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REVIEW ARTICLE

The role of croplands in carbon cycling: A review of net ecosystem carbon budget

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Abstract

The Net Ecosystem Carbon Budget (NECB) represents the balance of carbon entering and leaving an ecosystem, thereby determining whether the specific ecosystem is carbon source or sink. This review examines NECB on different croplands of rice, wheat, maize, sugarcane, cotton and sunflower, review highlighting its role on carbon sequestration and climate change mitigation. NECB values vary significantly, ranging from -26460 ± 4587 to 22500 kg C ha^{-1}. Rice cropland systems exhibited positive NECB values (carbon sink) between 572 and 2959 kg C ha^{-1} under biomass application, while wheat and sugarcane act as carbon sources with values of -4390 ± 105 kg C ha^{-1} and -26460 ± 4587 kg C ha^{-1}, respectively. Cotton also showed negative NECB (-4940 ± 150 kg C ha^{-1}), whereas sunflower with biochar application achieved 11570.9 ± 334.0 kg C ha^{-1}, compared with control (-19.9 ± 0.6 kg C ha^{-1}). Methodologies such as eddy covariance and static chamber techniques highlighted NECB variability due to environmental and management factors. Although maize under public-private partnership and large-scale farming recorded the highest NECB at 22500 kg C ha^{-1}, similar effective practices such as optimized irrigation, nutrient management and reduced soil disturbance can be practiced in rice cropland systems to enhance their carbon sequestration potential. Moreover, NECB varies across ecosystems and soil types, affecting whether croplands act as carbon sinks or sources. Adapting management practices to local environmental conditions is crucial for improving NECB across different crop systems and achieving sustainable agriculture and climate mitigation goals.

Keywords: climate change; croplands; greenhouse gases; net carbon budget; soil carbon

Introduction

The Net Ecosystem Carbon Budget (NECB) of cropland is essential in comprehending carbon dynamics and climate change mitigation. It comprises carbon losses from soil and plant respiration, decomposition, harvest and gains may be from photosynthesis and additions from organic amendments (1). A negative NECB of the ecosystem might be the loss of CO_2 into the atmosphere, which contributes to the climate change and positive NECB indicates a carbon sink, which adds and stores more CO_2, helping in mitigating climate change (2). Moreover, NECB improves soil health, resilience and output. Assessing and optimizing the balance between carbon inputs and outputs in cropland is the primary goal of NECB in order to promote sustainable agricultural practices and mitigate the effects of climate change (3). Agriculture accounts for approximately 12 % of global greenhouse gas (GHG) emissions, primarily from carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), making second-largest contributor after fossil fuel combustion. Agricultural soils can function as either a carbon sink or a source, depending on management practices employed. Sustainable strategies such as reducing fallow periods, incorporating cover crops and diversifying crop rotations enhance soil carbon sequestration by increasing carbon inputs and improving soil health. Croplands are extremely productive ecosystems that absorb huge amounts of CO_2 from the atmosphere during their short growing season but intensive growth season (4). Maize absorbs significantly more CO_2 throughout the growth season than the other crops like rice, wheat, maize, cotton and sugarcane and BIM-based frameworks can help in analysing embodied carbon in construction, promoting ecologically responsible practices (5). Carbon inputs, outputs and net ecosystem production vary across European agricultural sites, highlighting the impact of management on the NECB and greenhouse gas emissions (Fig. 1) (6). Furthermore, low-carbon city policies have proven beneficial in reducing carbon emission intensity through mechanisms such as industry structure optimization and technology innovation (7). The impact of grazing methods on net ecosystem exchange dynamics and carbon balance highlights the importance of management practices in carbon budgets (8). Furthermore, using rice husk ash in landfill building can help in minimizing carbon emissions and environmental impact, demonstrating the promise for eco-friendly waste management strategies (9).

