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# Accounting of carbon sequestration and tradeoff under various climatic scenarios in alternative agricultural system: a comprehensive framework toward carbon neutrality

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**Introduction:** The increase in atmospheric $CO_2$ concentration, which mainly is attributed to fossil-fuel combustion and deforestation, is often suggested as one of the prime causative factors toward accelerated global warming. This commends for sequestration of atmospheric carbon under terrestrial systems to partially offset fossil-fuel emissions. Concerning the same, agricultural sector presents an extensive opportunity, especially for countries such as India where over 55% of the population is engaged in the agriculture sector.

**Methods:** Sequestering atmospheric carbon in agriculture requires the adoption of climate-resilient alternative agriculture practices without compromising food security. The deliberated study highlights the options of alteration in current conventional farming practices and its economic evaluation for sequestrating carbon under two Climate Change (CC) scenarios, *viz.*, RCP 4.5 and 8.5, over three temporal scales, i.e., 2020, 2030, and 2050. Considering the current land-use pattern and existing growth rate in land-use shifting, three land-use policies, namely, Business as Usual (BaU), Optimistic, and Pessimistic scenario, integrated with CC scenarios were contemplated. Six possible futuristic scenarios were generated for the assessment of carbon sequestration and its valuation following the Integrated Valuation of Ecosystem Services and Tradeoff (InVEST) model.

**Results:** The results suggested that across the studied region adopting an optimistic policy over BaU and pessimistic scenario, carbon can sequestrate an additional 0.64 to 1.46 Mt. (2.35 to 5.36 million ton $CO_2$e) having an economic value of 193.4 to 504.8 million USD.

**Results:** Moreover, the outcomes of the study are advocated for the policy of carbon credit in the agriculture sector, which shall contribute toward meeting various nationally determined contributions (NDCs) and sustainable development goals (SDGs) as well.

KEYWORDS

**alternative agricultural system, carbon sequestration, climate change & land-use scenarios, zero-emission, NDCs, SDGs**

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## 1 Introduction

Challenges toward achieving Sustainable Development Goals (SDGs) in the global agricultural production system arise from the detrimental impacts of climate change (CC), land degradation, low energy efficiency, and adverse environmental outcomes. Designing and developing sustainable alternate agriculture food production systems that may be capable of ensuring household-level food security with a minimal environmental impact is indeed urgent. In the Indian sub-continent, it is crucial to maintain equilibrium in the food-energy tradeoff while preserving the ecosystem basis and reducing greenhouse gas (GHG) emissions to achieve livelihoods that are sustainable and complement the environment.

Global warming nowadays already has affected ecosystems, biodiversity, and agriculture (IPCC, 2018), creating impediments to achieving the SDGs. Reducing emissions from land-use change will be vital for global efforts to combat CC (Noble and Scholes, 2000). As a result, alterations in the management of land-use have multifaceted consequences not only on the state of the soil but also on the services provided by ecosystems (Admasu et al., 2023). The role of the soil health in maintaining ecological functionality and balance underscores its significance in the context of ecosystem services (Doran and Zeiss, 2000). Conventional farming practices such as over-tilling the soil, imbalance of chemical fertilization, and residue removal are harmful to agricultural soils and contribute to land degradation on a global scale (Bai et al., 2008; Hussain et al., 2021). Carbon (C) sequestration potential is crucial in knowing what proportions of the GHGs are captured through various crops under different cropping systems. As such terrestrial carbon sequestration is a key toward modulation of the CC impacts (Daily et al., 2011; Ali et al., 2023). Autret et al. (2019) stated that alternate agriculture systems such as Organic Farming (OF) and Agroforestry (AgF) have a greater potential toward sequestrating atmospheric carbon than conventional farming systems. The OF plays a significant role in sequestrating carbon through the utilization of benign inputs and improved soil health. Farmyard manure, applied in organic farming, has an average carbon sequestration potential of $0.292 \pm 0.132$ Mg C ha$^{-1}$ y$^{-1}$ (Freibauer et al., 2018; Bolinder et al., 2020). Organic solid manure application of 5 to 10 Mg ha$^{-1}$ y$^{-1}$ in temperate climates resulted in a C-sequestration rate of 0.160 Mg C ha$^{-1}$ y$^{-1}$ (Don et al., 2018). Sesbania/legume green manuring in organic farming has the potential to sequester 3.72 Mg C ha$^{-1}$ year$^{-1}$ (Ansari et al., 2022). Similarly, the residue recycling/retention in the cereal-legume cropping system significantly improved soil carbon by sequestrating up to 8.95 Mg C ha$^{-1}$ year$^{-1}$ of carbon (Ansari et al., 2022). Therefore, the organic production systems are validated as a better CC mitigation option than the conventional as they improve the regulating and supporting ecosystem services both above and below ground. Similarly, AgF also is a key support to mitigate the wood-timber demand, helping in reducing the pressure on natural forests. The additional benefits of sequestering atmospheric carbon include the reduction of various diseases in humans as increased concentrations of GHGs, especially $CO_2$, cause numerous health-related ailments, such as high blood pressure, dizziness, and asphyxia (Jose, 2009).

The management of trees in AgF has the potential to mitigate GHG emissions. Promoting the woodcarving industry facilitates long-term locking-up of carbon in carved wood, and new sequestration through intensified tree growing is a potential avenue toward carbon neutrality. An AgF system is a diverse group that includes all forms of trees growing in agroecosystems. Trees in AgF systems are an important resource providing products and services to society. AgF practices have the potential to store carbon and remove atmospheric carbon dioxide through enhanced growth of trees and shrubs. The Cacao agroforests in humid parts of west and central Africa hold up to 62% of carbon stocks found in primary forests (Duguma et al., 2001). Rizvi et al. (2020) concluded that the potential of $CO_2$ sequestration in poplar trees on the boundary is 99.2 Mg $CO_2$ equivalent, with an economic value of USD 1778 Mg$^{-1}$ $CO_2$ equivalent for 7 years of rotation, respectively. It has been demonstrated to be a promising mechanism of C-sequestration in India (Singh et al., 2000). The C-sequestration in Indian agroforests varies from 19.56 Mg C ha$^{-1}$ year$^{-1}$ in the North Indian state of Uttar Pradesh (Singh et al., 2000) to a carbon pool of 23.46–47.36 Mg C ha$^{-1}$ year$^{-1}$ in tree-bearing arid agroecosystems of Rajasthan. Another study in Indo-Gangetic plains in India concluded that poplar and eucalyptus have the potential to sequester carbon stock of 212.7 Mg C ha$^{-1}$ and 237.2 Mg C ha$^{-1}$, respectively. A similar study by Chauhan et al. (2015) inferred that block plantations of poplar with intercrops were projected to have a C-sequestration capacity of 9.24 Mg ha$^{-1}$ year$^{-1}$, whereas boundary plantation systems absorbed carbon at a rate of 5.54 Mg ha$^{-1}$ year$^{-1}$. Singh et al. (2020) calculated that Wheat (*Triticum assstivum*) and Seesham (*Dalbergia sissoo*)-based Agri-silviculture systems in Uttar Pradesh have the potential of carbon sequestration up to 76.62 Mg ha$^{-1}$ with good management practice. Jain and Ansari (2013) in their study in Madhya Pradesh found that a Teak (*Tectona grandis*)-based AgF system can sequester carbon ranging from 2.53 to 4.06 Mg ha$^{-1}$ year$^{-1}$.

