data sources and cost components

The primary data on the cost of cultivation was compiled from the Directorate of Economics and Statistics, Government of India [26]. The analysis uses the A1 cost of cultivation, which includes expenses such as hired human labor, owned and hired bullock, machinery costs, seeds, fertilizers, manure, pesticides, insecticides, irrigation, interest on working capital, land revenue, cess, and other taxes, as well as miscellaneous expenses. This comprehensive cost metric is essential for accurately reflecting the financial requirements of farming practices under different management scenarios. Adjustments were made to the standard cost components to align with the specific management practices simulated in APSIM. For instance, costs associated with fertilizers, manure, and irrigation were modified to reflect the specific inputs and quantities used in the simulation rules. These adjusted costs were then incorporated into the overall cost structure to ensure consistency between the simulated practices and the economic analysis.

2.3.2. Time series and price adjustments

The economic analysis spans from 1998 to 2020, with minimum support prices[3] (MSPs) for various crops being a critical input. These MSPs were sourced from the Directorate of Economics and Statistics and disaggregated at the state level for the relevant years. Since MSP data is available only from 1998, the economic evaluation was limited to this period, although simulations were conducted from 1990 to 2020. Fertilizer costs were adjusted using the 2020 price of urea [27] and converted to prices for other years using a consumer price index-based conversion factor, ensuring all costs were represented in 2020 currency values.

2.3.3. Cost estimation for biochar and irrigation

The cost of biochar was calculated based on methodologies outlined by the FAO [28] and discussion with the local stakeholders who worked on biochar production. The biochar production process assumed the use of two kilns with a maximum capacity of 30 tonnes each, yielding 10 tonnes of biochar per cycle. In our analysis, we considered half of the capacity. Therefore, the total Biomass used in two kilns is 30t (15t + 15t). For the initial level, the cost of biomass is nil because it is wasted in the farmer's farming system. Here, we are also not considering the fixed costs like preparing the kilns. The total variable cost for producing biochar was calculated at approximately INR 2.6 per kilogram in 2020, with detailed calculations provided in the following Table 1.

In this analysis, we assumed zero cost for biomass feedstock used in biochar production, based on the premise that the biomass considered (e.g., pruned residues, weed biomass, or non-fodder crop residues) has limited opportunity cost and is often underutilized or burned in the open. However, we acknowledge that in fodder-scarce regions, biomass availability may be constrained. For irrigation, costs were estimated by including the rental cost of an excavator (JCB) for digging a pit with a capacity of 500 m^3. The total cost of the irrigation structure in 2020 exceeded 100,000 INR, which was amortized over ten years. This structure, when filled with rainwater, will be sufficient to irrigate 6 ha The annual cost in 1998 was calculated at 510 INR per ha per irrigation, adjusted for inflation using a consumer price index specific to agricultural labor. Additional costs for pit maintenance after ten years were included, with irrigation costs further broken down per hectare based on the expected frequency of irrigation in both the Kharif and post-rainy seasons. Detailed cost estimations are provided in the following Table 2.

2.3.4. Analysis approach

The cost-benefit analysis compares the additional costs incurred by adopting different management practices against the baseline conventional system. The additional benefits were computed by multiplying the incremental yields obtained under each management practice with the corresponding crop prices. The benefit-cost ratios were then calculated as the ratio of these additional benefits to the additional costs, providing a precise measure of each management practice's economic efficiency.

The cost-benefit analysis compares each improved management practice against the conventional baseline by calculating the additional cost incurred and the additional benefit realized. Benefits were quantified as the monetary value of the simulated yield increase, calculated by multiplying the incremental yield per hectare (kg/ha) with the respective crop's Minimum Support Price (MSP) for each year, adjusted to 2020 price levels using the Consumer Price Index (CPI). Costs included all variable input costs (fertilizer, biochar, irrigation, labor) as derived from the Directorate of Economics and Statistics, with adjustments made for each management scenario simulated in APSIM. For biochar, we assumed a variable cost of ₹2.6 per kg based on local production estimates; irrigation costs were annualized over 10 years, assuming a 500 m^3 rainwater harvesting structure. Although the study focuses on productivity gains, the economic value of SOC sequestration was not directly monetized; instead, it was presented as a co-benefit alongside yield and BCR improvements. This approach reflects the difficulty in assigning market prices to SOC under current Indian policy and market conditions.

While the economic feasibility analysis in this study is based on historical cost and price data (1998–2020), we acknowledge the importance of incorporating forward-looking cost projections to inform long-term policy decisions. Future scenarios may involve rising labor

Table 1
Biochar Cost Estimation.

Item	Details	Cost (INR)
Biomass Used	30 t (15 t each kiln)	
Petrol cost to run shredder	2hrs/ton X 30 tons X 100 INR/liter	6000
Caretaker charges	1 man X INR 500/day X 30 days	15,000
Miscellaneous costs (water, mud etc.)		5000
Total variable costs		26,000
Output	10 t (5t from each kiln)	
Cost of biochar for 10 tons	monthly variable costs	26,000
Cost of biochar INR/kg in 2020		2.6

[3] MSP is the minimum price set by the Government of India for select crops grown during the kharif and post-rainy seasons, deemed remunerative for farmers and deserving of government support. Unlike procurement and issue prices, MSP is typically announced prior to the sowing or planting season.

Table 2
Estimation of cost of supplemental irrigation (INR/ha).

Cost component	Details	Cost (INR)
JCB rental cost for 20 hrs	20 × 1200	24,000
Irrigation motor of 2 HP capacity to pump water from pit to ground or fields		30,000
Electricity charges for motor/year (two months kharif, four months period of post-rainy)	6 × 1000	6000
Six water pipes (Ashirwad PVC pipes 2–3 m length each)	6 × 420	2520
Plastic sheet to cover pit (3 sheets of 50 ft* 30 ft)	3 X 9188	27,564
Labour charges	4 days X 500 INR/day X 4 men	8000
Miscellaneous		10,000
Total cost (current value) INR in 2020		108,084
Total cost INR in 1998		30,627.3
Yearly cost per irrigation of 1 ha (INR) in 2020		1801.4
Conversion in 1998	0.2834	
Per irrigation cost per ha in 1998		510
Maintenance charges for water harvesting structure from 2008 to 2020		
Plastic sheets		27,564
Electricity charges		6000
Miscellaneous		5000
Total Maintenance Charge		38,564
Per ha per irrigation maintenance cost in 2020		643
Per ha per irrigation maintenance cost from 2008 onwards		643 X conversion factor of that year

The tank will be filled twice during the rainy season. This will be sufficient for critical irrigation of 4 ha area in Kharif and 2 ha in Post-rainy.

and energy costs, potential reductions in biochar production costs due to technological innovation, or changes in crop price support mechanisms. Although this study does not perform a dynamic simulation of future economic conditions, our findings remain relevant as a baseline for evaluating the relative performance of integrated practices. We recommend that subsequent analyses apply sensitivity testing or scenario-based economic modeling to assess how shifts in key input/output prices may influence adoption and scalability. This will enhance the robustness of policy recommendations under evolving market and climate conditions.

2.4. Empirical framework

The empirical framework integrates biophysical and economic analyses to evaluate SOC sequestration practices using the APSIM simulation model across five districts in Maharashtra, India. It compares conventional farming practices with alternative integrated management strategies, to assess their impacts on crop yields and SOC dynamics over 28 years (1992–2020). Economic feasibility is analyzed through a cost-benefit framework, incorporating minimum support prices, adjusted input costs, and benefit-cost ratios (BCR) to measure economic efficiency. Statistical methods, including *t*-tests and panel regressions, identify significant differences in SOC and yield outcomes while isolating key drivers such as biochar, fertilizer, rainfall variability, and tillage intensity. This comprehensive approach combines localized data, robust modeling, and detailed economic evaluations to provide actionable insights for scaling sustainable agricultural practices that balance productivity and environmental sustainability.

To provide a comprehensive overview of the modeling framework, a schematic representation of the APSIM-based simulation process is presented in Fig. 1. This framework summarizes the sequence from data sourcing and experimental setup to intervention simulation, output generation, and final analysis.

3. Results

3.1. Trends of yield over time

Fig. 2 presents the yield patterns of various crops under different management systems. The trends in crop yields over time reveal that alternative management practices consistently outperform conventional methods across various cropping systems. Integrated approaches, demonstrate substantial productivity improvements compared to traditional practices. These strategies enhance soil quality and water use efficiency, contributing to sustained yield increases over the years.