The novelty of this article lies in its comprehensive assessment of NECB across multiple crops and diverse agricultural systems. Unlike previous studies that focus on a single crop or method, this work integrates data from various measurement techniques, including eddy covariance, static chambers and modeling. It uniquely compares different farming practices like mulching, irrigation and tillage under both field and climatic variations. The article provides a rare combination of maximum and minimum NECB values, offering critical benchmarks. It also addresses regional and seasonal influences on carbon flux. This wide scope helps identify carbon -efficient and climate-resilient farming strategies. In the overall, the study offers a valuable reference for sustainable agriculture and carbon management.

Methodology for NECB

The NECB methodology evaluates the balance of carbon influxes and effluxes in the ecosystems (10) with lateral export rates of Dissolved Inorganic Carbon (DIC) and Dissolved Organic Carbon (DOC) (11), as well as tracking Green House Gas (GHG) emissions and carbon balance in diverse agricultural practices are used to make this calculation (12). The NECB also included Net Ecosystem Exchange (NEE) of CO_2, volatile organic carbon loss and aquatic carbon transport (13). Researchers can simulate NECB responses to environmental stresses such salt, inundation and drought exposure using Peat Elevation Model (EvPEM) (14). The NECB methodology incorporate a variety of data sources to evaluate the carbon dynamics completely in agricultural ecosystems in understanding carbon storage, emissions and over all ecosystem health.

Implementation of modelling framework by Stella

Stella version 1.9.2 is used to create the Everglades Peat Elevation Model (EvPEM) framework (Fig. 2). Stella is a user-friendly, adaptable tool that provides rigorous simulations of framework incorporating various stocks, flows, connectors and converters (6). The model used six stocks, 11 internal and external flows to store, transfer and to quantify inflows and outflows of carbon. The required inputs for the model simulation is depicted in the Table 1. The simulation time unit is in days and a fractional Delta Time (DT) of 0.125 to run Stella. The Delta Time (DT) determines how many times the models' numerical values are computed per unit time. To simplify the daily time step, all the models' inputs were linearly downscaled from year today. In each iteration, the Stella model determines the system's inundation level by comparing the Peat Elevation (PE) and Water Level (WL) stated in the modelling framework. The WL is also linked to the option of including SLR (or rate of increase in inundation), a separate sea-level stock that is attached to the WL converter to account for sea-level change. After parameterizing the model with measured data, we simulated EvPEM for one year using treatment-specific data. For calibration, upscale the daily model-predicted PE change to the annual scale for each treatment. Using EvPEM, we identified critical marsh Net Primary Productivity (NPP) thresholds as a function of salinity. The carbon budgeting and modelling demonstrated the effects of saltwater intrusion, inundation and seasonal dry-down, reducing concerns about the fate of coastal peat wetlands after SLR (Sea-Level Rise) and freshwater restoration (11).

Global Carbon Assimilation System (GCAS), Version. 2

The Global Carbon Assimilation System, Version 2 (GCASv2) is used to estimate gridded surface carbon fluxes, mostly utilizing satellite XCO_2 retrievals (15) and Ozone and Related Chemical Tracers, Version 4 (MOZART-4) (16) is coupled to simulate 3-D atmospheric CO_2 concentrations and the Ensemble Square Root Filter (EnSRF) algorithm (17) is used to implement surface flux inversion. GCASv2 runs cyclically and in each cycle (DA window), a "two-step" computation technique to preserve quality. The prior fluxes are optimized using XCO_2 data and then the optimized fluxes are fed back into the MOZART-4 model to establish the initial condition (IC) of the window. To reduce the representative error of XCO_2, a "super observation" approach is used. This is determined by the correlation coefficient between simulated concentration ensembles at each observation point and the perturbed fluxes in current model grids, as well as their distances (11).