C-sequestration through the adoption of nature-positive agriculture practices created new avenues for carbon farming. The endorsement of these environment-complementing services by farmers and other landowners could provide a source of carbon credits which may be sold to GHG emitters toward attaining carbon neutrality. This shall provide an additional source of income to the farmers. The debate regarding C-sequestration and emissions associated with changes in agricultural practices has continued because data on the carbon inputs to agriculture are relatively uncertain and the inputs are variable across time, place, and crop type (Izaurralde et al., 2000; Schlesinger, 2000). However, a systematic framework for accounting of C-sequestration potentialities in terms of the quantity and its subsequent economic valuation under futuristic different CC scenarios in alternate cropping system mode with the inclusion of cereals (rice, wheat, etc.), commercial crops (sugarcane), millets (pearl millet), and tree (poplar/ sheesham) is relatively scarce. Considering the foregoing accompaniments, the deliberated study hypothesized that an alternate cropping system has greater C-sequestration potential to mitigate the CC impacts under varied climatic scenarios (RCP 4.5 & RCP 8.5) with minimal effect on food security for years 2030 and 2050. The contemplated study provides a comprehensive framework to study the carbon sequestration potential opportunities for different land-use and farming practices across the state of Uttar Pradesh in the Indian subcontinent. Moreover, the study

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Abbreviations: +, Gain; –, Loss; GOI, Government of India; INR, Indian Rupee; LiFE, Lifestyle for Environment; LULC, Land Use and Land Cover; MOEFCC, Ministry of Environment, Forests, and Climate Change; M, Million; RCP, Representative Concentration Pathways; USD, US Dollar.

cross-cuts the decrees of various national [Nationally Determined Contributions (NDCs)] and international initiatives (United Nations SDGs), such as NDC 1 (Mission LiFE), NDC 2 (adopt a climate-friendly and cleaner path), NDC 3 (to reduce emission intensity), NDC 5 (to create an additional carbon sink), NDC 6 (to better adapt to climate change by enhancing investments in development programs), and NDC 8 (to build capacities, create domestic framework, and international architecture for quick diffusion of cutting edge climate technology) and SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 15 (life on land). Additionally, the study finds itself in direct alignment with the recently launched Green Credit Program (GCP) of MOEFCC, GOI (MOEFCC, 2023).

## 2 Materials and methods

### 2.1 Geographical setup and land-use of the study area

Uttar Pradesh is the most populous and fourth largest state in India with a population of 199.8 million (Census 2011), accounting for ~16.5% of the total population of the country. The state encompasses a geographical extent of 240,928 sq. km and holds a share of 7.33% of the total geographical area of the country. Climate-wise, it is categorized under the tropical monsoon type, with three predominant seasons, namely, winter (November to February), summer (March to June), and southwest monsoon (July to October). Though retreating monsoon also exists, it has very sparse effects. Similarly, some mild showers can be observed in winter but are primarily due to Western Disturbances. Typically, the air temperature varies from 0°C to 46°C, while the annual average precipitation fluctuates between 1700 mm in the hilly region near the Uttarakhand-Uttar Pradesh boundary to 840 mm in the western region.[1] Economy-wise, the state is the third largest economy in the country with the gross domestic product (GDP) of the state for the year 2022–2023 being INR 20.48 trillion (USD 260 billion). With the agricultural sector being the major occupation of the residing populace, the state is also a major contributor to the national food grain stock producing 56 million tons of food grain in 2020, which equates to ~20% of the country's total production. The western portion of the state holds the largest share of 49.6% in agriculture and allied sectors, while the Bundelkhand region has the least (5.5%), respectively. Within the state Aligarh, Bulandshahr, Meerut, Hamirpur, and Mirzapur districts were selected for the study (Figure 1). The districts such as Aligarh, Bulandshahr, and Meerut fall in the western region with sugarcane–ratoon–wheat as the dominant cropping system in Bulandshahr and Meerut, while pearl millet-wheat is the principal cropping system in Aligarh, respectively. This is chiefly due to the ease of accessing water for irrigation via canals and soil types. Additionally, the existence of a large number of sugar mills in the region is an added advantage to the farmers. For Hamirpur, rice-wheat is the dominant cropping system. It nests in the Bundelkhand region which is often considered as one of the most underdeveloped and largely poverty-stricken regions of the state. These parcels are mostly dependent on rainfall for agriculture. The Mirzapur district is nestled in the eastern part of Uttar Pradesh in the Vindhyan zone with rice-wheat as a major cropping system.

### 2.2 Data source and computation

The LULC data with a spatial resolution of 1 km were extracted from the Data Centre for Resources and Environmental Sciences of the Chinese Academy of Sciences (Chen et al., 2022). Carbon stock data in various pools for the forest were acquired from the IPCC Tier-1 Global Biomass Carbon Map for the Year 2000 provided by CDIAC-Carbon Dioxide Information Analysis Center[2] at 0.0089 decimal degrees (~1 km × 1 km) spatial resolution. However, carbon stock for different crops was calculated in different pools (above, below, soil, and dead) based on various methods, and secondary data were acquired from peer-reviewed and widely accepted research paper journals, databases, and published reports. For the computation of C-stock in above and below the ground, dead matter was also employed from different data sources (Mekonnen and Bashir, 1997; Lal, 2004; Zhang et al., 2009; Newaj et al., 2012; Dhyani et al., 2013, 2019; Dwivedi et al., 2014; ICAR-CAFRI, 2014; Madhav et al., 2017; Mauri et al., 2017; ICAR-CAFRI, 2018; Rao et al., 2018; Toochi, 2018; Bhardwaj et al., 2019; Rakesh et al., 2019; Dhyani et al., 2020; Calderan-Rodrigues et al., 2021; ICAR-IIFSR, 2021; He et al., 2022; Panwar et al., 2022). The input data for the adapted methodologies for the estimation of C-stock in the four major pools was cumulated from the farmer's field surveys. Furthermore, the data in different pools of cropland, *viz.*, organic, inorganic, and agroforestry systems, which was site-specific, were calculated from the information obtained following the primary data collection procedures. Additionally, published peer-reviewed research papers and journals were also utilized for filling minor data discontinuities. The predominant cropping systems that were considered in the contemplated study are shown in Table 1.

### 2.3 Software: integrated valuation of ecosystem services (InVEST) tool

The study used the carbon storage and sequestration model of the Integrated Valuation of Ecosystem Services Tool (InVEST) for predicting C-sequestration. The model uses maps of land-use along with carbon stocks in four pools, namely, aboveground biomass, belowground biomass, soil, and dead organic matter, to estimate the amount of carbon currently stored in a landscape or the amount of carbon sequestered over time. Optionally, the market or social value of sequestered carbon, its annual rate of change, and a discount rate are also used to estimate the value of this ecosystem service.

The InVEST models are spatially explicit using maps as information sources and producing results in biophysical terms or economic terms. InVEST quantifies the ecosystem services and,

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[1] https://nri.up.gov.in/en/page/weather