For intercrop systems like soybean and pigeonpea, integrated management practices show a steady upward trajectory in yields, reflecting their effectiveness in addressing soil nutrient deficiencies and water retention challenges. Similarly, cotton-fallow systems exhibit marked

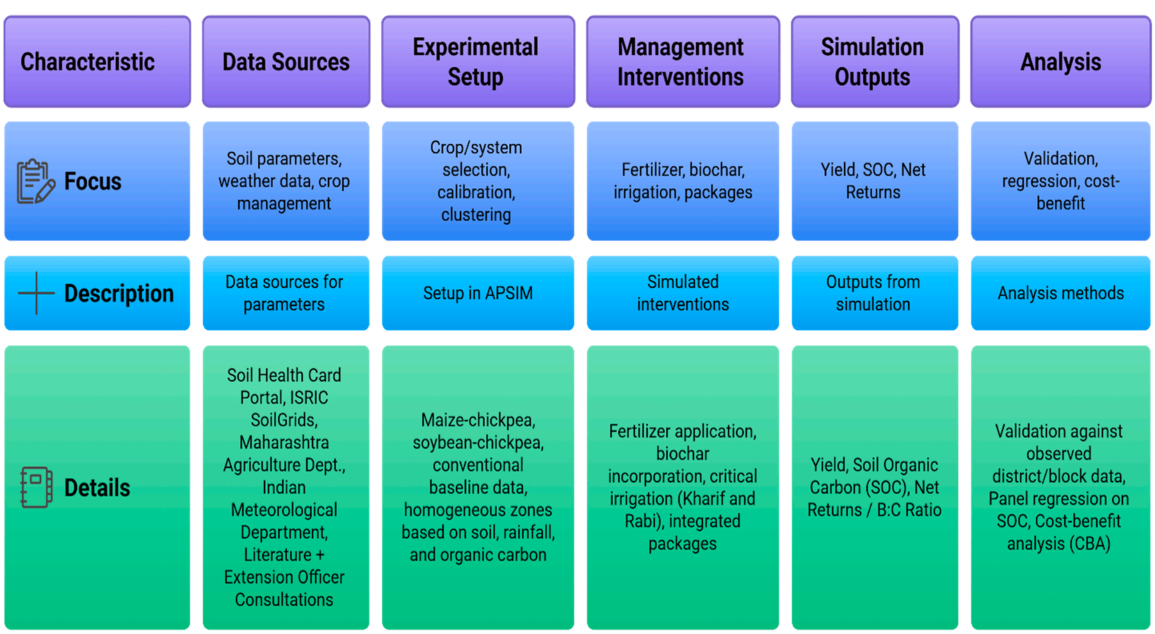

Fig. 1. Framework for simulating integrated management practices using APSIM.

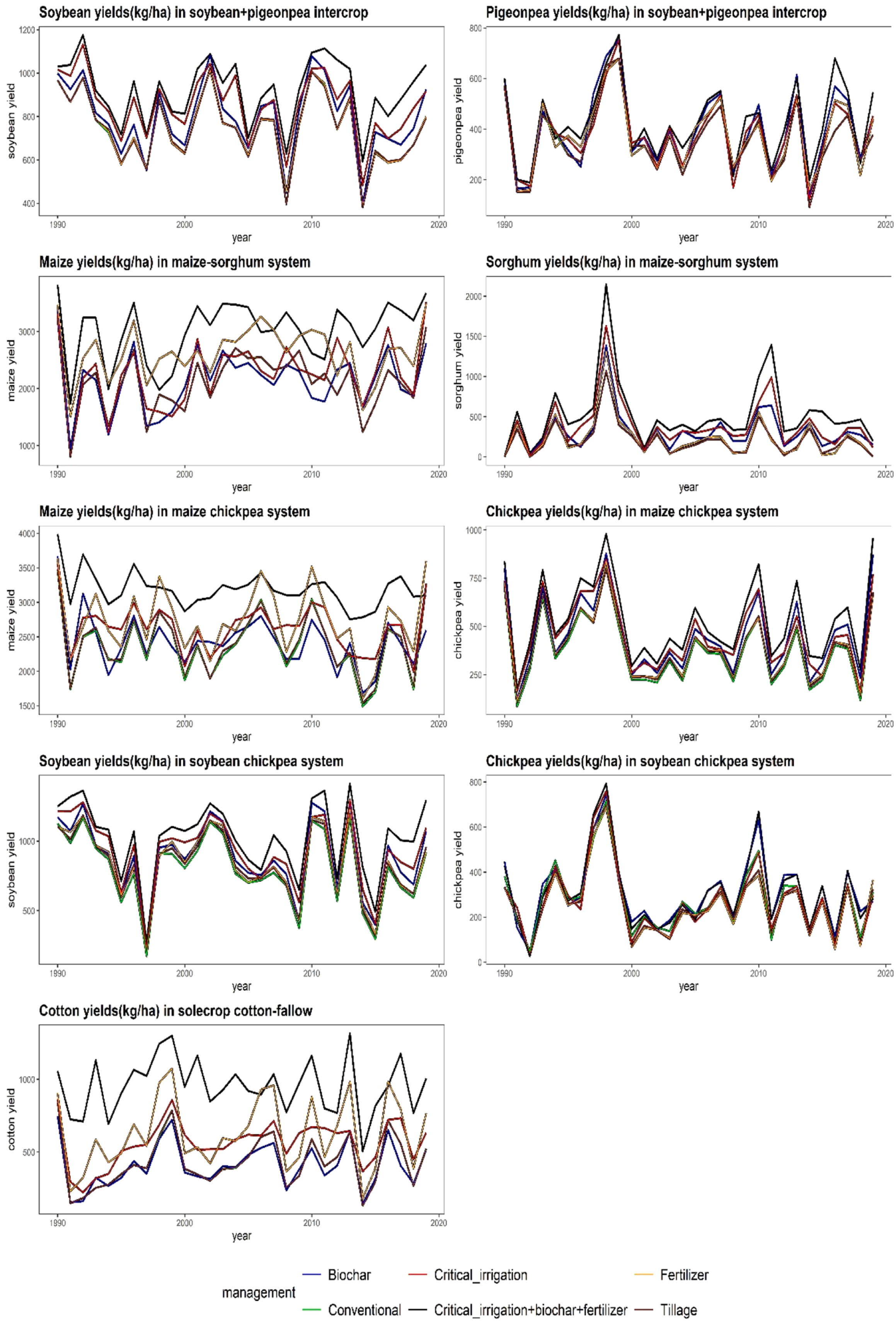

Fig. 2. Yields of crops simulated under different management systems in Maharashtra.

improvements in productivity, especially under integrated practices, highlighting their potential to mitigate yield limitations in semi-arid regions.

Cereal-based systems such as maize-chickpea and maize-sorghum also display significant yield enhancements over time with alternative practices. The adoption of biochar, coupled with optimized irrigation and fertilization, results in consistent yield growth, underscoring the resilience of these systems to climatic variability. However, while integrated practices improve chickpea productivity in soybean-chickpea systems, soybean yields under some alternative methods remain comparable to or slightly below conventional yields, indicating variability in response across crop types.

3.2. Descriptive statistics

Table 3 presents the average yield of different cropping systems under various management practices across five districts in Maharashtra.: Ahmednagar, Amravati, Dhule, Jalna, and Yavatmal. The systems include Soybean + Pigeonpea intercrop, Sole crop Cotton-fallow, Maize-Chickpea, Maize-Sorghum, and Soybean-Chickpea, each subjected to different management interventions such as biochar application, critical irrigation, fertilizer application, and a combination of biochar, fertilizer, and irrigation and reduced tillage management. These simulations were conducted using APSIM, which provides insights into the potential benefits of different management strategies in enhancing crop productivity.

Soybean + Pigeonpea Intercrop System: Using biochar, critical irrigation, and combined management practices resulted in higher average yields than conventional practices. For instance, the combined approach of critical irrigation, biochar, and fertilizer resulted in the highest average yield for soybean (921.32 kg/ha) and pigeonpea (429.92 kg/ha), compared to conventional yields of 741.55 kg/ha and 364.26 kg/ha, respectively. This indicates the effectiveness of combined management practices in improving crop yields, possibly due to improved soil moisture retention and nutrient availability.

Cotton-Fallow System: In the Cotton-Fallow System, critical irrigation, biochar, and fertilizer management significantly improved yields. The highest yield was observed under the combined practice of critical irrigation, biochar, and fertilizer (965.73 kg/ha) compared to conventional management (443.68 kg/ha). This substantial increase highlights the potential of integrated soil and water management practices in maximizing cotton productivity, which is critical in semi-arid regions like Maharashtra.

Maize-Chickpea System: The application of biochar and critical irrigation led to substantial increases in yields. The combined management approach yielded the highest average maize yield (3185.87 kg/ha) and chickpea yield (533.67 kg/ha), outperforming conventional yields of 2390.83 kg/ha for maize and 378.84 kg/ha for chickpeas. These results suggest that enhanced management practices can significantly improve productivity by optimizing soil conditions and water use efficiency, which is crucial in regions facing climate variability.

Maize-Sorghum System: Similar trends were observed in the Maize-Sorghum system, where the combined management practice yielded the highest average maize (2919.98 kg/ha) and sorghum (540.78 kg/ha) yields, compared to conventional yields of 2068.28 kg/ha for maize and 214.67 kg/ha for sorghum. This indicates the importance of integrated nutrient and water management for sustaining high yields in cereal-based cropping systems.

Soybean-Chickpea System: Conventional practices surprisingly showed higher average soybean yields (1006.35 kg/ha) compared to some improved practices like biochar (870.11 kg/ha) and critical irrigation (794.14 kg/ha). However, combined management practices for chickpeas still provided a competitive advantage, demonstrating the potential for targeted interventions to enhance specific crop outcomes.