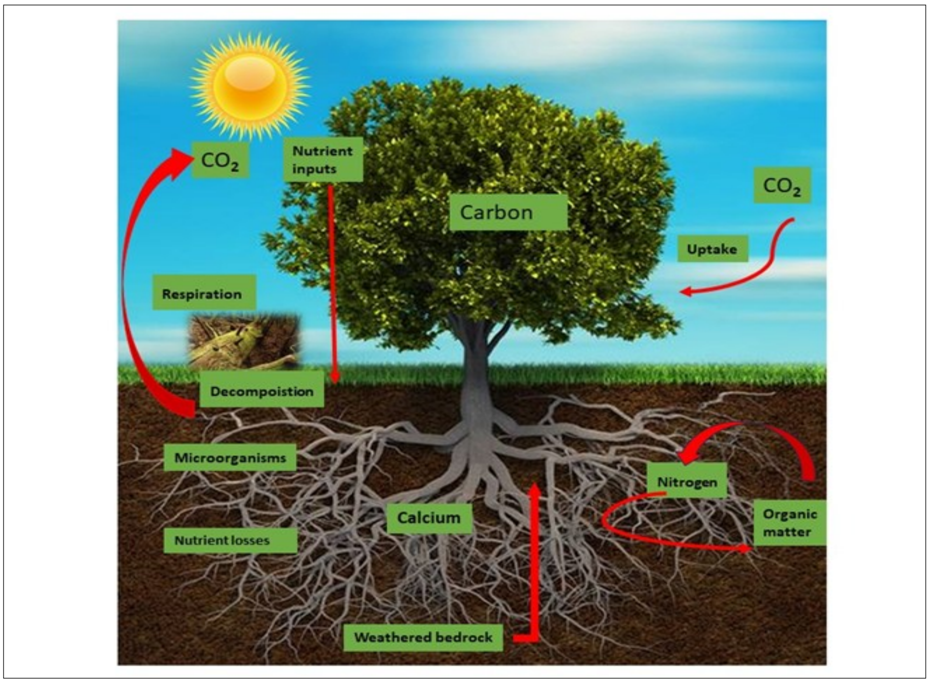

Fig. 1. Carbon cycle (6).