[2] http://cdiac.ornl.gov/

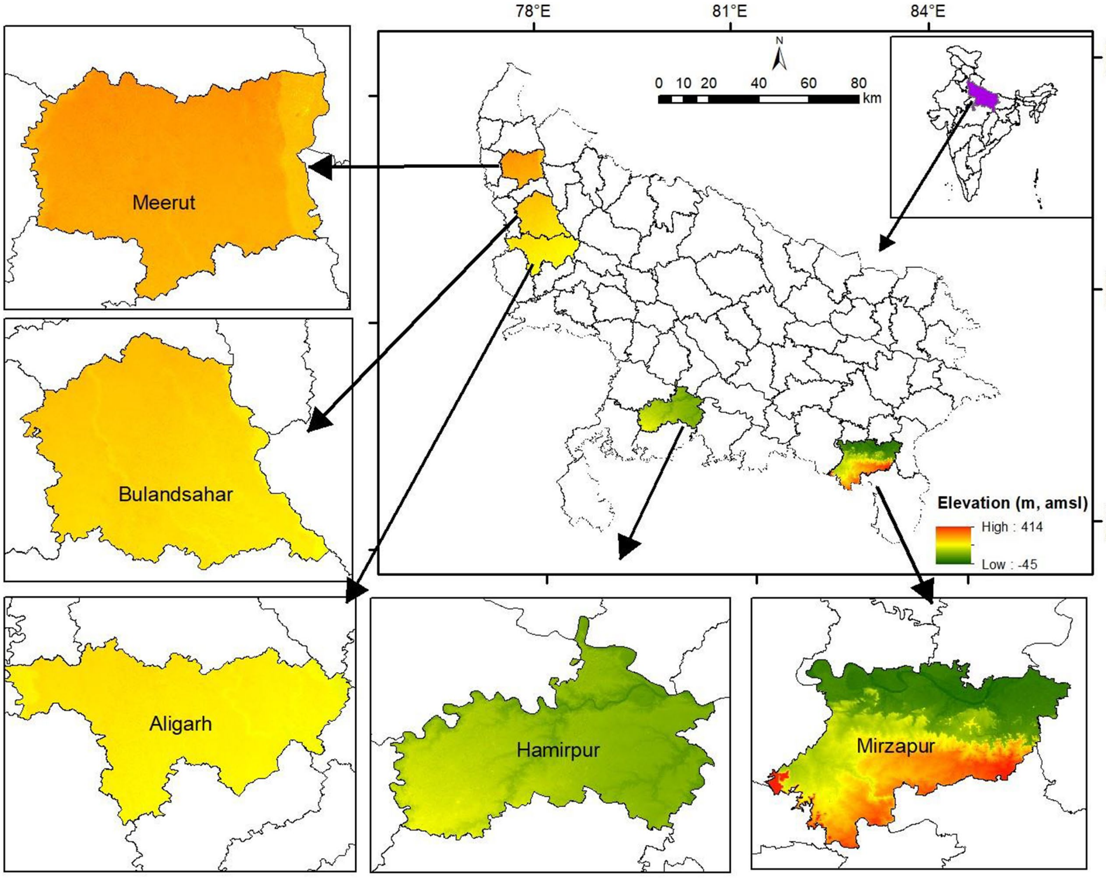

FIGURE 1
Target districts for the study.

TABLE 1 Predominant cropping system and agroforestry trees studied for the target districts.

| Location | Geographical area (*000 ha) | Predominant cropping system and cultivated area | | |
|---|---|---|---|---|
| | | Cropping system | Net cultivated area (*000 ha) | Dominant trees under agroforestry |
| Meerut | 259.0 | S-R-W: Sugarcane (*Saccharum officinarum*)-Ratoon-Wheat (*Triticum aestivum*) | 196.3 | *Populus alba L.* (Poplar) |
| Bulandshahr | 435.3 | S-R-W: Sugarcane (*Saccharum officinarum*)-Ratoon-Wheat (*Triticum aestivum*) | 299.1 | *Populus alba L.* (Poplar) |
| Aligarh | 365.0 | P-W: Pearl millet (*Pennisetum glaucum*)-Wheat (*Triticum aestivum*) | 305.1 | *Dalbergia sissoo* (Sheesham) |
| Hamirpur | 412.2 | R-W: Rice (*Oryza sativa*)-Wheat (*Triticum aestivum*) | 287.5 | *Populus alba/ Dalbergia sissoo* |
| Mirzapur | 452.1 | R-W: Rice (*Oryza sativa*)-Wheat (*Triticum aestivum*) | 211.0 | *Populus alba/ Dalbergia sissoo* |

thereby, values the ecosystem services that are provided on the current landscape. The carbon model calculates the carbon stored in all land-use/cover in the target geographic parcel. InVEST requires area-wide information on land-use/land cover, evapotranspiration, precipitation, and topography. These relevant data were acquired from the FSI (2019), based on the literature review and other open sources.

Based on the availability of input information, InVEST modeling was used for bio-physical estimation of carbon storage. The InVEST modeling process and outputs were then refined in stakeholder state and national-level stakeholder workshop with The Economics of Ecosystem and Biodiversity (TEEB), United National Environmental Program (UNEP), and external experts.

The InVEST scenario generator model was utilized to simulate potential future land use scenarios. This proximity-based model generates contrasting maps of land use change by converting habitats into different spatial configurations. Users specify which habitats can undergo conversion and their intended outcomes, as well as the desired spatial patterns based on their proximity to the edge of a focal habitat. This process allows for the development of diverse land use change patterns, such as the encroachment of pasture into forests, expansion of agriculture from existing crop areas, and forest fragmentation. The resulting land use maps serve as inputs for the InVEST models which were focused on ecosystem services. By allowing users to designate focal and converted habitats, this proximity-based scenario generator creates different conversion patterns. Consequently, the model has the potential to explore different scenarios of land use change and their impacts on biodiversity and ecosystem services, along with deliberating on how these relationships may vary based on different assumptions over the land use changes.

TABLE 2 Description of different LULC policies under two CC scenarios (RCP 4.5 and RCP 8.5).

| | |
|---|---|
| Scenario 1 (S1): BAU + RCP 4.5<br>Organic Farming: Expansion of organic farming @ 10% per year<br>Agroforestry: 10% of the cropped land<br>RCP 4.5: Medium GHG Emissions Scenario<br>Temporal scale: 2020, 2030, and 2050 | Scenario 2 (S2): BAU + RCP 8.5<br>Organic Farming: Expansion of organic farming @ 10% per year<br>Agroforestry: 10% of the cropped land<br>RCP8.5: High GHG Emissions Scenario<br>Temporal scale: 2020, 2030, and 2050 |
| Scenario 3 (S3): Optimistic Policy + RCP 4.5<br>Organic Farming: Expansion of organic farming @15% growth rate/year<br>Agroforestry: 33% of the cropped land<br>RCP4.5: Medium GHG Emissions Scenario<br>Temporal scale: 2020, 2030, and 2050 | Scenario 4 (S4): Optimistic Policy + RCP 8.5<br>Organic Farming: Expansion of organic farming @15% growth rate/year<br>Agroforestry: 33% of the cropped land<br>RCP 8.5: High GHG Emissions Scenario<br>Temporal scale: 2020, 2030, and 2050 |
| Scenario 5 (S5): Pessimistic Policy + RCP 4.5<br>Organic Farming: Reduction of area under organic farming @ 5% *per annum*<br>Agroforestry: no increase/no decrease – no change in area under agroforestry<br>RCP 4.5: Medium GHG Emissions Scenario<br>Temporal scale: 2020, 2030, and 2050 | Scenario 6 (S6): Pessimistic Policy + RCP 8 0.5<br>Organic Farming: Reduction of area under organic farming @ 5%<br>Agroforestry: no change in area under agroforestry<br>RCP 8.5: High GHG Emissions Scenario<br>Temporal scale: 2020, 2030 and 2050 |

## 2.4 Scenario setting for LULC and climate change in CMIP6

The Ministry of Agriculture and Farmers Welfare, GOI, had prepared a roadmap to promote environmental-friendly and sustainable OF in the state and other regions of the country in 2016–2017. OF is supposed to mitigate CC impacts, control GHG emissions, improve water management/conservation, and strengthen the soil-food quality. In addition to OF, it is also supposed that AgF has significant potential to abate CC impacts via the protection and stabilization of ecosystems, meeting the raw material requirement of the wood/pulp industries and reducing pressure on existing forests (MOA, 2014). Additionally, AgF can provide employment to a sizable population in production ventures, industrial avenues, and via the establishment of institutions toward mainstreaming agroforestry. ECR (2018) estimates showed that approximately 65% of the country's timber requirement is met from the trees grown on farms. In recent years, OF as a cultivation process has gained considerable momentum across the country. GOI has a target to promote OF all over the country through schemes that provide subsidies, on-farm participatory demonstrations, capacity building, and resources to farmers. Alone Uttar Pradesh has experienced an increase of 49.88% in the total land acreages under OF certification (cultivated + wild) from 2015 to 2016 (106292.39 ha) to 2020–2021 (159307.73 ha), with a total cultivated area of 67442.61 ha. Across the country, 10.17 Mha of land parcels are under the OF certification[3], placing the country in the fourth position globally in terms of organic certified area (Willer et al., 2022). However, the gross area under AgF in the country in 2018 was 28.427 Mha, which accounts for 8.65% of the total geographical area (Arunachalam et al., 2022). These states are relatively low even though AgF holds potential in increasing the overall green cover of the country, thus not only contributing toward biodiversity conservation but also in emanating other ecosystem services. Considering the aforementioned under the presented study, three agricultural farming policy scenarios—business as usual (BaU), optimistic, and pessimistic—were developed and integrated with two climate change (CC) scenarios, namely, RCP 4.5 and RCP 8.5. These scenarios reflect medium and high greenhouse gas (GHG) emission levels, respectively. The RCP 4.5 is an intermediate scenario, in which the emissions peak approximately 2040, and $CO_2$ concentrations start declining approximately 2045 to nearly half of 2050 levels by 2,100. It is often characterized as the most probable scenario as it takes into account the exhaustible attributes of fossil fuels (Höök et al., 2010). On the other hand, in RCP 8.5, emissions continue to increase throughout the 21st century and are often considered as the worst-case CC scenario. This led to the development of six scenarios (Table 2).