3.3. Statistical analysis of yield differences across management practices

In Table 3 and the above panels of trends (Fig. 2), we presented the average yield of different crops across various management practices across different cropping systems in Maharashtra. We conducted a *t*-test (Table A1 in Appendix) to evaluate whether yields under alternative management practices differed significantly from those under conventional systems across 38 cases. In thirty of these, the alternatives produced significantly higher yields at the 5 % significance level. Additionally, there were two instances where the differences were significant at the 10 % level. In four cases, the differences between conventional and alternative practices were not statistically significant, including instances where maize yield under biochar and tillage management in the Maize-Sorghum system, soybean yield under tillage management in the Soybean-Pigeonpea intercrop system, and pigeonpea yield under tillage management were higher. Furthermore, there were four cases where conventional practices resulted in higher yields than the alternative management practices, specifically in chickpea yield under Fertilizer and Irrigation management in the Soybean-Chickpea system and soybean yield under Fertilizer and Tillage management in the Soybean-Pigeonpea Intercrop system.

The *t*-test results demonstrate statistically significant yield improvements under integrated management practices across most cropping systems. These findings indicate that the yield advantages observed are not due to random variation but reflect the consistent, positive impact of biochar, optimized irrigation, and fertilizer use. The strong significance ($p < 0.05$) in 30 out of 38 scenarios suggests that integrated management is reliably more effective than conventional practices. This reinforces the argument for promoting such practices as part of a productivity and sustainability-enhancing strategy in semi-arid regions.

In addition to their role in improving yields, the integrated practices evaluated in this study also enhance the adaptive capacity of cropping systems under climate variability. While the study primarily evaluates the mitigation potential of integrated practices through SOC sequestration, the results also underscore their significant role in enhancing adaptation and resilience to climate variability. Integrated management practices improve soil structure, moisture retention, and nutrient availability—factors that are crucial for sustaining yields under erratic rainfall, prolonged dry spells, and increasing temperature extremes.

Biochar application, for instance, enhances the soil's water-holding capacity and buffering potential, enabling crops to withstand periods of water stress more effectively. This is particularly critical in semi-arid regions like Maharashtra, where rainfall variability and short dry spells increasingly threaten crop productivity. Similarly, precision irrigation ensures that water is applied strategically during critical crop growth stages, reducing vulnerability to intra-seasonal droughts. Optimized fertilizer management contributes to more stable nutrient availability in the root zone, supporting plant health even under stress conditions.

Moreover, higher SOC levels improve overall soil resilience by enhancing microbial activity, improving aggregate stability, and reducing erosion risks during heavy rainfall events. These co-benefits position integrated practices as central to building climate-smart cropping systems that can both mitigate emissions and adapt to ongoing climate risks.

3.4. Cost-Benefit analysis

Building on the earlier analysis of yield trends and SOC dynamics across management practices, Table 4 highlights the comparative effectiveness of different practices in enhancing yields, SOC sequestration, and economic returns over conventional methods. The results consistently indicate that integrated practices, deliver superior performance across cropping systems and regions.

In the Soybean-Pigeonpea intercrop system, integrated management yielded the most substantial benefits, with Ahmednagar achieving an additional soybean yield of 329 kg/ha, pigeonpea yield gain of 97 kg/ha,

Table 3
Average yield across different farm management and cropping systems.

Cropping system	Management	Average	Max	SD	Average	Max	SD
		Soybean			Pigeonpea		
Intercrop Soybean+ pigeonpea	Conventional	741.55	341.60	1460.40	364.26	284.81	1293.70
	Biochar	797.30	350.76	1452.10	404.43	296.94	1356.00
	Critical irrigation	852.57	295.87	1459.80	387.83	275.03	1260.20
	Fertilizer	747.07	334.53	1449.10	379.64	266.71	1276.10
	Tillage	741.93	341.18	1460.40	364.51	284.69	1293.70
	Critical irrigation+ biochar+ fertilizer	921.32	282.18	1448.90	429.92	263.41	1202.60
		Cotton					
Sole crop Cotton-fallow	Conventional	443.68	302.15	1963.40			
	Biochar	417.71	271.63	1517.00			
	Critical irrigation	577.78	244.20	1297.30			
	Fertilizer	641.96	413.68	2108.40			
	Tillage	443.89	302.26	1963.40			
	Critical irrigation +biochar+fertilizer	965.73	377.78	2173.70			
		Maize			Chickpea		
System maize-chickpea	Conventional	2390.83	1043.65	5071.80	378.84	265.59	1593.50
	Biochar	2427.78	888.31	5181.20	452.42	284.00	1666.80
	Critical irrigation	2637.27	821.64	4804.70	462.32	267.09	1598.50
	Fertilizer	2730.49	1226.87	5112.90	396.71	305.54	1591.30
	Tillage	2409.07	1033.28	5071.80	391.46	277.52	1593.50
	Critical irrigation+biochar+ fertilizer	3185.87	691.19	5230.90	533.67	284.05	1666.60
		Maize			Sorghum		
System maize-sorghum	Conventional	2068.28	1126.11	5192.00	214.67	353.07	4583.60
	Biochar	2076.49	1078.89	5549.90	321.02	467.71	3052.60
	Critical irrigation	2189.68	1099.77	4884.50	402.63	444.54	3107.70
	Fertilizer	2571.15	1259.48	5237.20	240.79	412.07	6222.90
	Tillage	2068.29	1126.32	5192.00	214.73	353.28	4592.30
	Critical irrigation +biochar+fertilizer	2919.98	1048.52	5236.90	540.78	530.50	3433.40
System soybean-chickpea		Soybean			Chickpea		
	Conventional	1006.35	537.98	1971.90	313.23	317.67	1679.60
	Biochar	870.11	546.62	1945.70	312.60	302.91	1545.60
	Critical irrigation	794.14	511.23	1868.40	281.81	288.82	1515.30
	Fertilizer	832.63	509.33	1843.50	255.94	281.67	1503.80
	Tillage	822.38	512.61	1868.00	261.09	286.03	1509.90
	Critical irrigation+ biochar+fertilizer	915.15	509.68	1920.40	275.25	300.59	1751.50

Source: Authors' calculation.
Note: Minimum value of yield is zero for all cases and has been omitted from the table to avoid redundancy.

and SOC gain of 1.59 over 28 years period and a Benefit-Cost Ratio (BCR) of 7. Similar outcomes were observed in Dhule and Yavatmal, where integrated practices consistently outperformed standalone strategies. This highlights the effectiveness of integrating soil amendments and water management in enhancing crop productivity and carbon sequestration.

For the Cotton-Fallow system, integrated management again proved to be the optimal practice. Amravati achieved an additional yield of 512 kg/ha, SOC gain of 1.5 and a BCR of 10, a significant improvement compared to individual practices like biochar or fertilizer application, which provided limited yield gains. This trend underscores the value of combining interventions to improve outcomes in semi-arid regions where cotton is a dominant cash crop.

The results in the Maize-Chickpea system further validate the superiority of integrated practices. In Ahmednagar, the combined approach delivered an impressive yield increase of 1257 kg/ha for maize, increase of 176 kg/ha for chickpea along with a SOC increment of 1.5 and a BCR of 6. Other regions, such as Jalna and Yavatmal, also recorded substantial gains under integrated practices. In contrast, isolated interventions, including critical irrigation or biochar alone, achieved moderate benefits but did not match the holistic impact of integration.

The Maize-Sorghum system exhibited similar trends, with integrated management emerging as the most effective approach. Yavatmal reported significant gains, with an additional yield of 889 kg/ha for maize and 422 kg/ha for sorghum, and a SOC increment of 1.53, achieving a BCR of 6 Standalone practices like fertilizer or irrigation management provided some yield improvement. However, they lacked the comprehensive benefits of the integrated approach, highlighting the need for combined resource management to sustain productivity in cereal-based systems.

The Soybean-Chickpea system presented mixed results, with integrated practices delivering notable improvements in chickpea yields. For instance, Ahmednagar recorded an additional soybean yield of 272 kg/ha and SOC gain of 1.5 % with a BCR of 2. However, isolated practices like fertilizer management often led to negative SOC changes in some regions, such as Ahmednagar and Yavatmal, where reductions of –0.01 % were observed. These results highlight the challenges of relying on single interventions and emphasize the importance of tailored, integrated strategies to optimize outcomes.

Across all cropping systems, integrated management practices consistently demonstrated superiority by maximizing yield gains, SOC increments, and economic returns. These findings reinforce the importance of adopting comprehensive approaches to resource management in addressing agriculture's productivity and sustainability challenges.

3.5. *Factors influencing SOC sequestration*

Building on the preceding analysis, it becomes essential to examine how SOC sequestration is influenced by various factors under different management practices. To achieve this, a panel regression was conducted to quantify these relationships. Table 5 provides the results of this analysis, offering a detailed evaluation of the drivers affecting SOC levels across diverse agricultural interventions.