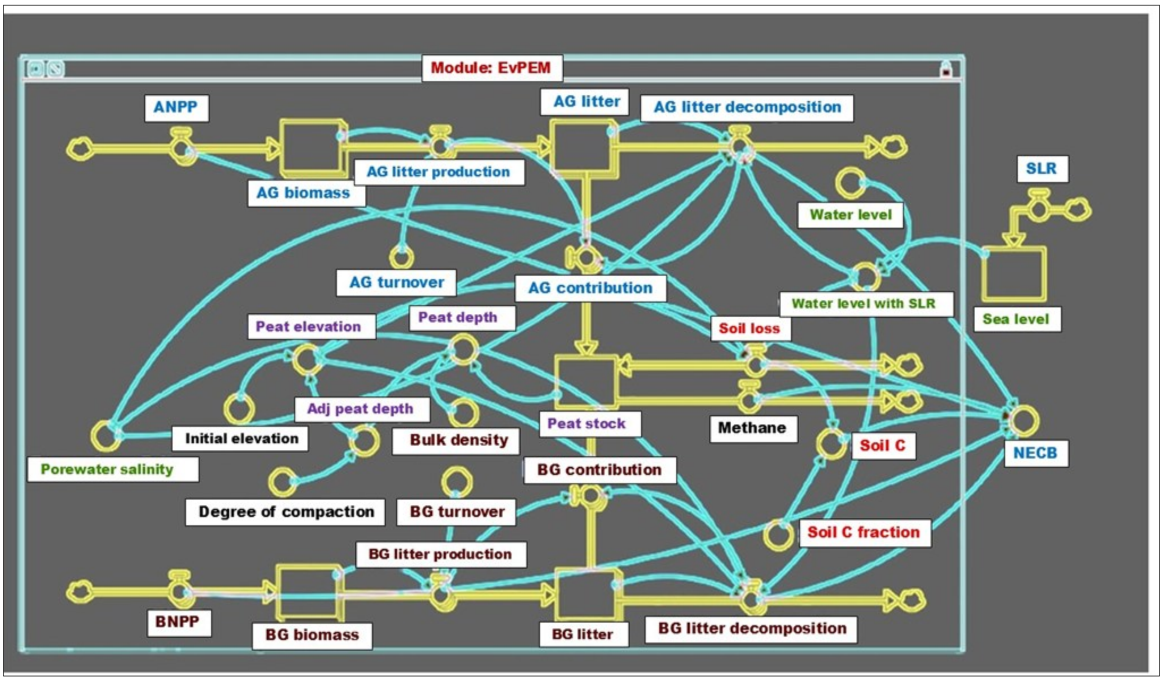

Fig. 2. Diagram of system dynamics Everglades Peat Elevation Model (EvPEM) used to simulate change in Peat Stock (PS) and Peat Elevation (PE). Adj, AG, ANPP, BG, BNPP, NECB and SLR refer to adjust, aboveground, aboveground Net Primary Productivity, belowground, belowground Net Primary Productivity, Net Ecosystem Carbon Balance and Sea-Level rise, respectively (11).

Table 1. Input variables, types of Stella building block and units required to simulate change in peat stock (MS) and elevation (PE) using EvPEM (14, 85).

Input variable	Stella building Blocks	Unit
Aboveground net primary productivity (ANPP)	Flow	gC m^{-2} day^{-1}
Belowground net primary productivity (BNPP)	Flow	gC m^{-2} day^{-1}
Methane flux (F_{CH4})	Flow	gC m^{-2} day^{-1}
Initial aboveground litter stock (LS_{AG})	Stock	gC m^{-2}
Initial belowground litter stock (LSBG0)	Stock	gC m^{-3}
Aboveground turnover rate (TRAG)	Converter	day^{-1}
Belowground turnover rate (TRBG)	Converter	day^{-1}
Initial peat elevation (PE0)	Converter	cm NAVD88
Initial peat stock	Stock	gm^{-2}
Soil bulk density (ρb)	Converter	g m^{-3}
Degree of compaction (α)	Converter	Unitless
Soil C fraction (fc)	Converter	Unitless
Porewater salinity (sal)	Converter	ppt day^{-1}
Water level (WL)	Converter	cm NAVD88 day^{-1}
Sea-lever rise (SLR)	Flow	cm day^{-1}

Energy audit and energy indices

Carbon inputs in croplands are photosynthesis and biomass production, organic matter additions (manure, compost, crop residues) and other factors influencing carbon inputs (18). Carbon outputs in croplands are respiration processes (plant, soil microorganisms, decomposers), harvest removal and biomass export, soil disturbance, tillage practices and factors influencing carbon outputs (19). Energy input under different cropping systems is estimated from the quantity of N, P_2O_5 and K_2O fertilizer used and their respective energy equivalents. Energy input through N, P_2O_5 and K_2O fertilizer is summed to estimate total energy input (E_I). The output energy is estimated from quantity of above-ground biomass produced by multiplying with their respective energy equivalents (20). The energy output (E_O) for each crop is obtained by multiplying the economic yield by its respective energy equivalents. The amount of energy produced from the above-ground biomass (grain plus straw in case of un husked rice and wheat, grain plus stalk in case of maize and seed cotton plus sticks in case of cotton) and yield of different crops were summed for estimating total energy output (E_O) (21). Different energy indices, *viz.*, energy productivity (E_P), specific energy (E_S), energy ratio or energy use efficiency (E_R) and net energy gain (NEG) for an individual crop are calculated by using the following equations.

$$\text{Specific energy } (E_s) \text{ in MJ Kg}^{-1} = \frac{\text{Total energy inputs } (E_I)}{Y_{\text{Economic + residues yield}}} \quad \text{(Eq. 1)}$$

$$E_p \text{ (Kg MJ}^{-1}) = \frac{Y_{\text{Economic + residues yield}}}{E_I} \quad \text{(Eq. 2)}$$

$$E_R = \frac{\text{Total energy output } (E_O)}{\text{Total energy inputs } (E_I)} \quad \text{(Eq. 3)}$$

$$\text{NEG (GJ ha}^{-1}) = \text{Total energy output } (E_O) - \text{Total energy inputs } (E_I) \quad \text{(Eq. 4)}$$