## 2.5 Modeling carbon storage and economic evaluation

InVEST models are spatially explicit, using maps as information sources and producing maps as outputs. InVEST return results in either biophysical terms (e.g., Mg of carbon sequestered) or economic terms (e.g., net present value of the sequestered carbon). The valuation model estimates the economic accounting of sequestration as a function of the amount of carbon sequestered, the monetary value of each unit of carbon, a monetary discount rate, and the change in the value of carbon sequestration over time. Thus, valuation can be done in the carbon model if there is a possibility of a future

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[3] https://apeda.gov.in/

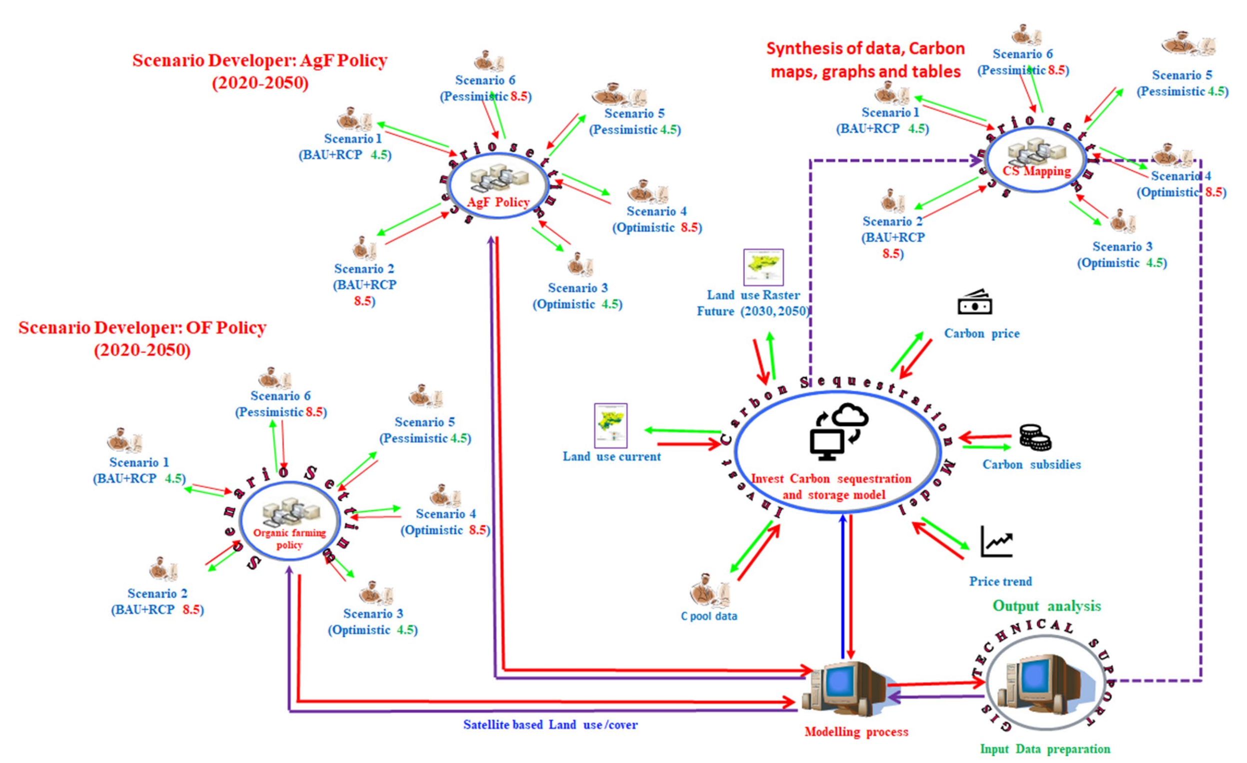

FIGURE 2
Methodology of the deliberated study.

scenario. Valuation of Carbon sequestration was applied in terms of the CO2 equivalent unit and valued as per Equation (1). The model was used to carry out simulations of carbon storage and distribution. A .csv file, containing carbon densities of aboveground, belowground, soil organic, and dead organic biomass for different LULC types, was entered into the model for estimation of C-sequestration potentialities. The mathematical principle followed by the model is as follows:

$$\text{Value}_{\text{seq}_x} = V\frac{s_x}{q-p}\sum_{t=0}^{q-p-1}\frac{1}{\left(1+\frac{r}{100}\right)^t\left(1+\frac{c}{100}\right)^t} \quad (1)$$

where,

V is the price per metric ton of carbon;

$s_x$ is the amount of carbon, in metric tons, sequestered in a parcel;

q is the future year;

p is the current year;

r is the yearly market discount rate for the carbon price (%);

c is the yearly rate of change in the price of carbon (%).

For economic evaluation of sequestered carbon, the price per ton of $CO_2$ equivalent is considered as 86 USD.[4] The annual market discount rate in the price of carbon, which reflects society's preference for immediate benefits over future benefits was taken as 0.36% from pricing greenhouse gas emissions: key findings for India at https://oe.cd/pricing-greenhouse-gas-emissions. The discount rate is not available for India; therefore, it was set to zero in the model. Figure 2 shows the methodology adapted for the presented study.

# 3 Results

## 3.1 C-stock under the current scenario

Total C-stock for the current year (2020) was estimated at 9.04, 12.42, 9.45, 55.5, and 10.24 Mt. for the Meerut, Bulandshahr, Aligarh, Mirzapur, and Hamirpur districts, respectively. These are considered as the baseline for the measurement of C-sequestration potential (CSP) for the target years, i.e., 2030 and 2050, under the dynamics of land use and future climatic projections.

## 3.2 CSP under BaU with RCP 4.5 and RCP 8.5 (S1 and S2)

For Meerut and Bulandshahr, where S-R-W (Sugarcane-Ratoon-Wheat) is the dominant cropping system, the CSP estimates w.r.t. the base year (2020) following the S1 scenario suggests a decrease of 0.01 Mt. (−3.7 MUSD) and an increase of 0.003 Mt. (+1.03 MUSD) for the

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[4] https://www.ghgplatform-india.org/

year 2030. Similarly, for 2050, an accession of 0.04 Mt., corresponding to an increment of 10.5 MUSD, and 0.11 Mt. leading to an additive return of 5.2 MUSD are contemplated. Under the S2 scenario, the CSP was estimated to decrease by 0.04 Mt. (−12.2 MUSD) and 0.01 Mt. (+3.5 MUSD), while for 2050, it is predicted to increase by 0.0005 Mt. (gain of 0.14 MUSD) and 0.05 Mt. (gain of 2.4 MUSD) for Meerut and Bulandshahr, respectively. In the context of Aligarh with P-W, as the dominant cropping system following S1 an increase in CSP of 0.012 Mt. (+3.62 MUSD) and 0.18 Mt. (+52.6 MUSD) for 2030 and 2050 is observed, while for S2, an increment of 0.002 Mt. (+0.51 MUSD) and 0.16 Mt. (+48.6 MUSD) is contemplated. For R-W-dominated districts, S1 suggests a reduction of 5.4 Mt. and 8.1 Mt. in CSP for Mirzapur and a decrease of 0.63 Mt. and 0.57 Mt. for Hamirpur in 2030 and 2050, respectively. These correspond to a decline of 1675.5 MUSD & 2420.7 MUSD in Mirzapur and 195.6 MUSD & 170.5 MUSD in Hamirpur for the years 2030 and 2050, respectively. Under S2, again a cutback in CSP of 15.5 Mt. (−4814.9 MUSD) and 24.8 Mt. (−7422.8 MUSD) was estimated for Mirzapur, while for Hamirpur, an abatement of 0.86 Mt. (−276.6 MUSD) and 0.68 Mt. (−205.2 MUSD) was noted, respectively. District-wise details for S1 & S2 scenarios are presented in Table 3. For S-R-W and P-W cropping systems, an increase in the total C-stock for the year 2050 under both S1 and S2 scenarios is observed, while the contrary is observed for the R-W complaint systems.