The lagged effect of biochar (Lag of biochar) exhibits a significant positive impact on SOC levels in both integrated management (0.148 kg/ha, $p < 0.001$) and biochar management (0.0722, $p < 0.01$). This result highlights the biochar's role in enhancing SOC retention in soil. The lagged effect of fertilizer (Lag of fertilizer applied) is the most pronounced driver of SOC across all practices. Under irrigation management, it exhibits an exceptional positive coefficient of 23.58 ($p <$

Table 4
Additional yields over conventional practice (28-year averages), SOC sequestered, and Benefit-Cost Ratios (BCR).

Practice	Biochar management				Fertilizer management				Critical irrigation				Biochar + Fertilizer + Irrigation			
Attributes	Yields (kg/ha)		SOC (%)	BCR	yields(kg/ha)		SOC (%)	BCR	yields(kg/ha)		SOC(%)	BCR	yields(kg/ha)		SOC(%)	BCR
Soybean + Pigeonpea intercrop																
	soybean	pigeonpea			soybean	pigeonpea			soybean	pigeonpea			soybean	pigeonpea		
Ahmednagar	38.00	38.00	1.66	4.00	4.00	20.00	0.00	8.00	238.00	42.00	0.00	8.00	329.00	97.00	1.59	7.00
Amravati	56.00	38.00	1.61	5.00	−2.00	6.00	0.00	2.00	66.00	8.00	0.00	3.00	128.00	45.00	1.56	4.00
Dhule	60.00	31.00	1.63	5.00	−4.00	5.00	0.00	1.00	78.00	16.00	0.00	3.00	144.00	65.00	1.57	4.00
Jalna	67.00	36.00	1.59	6.00	−3.00	13.00	0.00	1.00	139.00	33.00	0.00	6.00	234.00	66.00	1.55	5.00
Yavatmal	77.00	64.00	1.62	8.00	−5.00	19.00	0.00	6.00	29.00	19.00	0.00	4.00	106.00	76.00	1.57	5.00
Maize – Sorghum system																
	maize	sorghum			maize	sorghum			maize	sorghum			maize	sorghum		
Ahmednagar	94.00	5.00	1.63	2.00	295.00	36.00	0.09	13.00	399.00	150.00	0.10	2.00	1167.00	236.00	1.59	4.00
Amravati	−104.00	151.00	1.59	1.00	670.00	24.00	0.04	31.00	30.00	253.00	0.10	2.00	687.00	429.00	1.56	5.00
Dhule	21.00	82.00	1.58	3.00	534.00	11.00	0.04	25.00	130.00	223.00	0.08	2.00	961.00	305.00	1.55	4.00
Jalna	−28.00	51.00	1.55	1.00	327.00	16.00	0.05	14.00	77.00	179.00	0.07	1.00	780.00	311.00	1.51	3.00
Yavatmal	36.00	248.00	1.56	7.00	598.00	23.00	0.03	29.00	98.00	217.00	0.07	2.00	889.00	422.00	1.53	6.00
Maize - Chickpea system																
	maize	chickpea			maize	chickpea			maize	chickpea			maize	chickpea		
Ahmednagar	142.00	54.00	1.55	7.00	139.00	−6.00	−0.01	6.00	547.00	101.00	0.00	2.00	1257.00	176.00	1.51	6.00
Amravati	−141.00	100.00	1.51	3.00	487.00	45.00	0.00	29.00	63.00	82.00	0.00	1.00	445.00	178.00	1.49	5.00
Dhule	98.00	55.00	1.53	6.00	303.00	−8.00	0.01	14.00	242.00	91.00	0.00	2.00	841.00	142.00	1.50	5.00
Jalna	36.00	80.00	1.51	6.00	313.00	83.00	0.01	26.00	252.00	78.00	0.00	2.00	828.00	164.00	1.49	6.00
Yavatmal	−54.00	88.00	1.52	4.00	422.00	−13.00	0.00	19.00	49.00	54.00	0.00	1.00	541.00	138.00	1.49	6.00
Soybean - Chickpea system																
	soybean	chickpea			soybean	chickpea			soybean	chickpea			soybean	chickpea		
Ahmednagar	11.00	24.00	1.53	3.00	44.00	−46.00	−0.01	0.00	186.00	6.00	0.00	2.00	272.00	6.00	1.50	2.00
Amravati	45.00	34.00	1.48	6.00	−22.00	−25.00	0.00	−1.00	62.00	−5.00	0.00	1.00	164.00	−5.00	1.47	2.00
Dhule	47.00	33.00	1.50	6.00	−26.00	−14.00	0.00	−2.00	72.00	2.00	0.00	1.00	148.00	2.00	1.50	2.00
Jalna	66.00	44.00	1.47	7.00	−3.00	−11.00	0.01	−1.00	80.00	−11.00	0.00	1.00	189.00	−11.00	1.47	2.00
Yavatmal	81.00	52.00	1.48	9.00	6.00	−20.00	−0.01	2.00	11.00	−17.00	0.00	1.00	148.00	−17.00	1.48	2.00
Cotton-fallow																
	cotton				cotton				cotton				cotton			
Ahmednagar	−37.00		1.50	−2.00	157.00		0.00	35.00	172.00		0.00	3.00	460.00		1.60	6.00
Amravati	−18.00		1.50	−1.00	208.00		0.00	35.00	143.00		0.00	5.00	512.00		1.50	10.00
Dhule	−28.00		1.50	−2.00	214.00		0.00	36.00	193.00		0.00	4.00	617.00		1.60	9.00
Jalna	−43.00		1.40	−2.00	233.00		0.00	43.00	158.00		0.00	3.00	553.00		1.50	8.00
Yavatmal	−28.00		1.40	−2.00	239.00		0.00	41.00	104.00		0.00	4.00	502.00		1.50	11.00

Source: Authors' calculations.

Table 5
Panel Regression for understanding the factors affecting the SOC Sequestration.

Dependent Variable: soil carbon at the sowing stage in May month in the top 30 cm of soil (kg/ha)	All management	Irrigation management	Biochar management	Fertilizer management	Fertilizer + Irrigation + Biochar management	Tillage management
Lag of biochar	0.110***		0.0722***		0.148***	
	(0.00196)		(0.00217)		(0.00342)	
Lag of fertilizer applied	2.435***	23.58***	14.03***	0.774***	9.459***	13.43***
	(0.133)	(1.293)	(0.834)	(0.158)	(0.578)	(0.835)
Lag of rainfall	1.849***	1.266***	0.942***	2.193***	1.402***	1.363***
	(0.0634)	(0.161)	(0.124)	(0.171)	(0.190)	(0.142)
Lag of rainfall square term	−0.000826***	−0.000588***	−0.000396***	−0.000982***	−0.000721***	−0.000585***
	(0.0000413)	(0.000103)	(0.0000795)	(0.000112)	(0.000121)	(0.0000917)
Lag of kharif irrigation	4.127***	3.154***			1.768**	
	(0.314)	(0.456)			(0.541)	
Lag of post-rainy irrigation	−3.710***	−2.643**			−5.530***	
	(0.710)	(1.020)			(1.180)	
tillage dummy: 1 if tillage is done only once and	−342.5***					
0 if tillage is done twice	(26.61)					
Lag of soil temperature	−43.37***	−33.47***	−27.52***	−48.28***	−54.83***	−31.09***
	(3.836)	(9.633)	(7.279)	(10.35)	(10.94)	(8.502)
Constant	25,319.5***	24,251.9***	24,135.2***	25,393.5***	24,401.7***	24,450.3***
	(137.1)	(345.4)	(259.8)	(363.9)	(392.1)	(301.3)
Observations	47,850	7975	7975	7975	7975	7975
Corr(u_i, Xb)	0.1144	0.2452	0.183	0.2523	0.2308	0.237
sigma_u	4412.1711	4292.5798	4189.1258	4492.1467	4511.9404	4311.9023
sigma_e	1025.4306	1029.2282	804.63061	1125.2635	1203.6231	917.90747
Rho	0.94875384	0.94563609	0.96441948	0.94095675	0.93356472	0.95664771
R-sq:						
Within	0.1111	0.0854	0.1937	0.038	0.2797	0.0633
Between	0.0664	0.1699	0.1149	0.1376	0.2315	0.1302
overall	0.0641	0.1564	0.0992	0.1014	0.1574	0.1145

Source: Authors' calculation; Standard errors in parentheses * = $p < 0.05$, ** = $p < 0.01$, ***= $p < 0.001$.

0.001), indicating the synergy between irrigation and fertilizer application in enhancing SOC sequestration. This is followed by significant effects under tillage management (13.43, $p < 0.001$), biochar management (14.03, $p < 0.001$), and integrated management (9.459, $p < 0.001$).

The influence of lagged rainfall (Lag of rainfall) on SOC levels is significant across all models, showing a positive effect on SOC, with the highest impact observed under fertilizer management (2.193 kg/ha, $p < 0.001$). However, the quadratic term of rainfall (square term of Lag of rainfall) indicates diminishing returns with higher rainfall, as evidenced by consistently negative coefficients across practices. The lag of irrigation during the Kharif season (Lag of kharif irrigation) positively influences SOC in all management practices where it is considered, with the impact under general irrigation management (3.154 kg/ha, $p < 0.001$).