$$E_I \text{ (GJ ha}^{-1}) = \text{å} \, (E_N + E_{P2O5} + E_{K2O}) \quad \text{(Eq. 5)}$$

$$E_O \text{ (GJ ha}^{-1}) = \text{å} \, (E_{\text{Economic yield}} + E_{\text{Residues yield}}) \quad \text{(Eq. 6)}$$

where 'E_N', 'E_{P2O5}' and 'E_{K2O}' represent energy input (each in GJ ha^{-1}) through fertilizer N, P_2O_5 and K_2O, respectively, for rice-wheat, maize-wheat and cotton-wheat cropping system. The '$E_{\text{Economic yield}}$' and '$E_{\text{Residues yield}}$' represent the energy output (each in GJ ha^{-1}) as economic yield (grain/ seed cotton) and residues yield (straw/stalk/sticks) (each in kg ha^{-1}) under different ecosystems.

GHG emission, GWP and GHGI analysis methodology : The environmental impact of nutrient management in croplands ecosystems is assessed by estimating GHGs (Greenhouse gases) emissions, GWP (Global Warming Potential) and GHGI (Green House Gas Intensity). The fertilizer-induced GHGs (CO_2 and N_2O) emissions are estimated for each site with different cropping systems using CO_2 equivalents for N, P_2O_5 and K_2O from the literature. Therefore, the CH_4 emission from rice fields estimating GWP of a rice-wheat cropping system is based on region specific emissions of 55.7, 34.5 and 23.3 kg CH_4 ha^{-1} in continuously flooded (scenario 1), intermittently flooded with single aeration (scenario 2) and intermittently flooded with multiple aerations system (scenario 3), respectively (22). Since there is no CH_4 emission under upland cropping systems, *viz.*, maize-wheat and cotton-wheat, the GWP is calculated based on CO_2 and N_2O. The estimated CO_2 and N_2O emission were converted to CO_2 equivalent (CO_{2e}) using 100-years GWP of 1, 265 and 25 for CO_2, N_2O and CH_4, respectively.

$$\text{GWP (kg CO}_{2e}\text{ ha}^{-1}) = CO_2 + CH_4 \times 25 + N_2O \times 265 \qquad (\text{Eq. } 7)$$

The N_2O emissions from N applied through chemical fertilizer are estimated using this equation.

$$N_2O \text{ emission} = N \times EF_1 \times \frac{44}{28} \qquad (\text{Eq. } 8)$$

where N_2O emissions (kg N_2O ha^{-1}) from fertilizer N application and 'EF_1' = emission factor (0.01 for N_2O emissions from N inputs, kg N_2O-N kg^{-1} N input). Convert the mass of nitrogen (N) in nitrous oxide (N_2O) to the total mass of N_2O. Specifically, 44 is the molecular weight of N_2O (2 Nitrogen atoms at 14 each, plus 1 Oxygen atom at 16) and 28 is the atomic weight of two Nitrogen atoms (2 × 14). This conversion is necessary because emission factors often express emissions as the mass of N, while the desired unit is the mass of the entire N_2O molecule.

The GHGI is estimated from the ratio of GWP to that of the economic yield (grain in case of rice, wheat and maize and seed cotton in case of cotton) and expressed as kg CO_{2e} kg^{-1} economic yield (23, 24). Carbon Equivalent Emissions (CEE) and Carbon Efficiency Ratio (CER) are calculated by using the following equation (25).

CER = grain yield or seed cotton yield in terms of C/CEE

$$\text{CEE (Mg C ha}^{-1}) = \text{GWP} \times \frac{12}{44} \qquad (\text{Eq. } 9)$$

Convert the Global Warming Potential (GWP) from units of CO_2 equivalents (CO_2 eq.) to units of carbon (C) equivalents, specifically in megagrams per hectare (Mg C ha^{-1}). This conversion factor is derived from the molecular weight ratio of carbon (C) to carbon dioxide (CO_2). The C concentrations of 38 %, 39 %, 39 % and 40 % in the rice, wheat, maize grain and seed cotton, respectively, are used for estimating CER (26, 27).