## 3.3 CSP under optimistic scenario with RCP 4.5 and RCP 8.5 (S3 and S4)

Under the optimistic scenario, it is supposed that OF is expanding 15% per year and AgF is expanding 33% of the cropped land. It is replicated with RCP 4.5 & 8.5 for the development of two scenarios S3 and S4, respectively. In the context of S-R-W and P-W dominated districts, for the target years (2030 and 2050), an increase in CSP is observed for both S3 and S4 scenarios w.r.t. the base year (2020). Though converse is observed for an R-W-dominated system such as Mirzapur, a percent decline in CSP of 8.65 and 26.67% in 2030 and 12.61 and 42.34% in 2050 were predicted for S3 and S4 scenarios. For Hamirpur, the CSP is expected to increase by 0.01 Mt. and 0.67 Mt. in 2030 and 2050 under S3, while the same appears to recess off by 0.22 Mt. in 2030 and increase by 0.49 Mt. in 2050, respectively. In terms of economic valuation, for 2030, Aligarh with its P-W cropping system offers the highest return on CSP (+184.9 MUSD) under the S3, while Mirzapur has the greatest descent (−4599.7 MUSD) under the S4 scenario. Similarly, for 2050, again Aligarh (+373.5 MUSD) has the largest increase in the valuation of CSP, while the greatest recession is observed for Mirzapur (−7050.2 MUSD) both being under the S4 scenario. The particulars of C-stock and CSP for 2020, 2030, and 2050 for each of the target districts under S3 & S4 are shown in Table 3.

## 3.4 CSP under pessimistic scenario with RCP 4.5 and RCP 8.5 (S5 and S6)

The pessimistic policy follows a shrinkage rate of 5% in OF, while the acreages under AgF remains unchanged. Following replication with RCP 4.5 and 8.5, two scenarios, namely, S5 and S6, were developed. For the year 2030, all the target districts exhibited a declining CSP under both the scenarios. Under S5 and S6, the greatest recession is observed for Mirzapur with a reduction in CSP valuation of 1740.2 MUSD in S5 and 4890.3 MUSD in S6, while the least are noted for Bulandshahr with a decrement of 18.7 MUSD (S5) and 23.1 MUSD (S6), respectively. Similar pattern is observed for the year 2050 with Mirzapur, again showcasing the largest abatement in the CSP (−8.40 Mt. in S5 and − 25.2 Mt. in S6) and its subsequent valuation (−2527.5 MUSD in S5 and −7,555 MUSD in S6), while Bulandshahr demonstrating the least reduction of 0.08 Mt. (−3.7 MUSD) in S5 and 0.13 Mt. in S6 (−6.4 MUSD). Table 3 represents the CSP and its valuation for the target districts. District-wise total C-stock for current year and 2030 and 2050 under various policy landscapes is shown in Figure 3.

## 3.5 Farming practice trade-off and carbon sequestration under organic and agroforestry systems

The study emphasizes proposing sustainable farming practices that can sequester more carbon while addressing various NDCs and SDGs in relation to hunger, good health and well-being, and climate action. Additionally, the deliberated work is an attempt toward the estimation of the overall C-stock of key agricultural systems while switching among different farming practices such as OF, AgF, and conventional farming. Considering the same, C-stock of agricultural land in the target district was projected under BaU, optimistic, and pessimistic policies following two climatic scenarios, i.e., RCP 4.5 and RCP 8.5, to evaluate the impact of switching from conventional farming into the OF and AgF.

Following the weighted average method (based on the net cropped area), a single value for the percentage increase/ decrease of the C-stock from the target districts is assimilated. It is observed that for 2030 under RCP 4.5, the optimistic policy projects an average increase of 9.63% in the C-stock as compared with 3 and 1.62% from BaU and pessimistic policy, while these figures change to 12.49, 5.67, and 4.17% for optimistic, BaU, and pessimistic policy following RCP 8.5 climate scenario. For the year 2050 under RCP 4.5, the optimistic policy suggests an average accretion of 16.65% over the 2020 C-stock, while for the BaU and pessimistic policies, the increments are relatively low, i.e., 5.22 and 2.20%, respectively. Similarly, under RCP 8.5, optimistic offers an accession of 21.75% over the 2020 C-stock, while the same is 9.64 and 6.34% on considering BaU and pessimistic policies. Hence, policy-wise the optimistic class, with the S3 and S4 scenario, offers the best case in regard to the accretion of C-stock in comparison to BaU and pessimistic ones.

For the year 2030, the agricultural land of Meerut, which is dominated by S-R-W, has a C-stock of 8.84 Mt. This value is expected to increase by 4.86% in the S3 and 4.19% in the S4 scenario. Similarly, Bulandshahr, where S-R-W is a prevailing cropping system, has a current C-stock of 12.32 Mt., which is contemplated to increase by 4.79 and 3.81% in the S3 and S4 scenarios, respectively. For Aligarh, with most of its agricultural land area commanded under the P-W system, the 2020 C-stock is

TABLE 3 C-stock, CSP estimate and valuation under BaU, Optimistic and Pessimistic at RCP 4.5 and 8.5 climatic scenario.

| Location | Scenario | Total C-stock (Mt) | Total C-stock (Mt) | Change (2020–2030) | | Total C stock (Mt) | Change (2020–2050) | |
|---|---|---|---|---|---|---|---|---|
| | | | | CSP (Mt) | Value (MUSD) | 2050 | CSP (Mt) | Value (MUSD) |
| BaU (S3 & S4) | | | | | | | | |
| Meerut | S1 | 9.04 | 9.03 | −0.010 | −3.7 | 9.08 | 0.040 | 10.50 |
| | S2 | | 9.00 | −0.040 | −12.2 | 9.04 | 0.001 | −0.14 |
| Bulandshahr | S1 | 12.42 | 12.42 | 0.003 | 1.03 | 12.53 | 0.110 | 5.20 |
| | S2 | | 12.41 | −0.010 | −3.5 | 12.47 | 0.050 | 2.40 |
| Aligarh | S1 | 9.45 | 9.46 | 0.012 | 3.62 | 9.62 | 0.180 | 52.60 |
| | S2 | | 9.45 | 0.002 | 0.51 | 9.61 | 0.160 | 48.60 |
| Mirzapur | S1 | 55.5 | 50.1 | −5.400 | −1675.5 | 47.4 | −8.100 | −2420.7 |
| | S2 | | 40 | −15.500 | −4814.9 | 30.7 | −24.800 | −7422.8 |
| Hamirpur | S1 | 10.24 | 9.61 | −0.630 | −195.6 | 9.67 | −0.570 | −170.5 |
| | S2 | | 9.38 | −0.860 | −276.6 | 9.55 | −0.680 | −205.2 |
| Optimistic Policy (S3 & S4) | | | | | | | | |
| Meerut | S3 | 9.04 | 9.43 | 0.390 | 120.2 | 9.72 | 0.680 | 203.9 |
| | S4 | | 9.40 | 0.360 | 111.1 | 9.68 | 0.640 | 191.1 |
| Bulandshahr | S3 | 12.42 | 12.98 | 0.560 | 174.5 | 13.43 | 1.010 | 302.8 |
| | S4 | | 12.97 | 0.550 | 169.5 | 13.36 | 0.940 | 283.1 |
| Aligarh | S3 | 9.45 | 10.04 | 0.600 | 184.9 | 10.72 | 1.270 | 380 |
| | S4 | | 10.03 | 0.580 | 181.2 | 10.69 | 1.250 | 373.5 |
| Mirzapur | S3 | 55.5 | 50.70 | −4.800 | −1483.9 | 48.4 | −7.000 | −2108.3 |
| | S4 | | 40.70 | −14.800 | −4599.7 | 31.9 | −23.500 | −7050.2 |
| Hamirpur | S3 | 10.24 | 10.25 | 0.010 | 4.1 | 10.85 | 0.610 | 182.7 |
| | S4 | | 10.02 | −0.220 | −67.6 | 10.73 | 0.490 | 148.2 |
| Pessimistic policy (S5 & S6) | | | | | | | | |
| Meerut | S5 | 9.04 | 8.97 | −0.070 | −21.8 | 8.94 | −0.100 | −31.1 |
| | S6 | | 8.95 | −0.100 | −29.7 | 8.9 | −0.140 | −41.4 |
| Bulandshahr | S5 | 12.42 | 12.36 | −0.060 | −18.7 | 12.34 | −0.080 | −3.7 |
| | S6 | | 12.35 | −0.070 | −23.1 | 12.29 | −0.130 | −6.4 |
| Aligarh | S5 | 9.45 | 9.38 | −0.070 | 21.2 | 9.37 | −0.080 | −23.4 |
| | S6 | | 9.37 | −0.080 | 23.6 | 9.35 | −0.090 | −28.3 |
| Mirzapur | S5 | 55.5 | 49.9 | −5.600 | −1740.2 | 47 | −8.400 | −2527.5 |
| | S6 | | 39.7 | −15.700 | −4890.3 | 30.3 | −25.200 | −7,555 |
| Hamirpur | S5 | 10.24 | 9.51 | −0.730 | −225.2 | 9.39 | −0.850 | −254.1 |
| | S6 | | 9.28 | −0.960 | −297.6 | 9.27 | −0.960 | −289.1 |