The tillage dummy, which differentiates between single and double tillage operations, shows a robust negative effect (−342.5 kg/ha, $p < 0.001$), highlighting the adverse impact of intensive tillage on SOC retention. Soil temperature consistently shows a negative correlation with SOC across all practices, with the strongest effect observed under integrated management (−54.83 kg/ha, $p < 0.001$), suggesting that elevated temperatures accelerate organic matter decomposition and reduce SOC levels.

The regression diagnostics indicate that the robust model fits with high intra-class correlation coefficients (rho > 0.94), confirming the importance of unobserved heterogeneity in explaining SOC dynamics. The overall R-squared values, while moderate, reflect the complexity of SOC sequestration processes influenced by diverse environmental and management factors.

This study recognizes the importance of understanding how variability in input costs and climate conditions may influence the effectiveness and viability of integrated management practices. Although a formal sensitivity analysis was not conducted, our approach partially captures climatic heterogeneity by simulating outcomes across five districts with diverse rainfall and soil conditions. Additionally, biochar costs were conservatively estimated using locally sourced data and current production methods. However, we acknowledge that biochar prices may vary significantly depending on scale, biomass availability, and technology, and climate variability could further influence crop responses and SOC outcomes. Future research should incorporate structured sensitivity analyses—varying key inputs such as biochar costs, irrigation frequency, and rainfall scenarios—to better evaluate the robustness of results under different socio-economic and climatic conditions. This will strengthen the policy relevance and scalability of our findings.

To clarify the contribution of individual practices to SOC sequestration, we examined the marginal effects of biochar application, fertilizer use, and irrigation through a panel regression framework (Table 5). Among the standalone practices, fertilizer application exhibited the largest positive impact on SOC, especially when combined with irrigation (coefficient: 23.58, $p < 0.001$). Biochar also showed a consistently strong and significant effect across all models, with the highest SOC impact under integrated management (coefficient: 0.148, $p < 0.001$). Irrigation during the Kharif season had a smaller but significant positive effect, enhancing root biomass and microbial activity. While integrated practices offer the highest overall gains in SOC, this analysis confirms that each component—biochar, fertilizer, and irrigation—contributes distinctly to SOC dynamics, with fertilizer having the largest marginal effect, followed by biochar and irrigation. This breakdown complements the integrated view and helps inform targeted policy or resource allocation strategies.

4. Discussion

This study highlights the advantages of integrated agricultural management practices over conventional systems in enhancing crop productivity and SOC sequestration. By employing biochar application, optimized irrigation, and effective fertilizer management, integrated practices have demonstrated the potential to address the dual challenges of food security and environmental sustainability in semi-arid regions like Maharashtra.

Integrated practices consistently outperformed conventional farming systems in all studied cropping systems, as evidenced by substantial increases in crop yields. For instance, the maize-chickpea system saw maize yields increase by 795 kg/ha with integrated practices, compared to conventional practices, and chickpea yields improved by 155 kg/ha. These results align with earlier findings by Lehmann and Joseph [29], who noted that biochar application enhances soil water retention and nutrient availability, leading to improved crop performance.

Similarly, the soybean-pigeonpea intercrop system also benefitted significantly from integrated management, leading to yield increases of 180 kg/ha for soyabean and 66 kg/ha for pigeonpea compared to conventional practices. These improvements reflect the capacity of integrated practices to mitigate nutrient deficiencies and enhance water use efficiency, as also observed by Poeplau and Don [11] in similar cropping systems.

The cotton-fallow system also showcased notable productivity gains, with integrated practices resulting in an improvement in yielding by 522 kg/ha compared to conventional methods. This improvement underscores the relevance of biochar and optimized irrigation in semi-arid regions, where water scarcity and nutrient-poor soils often limit productivity [14]. In this system, with application of critical irrigation and fertilizer, there is a slight increase in the magnitude of soil organic carbon with fertilizer and critical irrigation, irrespective of the districts under study. The microbial biomass would have been enhanced with well-watered and improved nitrogen in the soil. Changes in management in soils with different water and temperature regimes will also alter the decomposability of the newly formed SOC, and these changes in turn alter the crop production and rates of carbon addition to soil. Chemical fertilizers promote biomass production, consequently a higher amount of plant residues, roots, and also root exudates, which contribute to the soil organic matter pool. However, inorganic fertilizers significantly reduce the total bacterial and fungal biomass in the soil.

In the maize-chickpea system, there was no notable improvement in SOC with conservation tillage and recommended fertilizer practices. There was a negligible shift in the magnitude of SOC in high rainfall receiving regions like Amravati and Yavatmal. The negative effects of fertilizer in semi-arid tracts were less noticed because the mobility of fertilizer is limited in semi-arid tracts. Hence, even with the application of fertilizer, no change was witnessed, unlike the soybean + pigeonpea system. Incorporation of leguminous crops like chickpea along with nitrogen-based fertilizers would have led to the improvement in dissolved C, and this would have, in turn, caused SOC penalties with fertilizer intervention [30]. With reduced tillage, there was an improvement in soil organic carbon compared to conventional practice. The short-term effects of soil disturbance contribute to higher CO_2 emissions [31], which leads to the loss of SOC, and hence conservation tillage would enhance SOC than in a conventional system.

While integrated practices consistently enhanced long-term SOC sequestration and system-level resilience, we acknowledge that certain interventions—particularly those involving biochar—may not always offer immediate profitability across all crops and regions. For example, in the soybean-chickpea system, the short-term yield response of soybean under biochar and irrigation treatments was sometimes lower than under conventional practices, despite positive effects on chickpea and SOC levels. This highlights a potential trade-off between long-term environmental benefits and short-term economic gains, which can influence adoption decisions, especially among small-holder farmers with limited financial buffers. Farmers are more likely to adopt practices that align with immediate income needs unless supported by subsidies, carbon credit incentives, or risk-sharing mechanisms. Future work should incorporate multi-year profit trajectories, include opportunity cost assessments, and explore adoption models that account for these trade-offs to better inform inclusive and farmer-centric policy frameworks.

The study also underscores the critical role of integrated practices in SOC sequestration, a key strategy for mitigating climate change.[4] Biochar application, emerged as a transformative practice, significantly enhancing SOC levels. For example, in the maize-sorghum system, SOC increased by 1.56 % by biochar application and 1.53 % under integrated management in Yavatmal, compared to negligible gains under conventional methods. This finding is consistent with earlier research by Rumpel et al. [14], emphasizing biochar's long-term stability and potential to act as a robust carbon sink.

Optimized irrigation further contributed to SOC improvements by enhancing root biomass and organic matter inputs, particularly in semi-arid regions where water availability is a limiting factor. The study findings align with the observations of Paustian et al. [8], who highlighted the role of water management in sustaining SOC levels under varying climatic conditions.

However, the variability in SOC responses across cropping systems and regions suggests that the efficacy of integrated practices is influenced by local factors such as soil type, climatic conditions, and crop-specific nutrient dynamics. For instance, while soybean-chickpea systems benefitted from integrated practices in chickpea yields, soybean yields under some treatments were comparable to conventional practices. This highlights the need for tailored interventions to maximize SOC gains and productivity, a view supported by Conant et al. [33].

While integrated practices consistently improved yields across most cropping systems, the extent of yield gains varied by crop type and region. For example, maize-chickpea and maize-sorghum systems showed larger yield improvements compared to soybean-chickpea systems, where responses were more variable. This variability arises from differences in crop physiology, soil fertility status, and water-use efficiency across systems. Additionally, district-specific agroecological conditions—such as baseline organic carbon, rainfall distribution, and soil texture—affect how crops respond to the same intervention. A detailed agronomic and modeling-focused comparison of cropping systems under identical interventions (e.g., biochar, irrigation, or fertilizer alone) is the subject of a separate manuscript and is beyond the scope of this paper. Nevertheless, our results suggest that tailoring integrated practices to local cropping contexts—e.g., by adjusting timing, nutrient dose, or irrigation frequency—may help mitigate variability and enhance consistency in yield responses across diverse systems.

The findings of this study are particularly relevant for semi-arid regions like Maharashtra, where agricultural productivity is constrained by water scarcity and poor soil quality. Biochar application emerged as a game-changer, improving soil water retention and nutrient cycling. The cost-effectiveness of biochar, as calculated in this study, makes it an economically viable option for farmers, aligning with recommendations by Grace et al. [34] for resource-limited farming systems.

Optimized irrigation practices, such as critical irrigation during water-stress periods, significantly enhanced crop performance and SOC

[4] A complementary analysis was conducted under RCP4.5 and RCP8.5 climate scenarios using the same APSIM framework across the studied cropping systems. Results showed negligible reductions in SOC compared to the baseline in most systems. Notably, biochar offset SOC losses under high-temperature regimes in cotton-fallow systems [32], while slight declines in SOC were observed in maize-chickpea and soybean + pigeonpea systems due to temperature-induced changes in microbial activity and nutrient solubility. Detailed results are part of a separate manuscript currently under review.

sequestration. For instance, the maize-sorghum system yielded a gain of up to 852 kg/ha of maize under integrated management, compared to conventional practices. This aligns with the findings of Smith [35], who emphasized the importance of efficient water use in adapting to climate variability.