NECB calculation : The NECB is an assessment of the carbon exchange between an ecosystem and atmosphere (28) and also considers many factors which influence the intake or release of carbon dioxide (CO_2) in the environment (29). Gross Primary Production (GPP) represents the entire quantity of carbon fixed by plants during photosynthesis and principal source of carbon into the environment. Autotrophic respiration (R_A) is the emission of CO_2 by plants during various metabolic processes, including growth, maintenance and reproduction (30). This component indicates the carbon released by the ecosystem. Heterotrophic respiration (R_H) involves the release of CO_2 by soil microbes and animals (31). Some other components are Carbon Equivalent Emission (CEE), Carbon Emission Ratio (CER), Energy Input (E_I), Energy Output (E_O), Energy Productivity (E_P), Energy Ratio (E_R), Green House Gas Intensity (GHGI), Gross Primary Production (GPP), Global Warming Potential (GWP), Net Ecosystem Exchange (NEE), Net Energy Gain (NEG), Net Ecosystem Productivity (NEP), Net Primary Production (NPP), R_A (Autotrophic respiration), R_E (Ecosystem respiration) and R_H (Soil heterotrophic respiration) (32).

$$\text{NECB} = \text{GPP} - (R_E + \text{Harvest} + CH_4) + C_{\text{Below ground biomass}} + C_{\text{Litter}} + C_{\text{Rhizodeposit}} \qquad (\text{Eq. } 10)$$

where 'GPP' is the gross primary production and is inferred from Net Primary Production (NPP) via ratio of NPP/GPP (33).Total NPP for different crops and cropping systems is estimated as a sum of NPP for different eco-systems' components, *viz.*, actual economic yield, above-ground biomass yield, below-ground biomass yield, litter and rhizodeposits (34).

$$\text{NPP} = \text{NPP}_{\textbf{Economic yield}} + \text{NPP}_{\textbf{Above ground yield}} + \text{NPP}_{\textbf{Below ground yield}} + \text{NPP}_{\textbf{Litter}} + \text{NPP}_{\textbf{Rhizodeposits}} \qquad (\text{Eq. } 11)$$

The $\text{NPP}_{\text{Economic yield}}$, $\text{NPP}_{\text{Above ground yield}}$ and $\text{NPP}_{\text{Below ground yield}}$ were estimated using equations (27).

$$\text{NPP}_{\text{Economic yield}} = \text{Economic yield} \times \text{dry matter fraction} \times C_{\text{fraction of economic yield}} \qquad (\text{Eq. } 12)$$

$$\text{NPP}_{\text{Above ground yield}} = \text{Economic yield} \times \text{dry matter fraction} \times \text{ratio of residue to economic yield} \times C_{\text{fraction of residue}} \qquad (\text{Eq. } 13)$$

$$\text{NPP}_{\text{Below ground yield}} = \text{Economic yield} \times \text{dry matter fraction} \times (1 + \text{ratio of residue to economic yield}) \times \text{ratio of roots to shoot} \times C_{\text{fraction of roots}} \qquad (\text{Eq. } 14)$$

The ecosystem respiration (R_E) of the cropland ecosystem represents the sum of autotrophic respiration (R_A) and soil heterotrophic respiration (R_H). The net ecosystem exchange (NEE) of CO_2 between the agro-ecosystem and atmosphere referred as of C lost or gained by an ecosystem and its amount estimated by using the following relationships (35, 36).

$$\text{NEE (kg C ha}^{-1}) = \text{GPP} - R_H - R_A \qquad (\text{Eq. } 15)$$

$$R_E = R_H + R_A \qquad (\text{Eq. } 16)$$

$$R_A = \text{GPP} - \text{NPP} \qquad (\text{Eq. } 17)$$

$$R_H = R_H - R_A \qquad (\text{Eq. } 18)$$

The change in soil organic carbon (ΔSOC) using the apparent average conversion rate of organic C to SOC. ΔSOC is computed from the NECB with a coefficient of 0.213.

$$\Delta\text{SOC} = 0.213 \times \text{NECB} \qquad (\text{Eq. } 19)$$

Amount of C added to SOC pool (kg C ha $^{-1}$) =

$$F \times C_{residues} + C_{root} \times F_R \quad \text{(Eq. 20)}$$

where 'F' is the proportion of above-ground biomass leaf in the soil and 'C residues' and 'C root' are the residue and root carbon, respectively. The plant roots are estimated to have a C content of 40 %. The 'F_R' represents the fraction of residue and root C transformed to SOC.