9.29 Mt., which is predicted to inflate by 7.10 and 6.67% under the S3 and S4 scenarios. The Mirzapur and Hamirpur districts, with most of their agricultural land being regulated under the dominated R-W, have a current C-stock of 6.25 Mt. and 9.19 Mt., respectively. The S3 scenario offers an increase of 8.71 and 20.64%, while the S4 offers an increment of 8.92 and 35.20% in the total C-stock, respectively. For the year 2050 following the S3 and S4 scenarios, the agricultural land of Meerut and Bulandshahr offers an increment of 7.81 and 6.79% and 8.52 and 7.47% over the 2020 C-stock, respectively. Similarly, for Aligarh, an increase of 14.10 and 13.24% over the present C-stock is estimated. In the case of Mirzapur and Hamirpur, an accession of 16.54 and 33.12% in the current C-stock is expected under the S3, while accrual of 16.65 and 58.72% in the C-stock is envisioned under the S4 scenario, respectively. Table 4 illustrates the C-stock under the different cropping systems for the considered policies in the target districts.

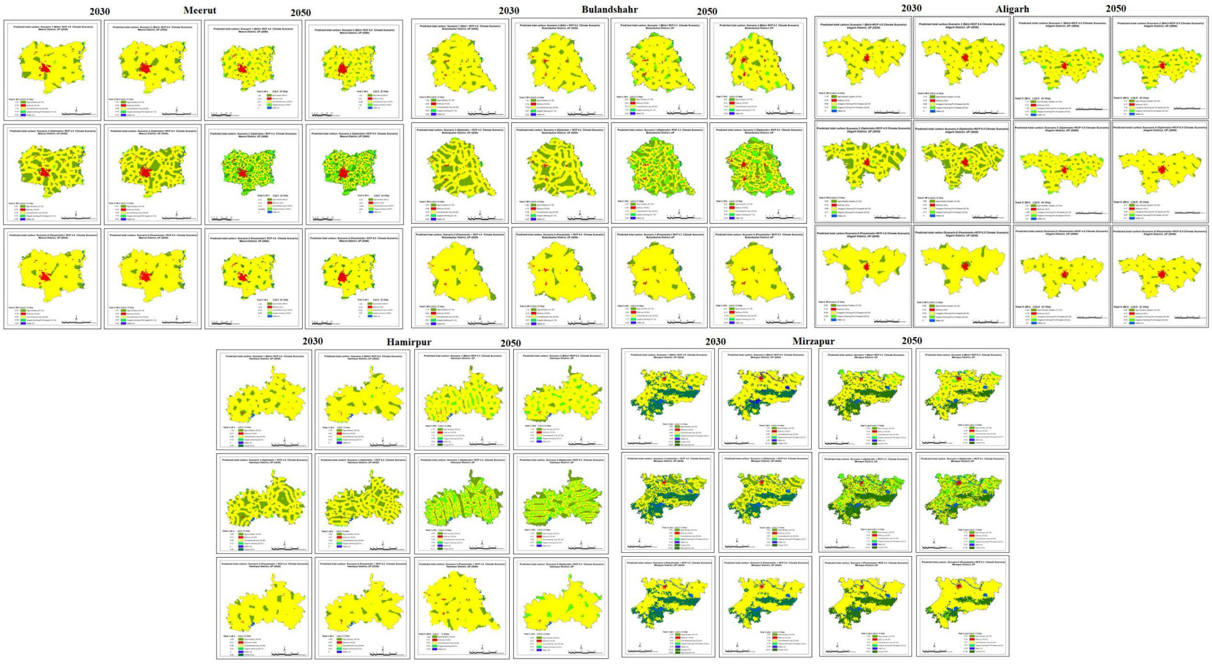

FIGURE 3
District-wise C-stock for current (2020) and 2030 and 2050 for the target districts.

**TABLE 4** C-stock of agricultural land of the target districts for different farming policies and CC scenarios.

| District | Current scenario 2020 | BAU | | Optimistic | | Pessimistic | |
|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | S4 | S5 | S6 |
| | | 2030 C-stock (Mt) | | | | | |
| Meerut | 8.84 | 8.87 | 8.81 | 9.27 | 9.21 | 8.81 | 8.76 |
| Bulandshahr | 12.32 | 12.36 | 12.24 | 12.91 | 12.79 | 12.29 | 12.17 |
| Aligarh | 9.29 | 9.36 | 9.33 | 9.95 | 9.91 | 9.28 | 9.25 |
| Mirzapur | 6.25 | 6.91 | 7.76 | 7.54 | 8.45 | 6.70 | 7.51 |
| Hamirpur | 9.19 | 9.35 | 9.37 | 9.99 | 10.01 | 9.25 | 9.27 |
| | | 2050 C-stock (Mt) | | | | | |
| Meerut | 8.84 | 8.88 | 8.80 | 9.53 | 9.44 | 8.74 | 8.66 |
| Bulandshahr | 12.32 | 12.47 | 12.35 | 13.37 | 13.24 | 12.29 | 12.17 |
| Aligarh | 9.29 | 9.51 | 9.44 | 10.60 | 10.52 | 9.25 | 9.18 |
| Mirzapur | 6.25 | 7.28 | 8.67 | 8.32 | 9.92 | 6.92 | 8.23 |
| Hamirpur | 9.19 | 9.53 | 9.54 | 10.71 | 10.72 | 9.25 | 9.26 |

## 3.6 Impact of farming practice trade-off on carbon economics

Transition from conventional farming to OF & AgF following optimistic guidelines (S3 and S4) in agricultural lands sequesters additional carbon in contrast to BaU (S1 & S2) and the pessimistic (S5 & S6) policies (section 3.5). This corresponds to the additional dividends evaluating to millions of USD. For the year 2030, agricultural acreages of Meerut, following S3 and S4, can produce an appended revenue of 7.81 MUSD and 6.79 MUSD against the 2020 stock, while for Bulandshahr, it transits to 8.82 MUSD and 7.47 MUSD, respectively. Similarly, agri-parcels of Aligarh, Mirzapur, and Hamirpur can conceive a supplemental credit of 14.10 and 13.24 MUSD, 3.81 and 16.54 and 16.65 MUSD, and 33.12 and 58.72 MUSD under the S3 and S4 scenarios, respectively. Similarly, for 2050, these values transit to an additional 1.49 and 1.30 MUSD for Meerut, 1.62 and 1.42 MUSD for Bulandshahr, 1.76 and 1.66 MUSD for Aligarh, 7.21 and 12.79 MUSD for Hamirpur, and 4.56 and 4.59 MUSD for Mirzapur under the S3 and S4 scenarios w.r.t. 2020 valuation, respectively. Figure 4 illustrates the economic valuation of C-stock for agricultural lands of the target districts under the BaU, optimistic, and pessimistic policies.