Moreover, fertilizer management under integrated practices contributed to consistent productivity gains while maintaining SOC levels. By applying the recommended dosage and timing of fertilizers, integrated systems mitigated the adverse environmental impacts often associated with excessive chemical input use, a concern highlighted by Chien et al. [36]. While this study focused on urea as the primary nitrogen source due to its widespread use and accessibility among smallholder farmers, we acknowledge that fertilizer application in many parts of India is already skewed toward excessive nitrogen use. This imbalance can lead to soil nutrient depletion, reduced fertilizer efficiency, and environmental risks. Future work should incorporate site-specific nutrient management and balanced fertilization strategies that include phosphorus, potassium, and micronutrients. From a policy standpoint, the results support the need for integrated nutrient management that not only improves productivity and SOC but also aligns with national efforts to correct nutrient imbalances in Indian agriculture.

The consistently superior outcomes observed under the integrated management treatment also point to the interacting benefits of

Box 1: Farmer Perspectives on Feasibility and Adoption of Integrated Practices in Semi-Arid Maharashtra insights from the field.

As part of a broader effort to contextualize the feasibility of the modeled integrated practices, focus group discussions (FGDs) were conducted with smallholder farmers in Jalna, Amravati, and Yavatmal districts of Maharashtra. These discussions were organized in collaboration with local extension officers and self-help group (SHG) facilitators and included both male and female farmers representing different landholding sizes and crop systems.

A recurring theme was that awareness and exposure to new practices play a critical role in shaping adoption. While most farmers were familiar with fertilizer management and irrigation scheduling, biochar was largely unknown or misunderstood. Many had heard of “charcoal” or burning residues but did not connect it to soil improvement. When the concept was explained in the local language using images and soil samples from earlier trials, farmers expressed interest but also raised concerns.

“After harvest, we usually leave the stalks for animals or burn them. Making biochar is extra work. Who will do this unless someone helps?” — *Farmer, Ghansawangi block, Jalna*

Farmers highlighted three main barriers to biochar adoption:

- **Labour and time constraints** — for biomass collection post-harvest, especially when family labor is stretched.
- **Fodder scarcity** — crop residues are commonly used for livestock, especially in drought-prone areas.
- **Lack of kilns and technical know-how** — no farmer in the groups reported having access to a biochar pit or equipment.

Some marginal farmers suggested that if village-level kilns were built and managed by youth or SHGs, they might be willing to bring biomass for processing in exchange for biochar, especially if they see benefits on demonstration plots. In contrast, precision irrigation was more familiar, particularly among vegetable and cotton growers. Farmers in Amravati and Yavatmal who received micro-irrigation support under the *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)* noted improved water efficiency and better yields, but maintenance was a major challenge.

“Drip is good, but rats bite the pipes, and repairs are expensive. And the filters clog in our water.” — *Woman farmer, Dhamangaon block, Amravati*

They recommended community-level systems with repair services or shared irrigation cooperatives to reduce individual risk and cost. Access to power supply was also cited as a limiting factor for pump-based irrigation.

Fertilizer optimization was more positively viewed. Many farmers were already experimenting with lower doses or more frequent applications, often based on advice from agri-input dealers rather than soil test labs. While some had received *Soil Health Cards*, most said the recommendations were too generic or not explained properly.

“They gave us the paper, but no one came to tell us what it means. We don’t understand the numbers.” — *Farmer, Yavatmal*

Farmers expressed a need for more localized, crop-specific fertilizer guidance, and welcomed the idea of using organic supplements like compost or farmyard manure if linked to yield gain.

The discussions revealed that adoption of integrated practices depends not only on economic viability but also on enabling support systems. Farmers emphasized the need for:

- Demonstration plots to see visible results
- Group-based extension programs
- Input support or subsidies, especially for biochar and irrigation equipment
- Local resource persons or trained youth for technical troubleshooting

These perspectives emphasize that technical feasibility must be paired with institutional innovation and community engagement to realize the potential of carbon-enhancing practices in resource-constrained, risk-prone farming systems.

While integrated practices show strong technical and economic potential, their widespread adoption is shaped by a range of socio-economic factors. From our discussion with the farmers, the key barriers include limited access to credit and upfront capital, particularly for irrigation infrastructure or biochar production; insecure land tenure, which discourages long-term investment in soil health; labor constraints during post-harvest periods; and limited access to tailored extension services. Risk aversion among smallholder farmers, especially in rainfed areas, further reduces willingness to experiment with unfamiliar practices. These constraints suggest that successful scaling of integrated approaches will require not only financial and technical support, but also institutional mechanisms that address socio-economic vulnerabilities—such as inclusive input delivery systems, peer learning platforms, and targeted support for women and tenant farmers.

combining multiple practices. While the panel regression isolated the marginal influence of individual measures, the simulations that applied biochar, irrigation, and fertilizer together captured the cumulative effects of these interventions. The higher SOC gains and yield improvements recorded under the integrated package (Table 4) suggest that the combined application generates advantages beyond those of single practices alone. Although formal econometric interaction terms were not estimated, these results can be interpreted as evidence of synergistic effects, reinforcing the importance of adopting integrated strategies to strengthen both productivity and soil carbon sequestration in semi-arid farming systems.

It is important to consider the longer-term sustainability of these practices in real-world farming systems. Although this study simulates outcomes over a 28-year period, the integrated practices examined—particularly biochar application, precision irrigation, and optimized nutrient management—have the potential to deliver sustained agronomic and environmental benefits well beyond this timeframe. Biochar, due to its chemical stability and low decomposition rate, can continue enhancing soil structure, cation exchange capacity, and water retention for decades, thereby contributing to the long-term restoration of degraded soils. Similarly, precision irrigation, if maintained and adapted to future climatic shifts, supports sustainable water use and can reduce long-term pressure on groundwater resources. Optimized fertilization minimizes nutrient runoff and promotes nutrient-use efficiency, maintaining soil fertility while reducing environmental externalities. Together, these practices not only safeguard soil health and water systems but also stabilize yields and improve economic resilience for smallholder farmers in the face of ongoing climatic and market uncertainties.

To ensure sustainability and track long-term impacts, it is essential to establish monitoring systems that integrate soil health indicators (e.g., SOC levels, bulk density, nutrient balance), water-use metrics (e.g., irrigation frequency, water productivity), and socioeconomic indicators (e.g., input costs, net returns, adoption trends). Strengthening institutional frameworks—such as expanding the Soil Health Card program into a longitudinal monitoring platform and integrating remote sensing tools—can facilitate real-time data collection and adaptive management. These measures are crucial for managing the evolving impacts of integrated practices and ensuring their long-term viability for both productivity and resilience goals.

5. Policy recommendations

The findings of this study align closely with and have important implications for both national and international agricultural and climate policy frameworks. The demonstrated benefits of integrated management practices not only support India's national goals for agricultural sustainability and climate resilience but also resonate with global commitments under the Paris Agreement, the Sustainable Development Goals (SDGs), and the 4p1000 initiative.

Alignment with National Policies: The integrated agricultural practices promoted in this study are highly congruent with India's overarching policy priorities on sustainable agriculture, climate adaptation, and soil health. These practices directly support the National Mission for Sustainable Agriculture (NMSA), a core component of the National Action Plan on Climate Change (NAPCC), by addressing the twin objectives of enhancing productivity and building climate resilience. Furthermore, they are operationally aligned with flagship programs such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), which emphasizes efficient water use, and the Soil Health Card Scheme, which seeks to promote balanced nutrient management.

The study's emphasis on improving Soil Organic Carbon stocks and resource-use efficiency reinforces India's commitments under the National Policy for Farmers and the National Agroforestry Policy, both of which advocate for ecologically sound and economically viable farming systems. Importantly, the demonstrated cost-effectiveness of these practices complements the Government of India's growing focus on mainstreaming climate-smart agriculture within its developmental planning frameworks, including state-level climate-resilient agriculture roadmaps and centrally sponsored soil and water conservation programs. By advancing evidence-based strategies that are scalable, economically attractive, and environmentally regenerative, the findings provide a critical evidence base to inform policy coherence across ministries and programs.

Alignment with International Frameworks: At the international level, the study's findings are strongly aligned with key global frameworks addressing climate change, sustainable agriculture, and land restoration. The integrated management practices support India's commitments under the Paris Agreement, particularly with respect to mitigation co-benefits in the agriculture, forestry, and other land use (AFOLU) sector. By promoting SOC sequestration as a climate mitigation strategy, the study advances the objectives of Article 4 of the Paris Agreement, which encourages the adoption of nature-based solutions within national climate policies.

The research also contributes meaningfully to the realization of the Sustainable Development Goals (SDGs)—specifically SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land)—by demonstrating how productivity, environmental resilience, and economic sustainability can be simultaneously achieved in smallholder farming systems. Additionally, the practices align with the principles of the 4p1000 initiative, which emphasizes increasing global soil carbon stocks as a pathway to climate stability and improved food systems.

By providing empirical evidence of economically viable, carbon-sequestering agricultural innovations in a semi-arid context, the study strengthens India's leadership in promoting climate-resilient food systems globally. These findings offer a valuable resource for multilateral climate finance institutions, technical cooperation agencies, and global platforms focused on sustainable land management and agroecological transitions.