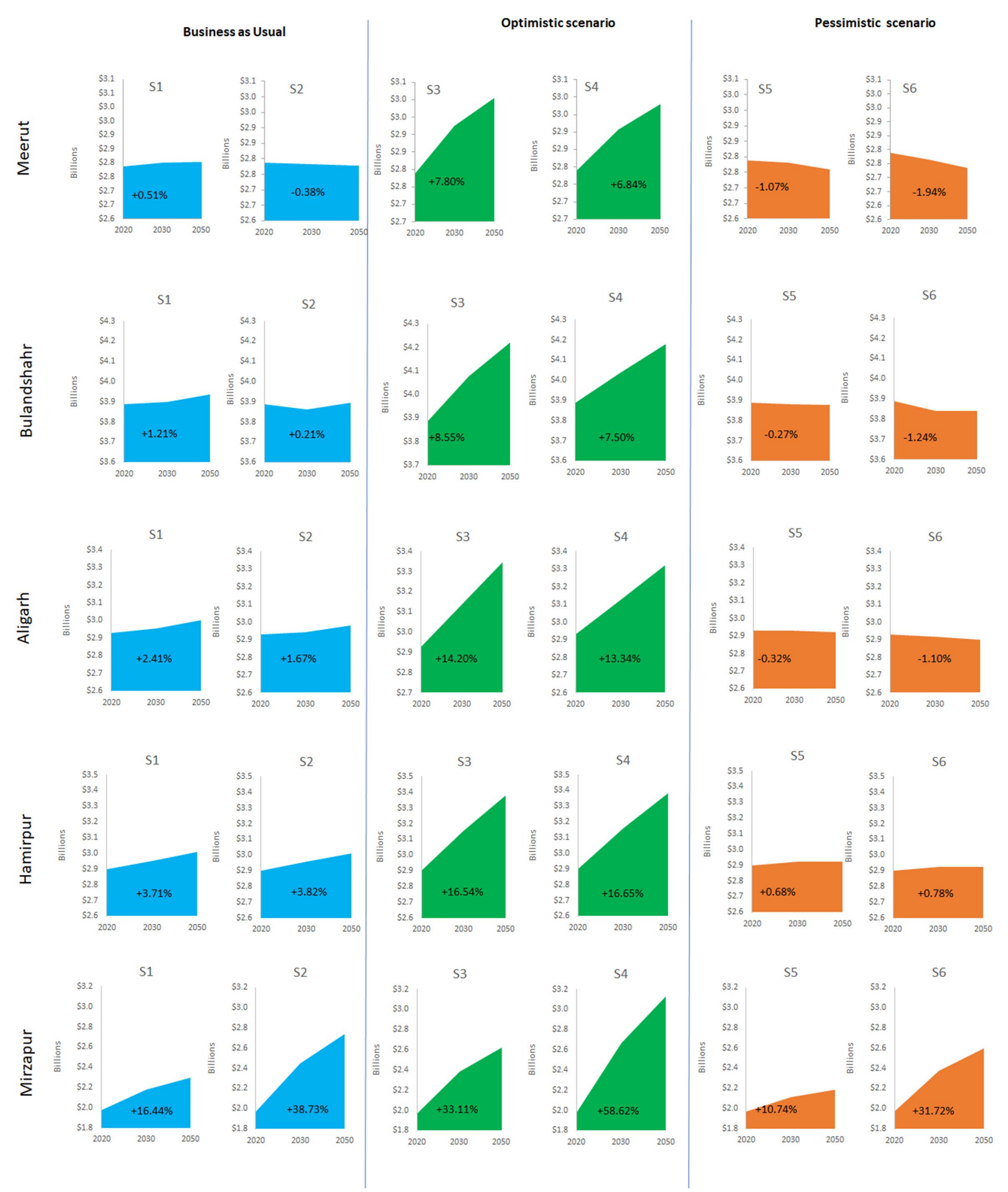

FIGURE 4
Economics of sequestered carbon by agricultural land under different land-use and CC scenarios.

# 4 Discussion

The data of C-stock (see Supplementary Figures), as computed for the alternate agriculture systems, across the target districts suggest that OF and AgF have 26.88 and 26.07% greater C-stock per unit ha of land as compared with conventional farming. These relatively large differences in the crop C-stock across different alternate agriculture systems suggest that geographic targeting and prioritizing OF and AgF over conventional farming would significantly improve the potential of crop C-sequestration following the optimistic pathway (S3 and S4) in the agricultural landscape (as evidenced from section 3.3 to 3.7). Another important finding of the study suggests that Mirzapur has a relatively high economic valuation than the other target districts. This is due to its greater current C-stock (55.5 Mt) owing to a larger land acreage under the forest cover (~1,561 sq. km). However, one must recognize that other districts might be getting co-benefits, such as employment, agri-income, food security, of similar or greater valuation than Mirzapur, attributing to their larger geographic parcels under the agri-cover.

Moreover, the results from the study can be extrapolated toward providing a generalized understanding of the additional C-stock and its valuation that can be sequestered following the best policy recommendations for transitioning farming practices. In India, the total area under sugarcane (sugarcane only/sugarcane–ratoon/sugarcane–ratoon–wheat/sugarcane–rice) as the first predominant cropping system is approximately 2.15 M ha. Similarly, land parcels dictated by pearl millets (pearl millet–wheat/other crops) and rice (rice–wheat/other crops) crops contribute to 2.93 M ha and 26.93 M ha, respectively (Singh et al., 2023). Following optimistic policy, i.e., transitioning from conventional to OF and AgF, sugarcane, pearl millets, and rice-predominated acreages hold the potential to sequester 13.29 Mt. and 14.77 Mt., 25.26 Mt. and 19.78 Mt., and 230.25 Mt. and 221.09 Mt. of additional carbon, respectively. These cumulatively can account for an additional revenue of 84.84 billion USD in OF and 80.69 billion USD in AgF alone in carbon farming.

## 4.1 Importance for national and international initiatives targeting C-stocks

Global CC and its impacts, which primarily are accelerated by the overabundance of GHGs in the atmosphere of the earth's (Allen et al., 2018; Lynas et al., 2021), are possibly the most challenging contention being faced by the world today (IPCC, 2019). The adoption of certain farming practices in the sector of agriculture can capture the excess $CO_2$ that is released into the atmosphere from various anthropogenic activities in terrestrial systems. These hold the potential to address the drivers of change in the context of global CC impacts. The agricultural landscapes may act as a carbon sink via sequestering and binding GHGs, such as $CO_2$ as plant biomass. The induction of policy prescriptions that abide toward carbon sequestration in agri-landscapes may further support GHG mitigation efforts.

In the present study, the agricultural land parcels across the target districts opting for optimistic policy (S3 and S4) have the potential to create an additional carbon sink with C/CS potential of 0.40 to 0.64 Mt. and 0.40 to 0.69 Mt. in 2030 over BaU policy (S1 and S2). For the same acreages, the C/CS potential adjusts to 0.46 to 0.84 Mt. and 0.45 to 0.94 Mt. by 2030 if one opts for the optimistic over pessimistic (S5 and S6) policies, respectively. These carbon potential indices change to 0.65 to 1.18 Mt. over BaU and 0.78 to 1.68 Mt. over pessimistic, respectively, when projected for the year 2050. The same can be implicated for other districts of Uttar Pradesh, where the adoption of apt framing practices can account for carbon sequestration worth millions of dollars.

Following the updates of its NDCs at the COP26 in November 2021, India wishes to create a carbon sink of 2.5 to 3 billion tons of $CO_2$ equivalent by 2030 and envisage achieving the net-zero mark by 2070 (MOEA, 2021). The country intends to achieve the same via the promotion of energy conservation practices, accession of alternative fuels following improved use of renewables, afforestation, conservation of water, and sustainable land use and waste management. Additionally, policy briefs toward action in CC mitigation/adaptation should be promoted through the National Action Plan on CC (NAPCC). As such, the agricultural sector following the improved adoption of OF and AgF can aid in attaining these contributions. However, the issue lies majorly in driving the Producer Groups (PGs) to practice OF and AgF. Most of the PGs belong to relatively economically weaker sections and reside in rural areas with their key motivators being clear benefits, yield increase, and long-term economic profitability (Amelung et al., 2020). Hence, there is a pressing need to consider innovative mechanisms for exploring markets, developing value chains, and designing payment of ecosystem services (PES) schemes within the framework of the National Agriculture Policy. These mechanisms have the potential not only to economically empower local farming communities through revenue generation but also to contribute to global climate change mitigation efforts (Watson et al., 2000). Unmistakably, the package developments that complement global soil carbon stocks, prevent the loss of soil carbon, along with augmenting knowledge transfer policies to cater to 'win-win' solutions are a prerequisite.