Specific Policy Recommendations: To translate the findings of this study into actionable policy, several specific recommendations are warranted.

- **Mainstream SOC Sequestration into National Climate Strategy:** There is a need to mainstream Soil Organic Carbon (SOC) sequestration into India's national climate strategy. This entails explicitly incorporating SOC enhancement into the country's Nationally Determined Contributions (NDCs) under the UNFCCC and encouraging its integration within State Action Plans on Climate Change (SAPCCs). Recognizing SOC as a key climate mitigation strategy can help direct policy attention and resources towards sustainable land management practices.
- **Subsidize Biochar Production and Application:** The government should consider subsidizing biochar production and application, particularly in semi-arid regions. Financial incentives and technical support could facilitate the establishment of decentralized biochar production units using locally available biomass. These subsidies, potentially linked to carbon credit mechanisms, would make biochar more accessible to smallholder farmers and accelerate its adoption. In addition to positive incentives, disincentive-based policy tools such as eco-taxation may also play a role in accelerating the transition to sustainable agricultural practices. Recent work by Dragicevic and Pereau [37] highlights the potential of eco-taxes in influencing input use and promoting environmentally responsible behavior across networked agricultural supply chains. For instance, applying targeted eco-taxes on excessive nitrogen fertilizer use or unsustainable tillage could internalize environmental externalities and shift farmer behavior toward more carbon-friendly practices. When complemented by support mechanisms—such as training, access to alternatives like biochar, or input subsidies—eco-taxation could

serve as part of a broader policy mix to realign incentives with sustainability goals.

- **Expand Precision Irrigation Infrastructure:** Expanding infrastructure for precision irrigation should be a policy priority. This includes enhancing support for micro-irrigation systems such as drip and sprinkler irrigation under existing programs like the Pradhan Mantri Krishi Sinchayee Yojana. The integration of affordable soil moisture sensors and advisory services on irrigation scheduling within extension programs would further improve water-use efficiency and crop performance.
- **Promoting Public-Private Partnerships:** Strengthening public-private partnerships (PPPs) will be vital to scale these innovations. Collaborative models involving agri-tech companies, local entrepreneurs, and producer organizations can help build robust supply chains for biochar, inputs, and irrigation equipment. PPPs can also drive innovations in service delivery and reduce upfront costs for farmers through shared infrastructure or rental models.
- **Integrate Practices into Crop Insurance and Risk Mitigation Schemes:** Integrated soil and water management practices should be linked with risk mitigation and crop insurance schemes. For instance, adoption of SOC-enhancing practices can be incentivized through premium reductions under the Pradhan Mantri Fasal Bima Yojana. Furthermore, carbon-rich soils should be recognized as a resilience factor in drought-prone areas, guiding the targeting of climate adaptation support and relief measures.
- **Establish a National Soil Carbon Monitoring Network:** The establishment of a national SOC monitoring system is essential. Building upon existing initiatives such as the Soil Health Card Scheme, a coordinated effort should be made to collect time-series data on SOC levels across agroecological zones. This should be supported by investments in geospatial tools and decision-support systems that help identify priority areas for intervention.
- **Address Barriers to Scaling in Resource-Constrained Contexts:** Despite the strong case for integrated practices, several barriers hinder their large-scale adoption in resource-constrained regions. These include high initial costs, lack of access to credit and technical support, fragmented input and service delivery systems, and limited farmer awareness. Addressing these challenges requires a combination of targeted public investment, blended financing models, robust extension support, and decentralized service provision. Strengthening rural institutions such as FPOs and encouraging local entrepreneurship through public-private models will be essential to improve last-mile delivery and ensure inclusive scaling.
- **Mobilize International Climate Finance:** Mobilizing international climate finance is a critical step for scaling up these interventions. India should actively develop proposals for support from the Green Climate Fund, Adaptation Fund, and other bilateral or multilateral donors. The empirical evidence generated by this study provides a robust basis for designing and implementing carbon farming pilots and larger-scale landscape restoration programs.
- **Expand Financial Access for Smallholders through Tailored Mechanisms:** To enable smallholder adoption of integrated practices, dedicated financing instruments should be established. These may include interest-free or low-interest loans provided through SHGs, FPOs, or cooperative banks, particularly for investments in biochar production or irrigation infrastructure. Government-backed credit guarantees, and blended finance schemes can de-risk private investment, while carbon markets and international climate finance platforms (e.g., Green Climate Fund) can offer performance-linked incentives for practices that enhance soil carbon. Integrating financial access with technical support and community-based service models will be key to inclusive and sustainable scaling.
- **Promote Agroecological Integration through Extension Systems:** Agroecological integration of carbon-enhancing practices must be strengthened through training and extension systems. Agricultural extension personnel should be trained in the benefits and application of integrated practice. In parallel, Farmer Producer Organizations, cooperatives, and NGOs should be engaged to promote community-level awareness and capacity-building, thereby enhancing adoption at scale.
- **Awareness Campaigns and Farmer Training:** Raising awareness and building local capacity are critical for scaling integrated practices. Targeted campaigns through mass media, farmer fairs, and digital platforms should highlight both the economic and climate benefits of practices like biochar, optimized fertilization, and precision irrigation. Simultaneously, farmer training and strengthened extension services should provide hands-on support, with FPOs and women's self-help groups acting as key channels for peer learning and community-level adoption.

6. Conclusions

This study highlights the transformative role of integrated agricultural practices—in addressing key challenges such as low productivity, soil degradation, and climate variability in semi-arid regions like Maharashtra. The findings consistently demonstrated that integrated practices outperformed conventional farming systems across all studied cropping systems. For instance, the maize-sorghum system achieved a significant increase in maize yields by 852 kg/ha under integrated practices compared to conventional management. Similarly, the soybean-pigeonpea intercrop system benefitted greatly, with soybean yields increasing by 180 kg/ha and pigeonpea yields improving by 18 %. These results validate the role of biochar in enhancing soil water retention and nutrient availability, while critical irrigation and optimized fertilizer management contribute to sustainable yield improvements.

In addition to productivity gains, integrated practices have shown substantial benefits in SOC sequestration. For example, in the maize-sorghum system, biochar application increased SOC levels by 1.63 % and integrated practices by 1.59 % in Ahmednagar over a period of 28 years, a marked improvement over the negligible changes under conventional methods. These findings echo global research, such as the work by Rumpel et al. [14], which emphasizes the long-term carbon sequestration potential of biochar and its role in improving soil resilience.

The economic analysis further supports the viability of these practices, with higher benefit-cost ratios observed across all systems. The cotton-fallow system, for instance, recorded a doubling of cotton yields and a benefit-cost ratios ranging from 6 to 11 under integrated management. These results confirm that adopting such practices is not only environmentally beneficial but also economically rewarding, making them feasible for smallholder farmers in resource-constrained regions.

Given these promising outcomes, the next steps involve scaling up the adoption of integrated practices. Governments must prioritize policies that incentivize the use of biochar and precision irrigation technologies. Introducing financial mechanisms, such as carbon credit schemes, could provide additional income for farmers while promoting sustainable farming practices. Furthermore, community-level infrastructure investments in water harvesting systems and biochar production units would reduce costs and improve accessibility.

Research and development should continue to play a pivotal role, focusing on adapting these practices to diverse local conditions. Long-term monitoring and evaluation systems need to be established to measure the sustained impacts of integrated practices on productivity, SOC dynamics, and economic viability. These efforts will ensure that the benefits observed in this study can be scaled effectively and equitably across regions. By integrating these actions into agricultural development plans, policymakers and stakeholders can foster a transition to resilient farming systems that address both productivity and environmental sustainability, contributing significantly to global food security and climate change mitigation goals.

CRediT authorship contribution statement

Anupama GV: Writing – original draft, Formal analysis. **Abhishek Das:** Writing – review & editing. **Thomas Falk:** Funding acquisition. **Mequanint Melesse:** Project administration. **Girish Chander:** Project administration. **Cuba Perumal:** Methodology. **Abbhishek Kumar:** Validation. **Ajay Singh:** Investigation. **Roja Mandapati:** Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Appendix: Table: A1

Results of t-tests comparing yields of management practices against conventional system.

Cropping System	Management Practice	Crop	Yield
Cotton-Fallow	Biochar	Cotton	< Conventional
	Fertilizer	Cotton	> Conventional
	Irrigation	Cotton	> Conventional
	Combination	Cotton	> Conventional
	Tillage	Cotton	> Conventional
Maize-Chickpea	Biochar	Maize	> Conventional
		Chickpea	> Conventional
	Fertilizer	Maize	> Conventional
		Chickpea	> Conventional
	Irrigation	Maize	> Conventional
		Chickpea	> Conventional
	Combination	Maize	> Conventional
		Chickpea	> Conventional
	Tillage	Maize	> Conventional
		Chickpea	> Conventional
Maize-Sorghum	Biochar	Maize	> Conventional (Not Significant)
		Sorghum	> Conventional
	Fertilizer	Maize	> Conventional
		Sorghum	> Conventional
	Irrigation	Maize	> Conventional
		Sorghum	> Conventional
	Combination	Maize	> Conventional
		Sorghum	> Conventional
	Tillage	Maize	> Conventional (Not Significant)
		Sorghum	> Conventional
Soybean-Chickpea	Biochar	Soybean	> Conventional
		Chickpea	> Conventional
	Fertilizer	Soybean	> Conventional
		Chickpea	< Conventional
	Irrigation	Soybean	> Conventional
		Chickpea	< Conventional
	Combination	Soybean	> Conventional
		Chickpea	> Conventional
	Tillage	Soybean	> Conventional
		Chickpea	< Conventional
Soybean-Pigeonpea Intercrop	Biochar	Soybean	> Conventional
		Pigeonpea	> Conventional
	Fertilizer	Soybean	< Conventional
		Pigeonpea	> Conventional
	Irrigation	Soybean	> Conventional
		Pigeonpea	> Conventional
	Combination	Soybean	> Conventional
		Pigeonpea	> Conventional
	Tillage	Soybean	< Conventional (Not Significant)
		Pigeonpea	> Conventional (Not Significant)

Data availability

Data will be made available on request.