One such initiative taken by MOEFCC, GOI prior to COP28 is the GCP, which aspires to expedite the efforts to comply with NDCs under UNFCCC signed during the Earth Summit-1992 and the Paris Agreement-2016 (UNFCCC, 1992; 2016). The program wishes to apply the principle of Payment for Ecosystem Services (PES). Thus, to incentivize the stakeholders, OF and AgF avenues can be explored for the renewed role in emanating the economic benefits from the Green Credits (GCs). The presented study caters to the three aspects of the GCP, namely, (i) tree-plantation-based GCs, (ii) sustainable agriculture-based GCs, and (iii) eco mark-based GCs. Additionally, the methodology adapted for the study can be purveyed as a Standard Operating Procedure (SOP) for the measurement of tree-plantation and sustainable agriculture-based GCs following minor adjustments depending on the area of interest. The advocated agri-interventions also find linkages in managing other sustainable development objectives such as enhancing food production, eliminating rural poverty, and reducing environmental degradation, on one hand, along with the prospects to imbibe immediate GHG emissions related to anthropogenic activities such as deforestation and shifting agriculture.

## 4.2 Implications of global markets and targeting funds for C-sequestration

In the past 20 years, the global market for carbon trading has inflated quite swiftly, with Europe and America emerging as the biggest and the most liquid markets (S&P Global, 2022). Increase the apportionment of emissions reduced by twice the proportion as dictated by the Europe Emissions Trading System (Liu et al., 2019; WBG, 2019). Lately, the United States Department of Agriculture (USDA) also declared to reduce the carbon footprint of agriculture in the United States (US) by 40% by 2050. Some studies suggested that the plausible demand for carbon credits in the context of agriculture alone in the US is ~190 million tons/year, with a market size of USD5.2 billion over annual timescales (Jennifer, 2022). In the US and the West, carbon farming mechanisms are dominated by sources of private and corporate origin, which typically are linked either to voluntary carbon markets/certification programs or to the farm sector/supply chain companies. Support from these private sector enterprises often holds prospects for fiscal provisioning toward carbon farming. Recently, the West has witnessed an accession in the number of these enterprises with the private actors paying for the generated carbon offsets which usually are typified under result-based payments (Cevallos et al., 2019). These enterprises in exchange for emission reductions on farm-based activities, such as livestock, sell the emission reduction certificates to business ventures and other private buyers (Cevallos et al., 2019). Farmers are then paid per ton of $CO_2$ equivalent emissions that are being reduced, along with administrative and training expenses, using the proceeds from the sale of emission reduction certificates. Sometimes, companies who wish to lessen the carbon footprint of their products provide corporate supply chain financing for carbon farming. Toward achieving the same, they provide farmers in their supply chain with a modest financial incentive to deploy action-based carbon farming, with Measurement, Reporting, and Verification (MRV) costs lower than that of the carbon market.

From the Indian perspective, the carbon farming market is less explored and, therefore, offers opportunities for the agricultural sector, especially for the farmers, which can be leveraged following the adoption of de-carbonization operations for revenue generation. However, certain bottlenecks and challenges prevail in the section. First is the absence of standardization in terms of estimation of sequestered carbon, which is attributed to its indirect nature and difficult verification, along with the determination of values of carbon credits, which currently displays a wide spectrum depending on the region Carbon Credits, Live Carbon Prices Today, exigencies for immediate addressal. This frequently has questioned the credibility of certification providers (Greenfield, 2021), often leading companies/buyers to be more dissenting in the context of purchasing the credits (Holger, 2023). Second, the criteria for assessing the quality of created credits should be well-defined. Features such as baseline measurements, additionality, leakage, permanence, co-benefits, oversight prevention, and double counting should be addressed well. Some pathways that might prove useful in this regard include (i) development of SOPs toward sequestration estimation for different geo-climatic conditions and management practices with global acceptance, (ii) creation of conscientious baseline data toward credit assessment, (iii) fixation of credit prices along with revisioning provisions, and (iv) ensuring integrity to avoid the sale of bogus credits with a robust monitoring system leading to a greater degree of transparency and accountability. The growing global population has increased food demand resulting in a carbon footprint from agricultural activities that account for 11% of global greenhouse gas emissions which impact the environment negatively. While agriculture is part of the problem, it can also become a part of the solution (MOEFCC, 2021; Sharma et al., 2021). In response, carbon markets tailored to farming and agricultural activities are emerging with increasing interest from farmers, private sectors, and governments (Zerssa et al., 2021). Cost-efficient crop-based carbon sequestration provides a relatively low cost of carbon sequestration solution by agricultural land (Rumpel et al., 2020).

## 5 Conclusion and recommendations

The global-scale agriculture sector contributes to 18% of GHG emissions (Ozlu et al., 2022). However, the same section can act as a carbon sink, sequestering the atmospheric carbon in soils and terrestrial systems following the adoption of apt farming practices and, therefore, can be an instrument for counteracting and mitigating CC impacts. The undertaken study exposits the same following endorsement of OF and AgF in various land use scenarios at varying rates, i.e., BAU, optimistic, and pessimistic, respectively, for the current situation and future projections (2030 and 2050) under two RCP scenarios (4.5 and 8.5) in the Indo-Gangetic Plains (IGP) of Uttar Pradesh, India. Additionally, the study also deliberates the valuation of sequestered carbon from the ventured circumstances. The results suggest that the optimistic scenario with OF at the growth rate of 15% *per annum* and AgF with 33% apportionment in cropped acreages offered a premium choice under both RCP 4.5 and 8.5 projections. Attaining the same shall require interventions/prescriptions in the landscape of agriculture policies at the national level for the increased adoption among the Producer Groups (PGs). This requires exploration of the market for carbon credits/offsets and incentivizing the same for wider uptake and upscale of the initiative. Unlike typical carbon sequestration projects, agricultural ventures are not plagued with the problem of 'non-additionality', i.e., they already contribute toward achieving other benefits by finding linkages with SDGs 1 (no poverty), 2 (zero hunger), and 3 (good health and well-being). Though irrefutably, there do exist several challenges and bottlenecks that are required to be addressed. Key of these include (i) standardization of procedures toward the estimation of sequestered carbon in soils and terrestrial systems with global acceptance, (ii) development of reliable baseline emissions, (iii) establishment of minimum price brackets to crop out poor quality offsets, (iv) integrity criteria, thus, ensuring the developed credit avoids or reduces $CO_2e$ emissions in actuality, and (v) development of centralized Monitoring and Evaluation System (MES) providing a higher level of transparency, accountability, and robust governance, addressing issues such as what types of deals have been made and to whom, duplicity in the selling of credits. Furthermore, firm ground rules must be established over how the incentives received from the selling of C-credits shall equitably benefit the local community and indigenous people. Moreover, other limitations such as the selection of tree species for the AgF systems that not only sequester atmospheric carbon at a higher rate but also contribute toward conserving local biodiversity also require addressal. Following curation of the above-stated peculiarities, an environment contributory, sustainable, and CC impacts extenuating carbon sequestration value-chain can be solicited.

## Data availability statement

The datasets presented in this study can be found in online repositories and manuscript. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

## Author contributions

MA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. NR: Conceptualization, Data curation, Investigation, Project administration, Supervision, Writing – review & editing. MS: Conceptualization, Data curation, Investigation, Software, Writing – review & editing. MR: Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. APr: Methodology, Writing – review & editing. RS: Data curation, Investigation, Writing – review & editing. RK: Investigation, Methodology, Writing – review & editing. HJ: Data curation, Formal analysis, Methodology, Software, Writing – review & editing. SK: Conceptualization, Investigation, Project administration, Supervision, Visualization, Writing – review & editing. APa: Investigation, Project administration, Supervision, Visualization, Writing – review & editing. MK: Data curation, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## Author Disclaimer

SK refers to Director, ICAR- Indian Institute of Farming Systems Research, Modipuram, India.

## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1371255/full#supplementary-material

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