References

[1] G. Chataut, B. Bhatta, D. Joshi, K. Subedi, K. Kafle, Greenhouse gases emission from agricultural soil: a review, J. Agric. Food Res. 11 (2023) 100533.

[2] R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, D.J Dokken, Land Use, Land-Use Change, and Forestry: A Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2000.

[3] H. Pathak, Impact, adaptation, and mitigation of climate change in Indian agriculture, Environ. Monit. Assess. 195 (1) (2023) 52.

[4] R. Lal, Soil carbon sequestration impacts on global climate change and food security, Science 1979 304 (5677) (2004) 1623–1627, https://doi.org/10.1126/science.1097396.

[5] P. Alexander, M.D.A. Rounsevell, C. Dislich, J.R. Dodson, K. Engström, D. Moran, Drivers for global agricultural land use change: the nexus of diet, population, yield, and bioenergy, Glob. Environ. Change 35 (2015) 138–147, https://doi.org/10.1016/j.gloenvcha.2015.08.011.

[6] B. Minasny, A.B. McBratney, D. Arrouays, A. Chabbi, D.J. Field, P.M. Kopittke, C. Rumpel, Soil carbon sequestration: much more than a climate solution, Environ. Sci. Technol. 57 (48) (2023) 19094–19098.

[7] C.I.D. Rodrigues, L.M. Brito, L.J. Nunes, Soil carbon sequestration in the context of climate change mitigation: a review, Soil. Syst. 7 (3) (2023) 64.

[8] K. Paustian, J. Lehmann, S. Ogle, D. Reay, G.P. Robertson, P. Smith, Climate-smart soils, Nature 532 (7597) (2016) 49–57.

[9] S. Kuyah, T. Muoni, J. Bayala, P. Chopin, A.S. Dahlin, K. Hughes, I. Öborn, Grain legumes and dryland cereals contribute to carbon sequestration in the drylands of Africa and South Asia, Agric. Ecosyst. Environ. 355 (2023) 108583.

[10] R.S. Meena, S. Kumar, S. Sheoran, M.K. Jhariya, R. Bhatt, G.S. Yadav, R. Lal, Soil organic carbon restoration in India: programs, policies, and thrust areas. Soil Organic Matter and Feeding the Future, CRC Press, 2021, pp. 305–338.

[11] C. Poeplau, A. Don, Carbon sequestration in agricultural soils via cultivation of cover crops–a meta-analysis, Agric. Ecosyst. Environ. 200 (2015) 33–41.

[12] H. Blanco-Canqui, Cover crops and carbon sequestration: lessons from US studies, Soil Sci. Soc. Am. J. 86 (3) (2022) 501–519.

[13] FAO, Soil Organic Carbon: The Hidden Potential, Food and Agriculture Organization of the United Nations, Rome, Italy, 2017. http://www.fao.org/3/I9183EN/i9183en.pdf.

[14] C. Rumpel, F. Amiraslani, C. Chenu, M. Garcia Cardenas, M. Kaonga, L.S. Koutika, E. Wollenberg, The 4p1000 initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy, Ambio 49 (2000) 350–360.

[15] D.J. Pannell, Public benefits, private benefits, and policy mechanism choice for land-use change for environmental benefits, Land. Econ. 84 (2) (2008) 225–240, https://doi.org/10.3368/le.84.2.225.

[16] D.P. Akinyi, S. Karanja Ng'ang'a, M. Ngigi, M. Mathenge, E. Girvetz, Cost-benefit analysis of prioritized climate-smart agricultural practices among smallholder farmers: evidence from selected value chains across sub-Saharan Africa, Heliyon. 8 (4) (2022).

[17] A.T. Belafoutis, D.L. Antille, M.R.C. Cordeiro, S. Fountas, Precision agriculture in Brazil: a social network analysis of expert and farmer perceptions, Precis. Agric. 18 (2017) 833–861, https://doi.org/10.1007/s11119-017-9516-1.

[18] R.K. Gupta, D.L.N. Rao, Y.V. Singh, S. Bhan, Soil organic matter dynamics under intensive cropping systems of India, Soil. Use Manage 8 (2) (1992) 84–89, https://doi.org/10.1111/j.1475-2743.1992.tb00791.x.

[19] C. Srinivasarao, S. Kundu, B.S. Yashavanth, S. Rakesh, K.N. Akbari, G.S. Sutaria, B. Venkateswarlu, Influence of 16 years of fertilization and manuring on carbon sequestration and agronomic productivity of groundnut in vertisol of semi-arid tropics of Western India, Carbon. Manage 12 (1) (2021) 13–24.

[20] J.P. Aryal, T.B. Sapkota, R. Khurana, A. Khatri-Chhetri, D.B. Rahut, M.L. Jat, C. limate change and agriculture in South Asia: adaptation options in smallholder production systems, Environ. Dev. Sustain. 22 (6) (2020) 5045–5075.

[21] R. Lal, Soil organic matter content and crop yield, J. Soil. Water. Conserv. 75 (2) (2020) 27A–32A.

[22] P.K. Aggarwal, A. Jarvis, B.M. Campbell, R.B. Zougmoré, A. Khatri-Chhetri, S. J. Vermeulen, B.T. Yen, T.he climate-smart village approach, Ecol. Soc. 23 (1) (2018).

[23] Government of India (GOI), Department of agriculture and farmers welfare, https://soilhealth.dac.gov.in/, 2020 [accessed 10 February 2020].

[24] Government of Maharashtra, Department of Agriculture, https://krishi.maharashtra.gov.in, 2020 [accessed 18 January 2020].

[25] L. Poggio, L.M. de Sousa, N.H. Batjes, G.B.M. Heuvelink, B. Kempen, E. Riberio, D. Rossiter, SoilGrids 2.0: producing quality-assessed soil information for the globe, Soil (2020) 1–37.

[26] Government of India (GOI), Directorate of economics and statistics, https://www.data.gov.in/ministrydepartment/Directorate%20of%20Economics%20and%20Statistics%20, 2020 (DES), [accessed 25 February 2020].

[27] Government of India (GOI), Department of Fertilizers, https://fert.nic.in/urea, 2020 [accessed 7 January 2020].

[28] Food and Agriculture Organization (FAO), Website accessed, https://www.fao.org/3/x5328e/x5328e08.htm, 5 March 2020. Website accessed.

[29] J. Lehmann, S. Joseph (Eds.), Biochar for Environmental Management: Science, Technology and Implementation, Taylor & Francis, 2024.

[30] F.E. Jalal, Y. Xu, B. Jamhiri, S.A. Memon, On the recent trends in expansive soil stabilization using calcium-based stabilizer materials (CSMs): a comprehensive review, Adv. Mater. Sci. Eng. (1) (2020) 1510969.

[31] G. Tóth, T. Hermann, M.R. da Silva, L. Montanarella, Monitoring soil for sustainable development and land degradation neutrality, Environ. Monit. Assess. 190 (2018) 1–4.

[32] E. Haas, M. Carozzi, R.S. Massad, K. Butterbach-Bahl, C. Scheer, Long term impact of residue management on soil organic carbon stocks and nitrous oxide emissions from European croplands, Sci. Total Environ. 836 (2022) 154932, https://doi.org/10.1016/j.scitotenv.2022.154932.

[33] R.T. Conant, K. Paustian, E.T. Elliott, Grassland management and conversion into grassland: effects on soil carbon, Ecol. Appl. 11 (2) (2001) 343–355.

[34] P.R. Grace, J. Antle, P.K. Aggarwal, S. Ogle, K. Paustian, B. Basso, Soil carbon sequestration and associated economic costs for farming systems of the Indo-Gangetic Plain: a meta-analysis, Agric. Ecosyst. Environ. 146 (1) (2012) 137–146.

[35] P. Smith, Soils and climate change, Curr. Opin. Environ. Sustain. 4 (5) (2012) 539–544.

[36] S.H. Chien, L.I Prochnow, A.H. Cantarella, Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts, Adv. Agron. 102 (2009) 267–322.

[37] A.Z. Dragicevic, J.C. Pereau, Comparing climate pledges and eco-taxation in a networked agricultural supply chain organisation, Eur. Rev. Agric. Econ. 51 (2) (2024) 354–398.