NECB of croplands

NECB of rice

Rice serves as a staple food for over half of the global population. China, the leading producer of rice, accounts for approximately 19 % of the worlds' rice cultivation area and contributes around 32 % to the global rice yield. The NECB of rice fields can fluctuate based on various factors such as irrigation methods, tillage practices and cropping systems (37). Research indicates that rice-based cropping systems can function as carbon sinks, capturing carbon from the atmosphere (38, 39). China, traditional flood irrigation methods have been increasing and replaced by water-saving irrigation techniques in recent years to enhance environmental benefits (Table 2). A two-year field study conducted from 2018 to 2019 in Northeast China evaluated the impact of three different irrigation regimes such as conventional irrigation (FN), controlled irrigation (CN) and intermittent irrigation (IN) along with two nitrogen (N) fertilization rates (110 and 165 kg N ha^{-1}) (40). And the result showed the water-saving irrigation enhanced soil aeration by managing soil moisture levels, improved soil aerobic conditions, boosted microbial activities and soil respiration, leading to the increased CO_2 production and released from the soil through roots and respiration. It was found that the mode, volume and frequency of irrigation significantly the CO_2 emissions (32). It was observed that open path eddy covariance for different stages of crop significantly influenced soil respiration, thereby reducing net ecosystem exchange (NEE) in paddy fields (41). To evaluate the role of rice-based cropping in lowland coastal ecosystems on environmental changes, studies measured energy budgets, carbon footprint (CF), CO_2 exchange and fluxes of non-CO_2 greenhouse gases (GHGs) across various conservation tillage practices within rice-rice (RR) systems. These practices included different tillage intensities namely zero tillage (ZT), reduced tillage (RT) and conventional tillage (CT) as well as treatments with residue (R) and without residue (NR). The findings indicated that conservation tillage methods in rice-based cropping systems enhanced soil organic carbon levels and for carbon sinks (42). Flooded rice fields can act as net CO_2 sinks in tropical region (43), with the ecosystem overall functioning as a carbon sink (41). These findings highlighted the crucial role of sustainable agricultural practices in managing the carbon budget of rice ecosystems (44).

Intermittent drainage of rice fields changes soil redox potential, leading to reduced CH_4 emissions, which may decrease the Net Primary Production (NPP) during rice cultivation. The NECB and net GWP were assessed under two water management regimes *viz.*, continuous flooding and intermittent drainage with four levels of biomass incorporation (0, 3, 6 and 12 Mg ha^{-1}) (37). The cultivation practices affect the sustainability of the soils' annual net carbon balance (ANCB) in cover crop-rice cropping systems on paddy soil. The Water-

Table 2. Different NECB of rice with different measurements

Implementing water-saving Irrigation (40)				**Open path Eddy covariance** (41)		
Treatment	**NPP g C m^{-2} day^{-1}**	**NECB kg C ha^{-1}**	**Net GWP kg C ha^{-1}**	**Treatment**	**Net ecosystem CO_2 exchange (NEE) μ mol m^{-2} s^{-1}**	**GPP μ mol m^{-2} s^{-1}**
FN110	4742 ±119	1255 ± 115	19377 ± 819	Vegetative stage	- 16.94 (decreasing)	19.32 (increasing)
FN165	6343 ±159	1999 ± 112	17441 ± 862	Tillering to panicle Initiation stage	- 21.16 (decreasing)	24.40 (increasing)
CN110	6552 ±213	1151 ± 134	9341 ± 1133	Reproductive stage	- 24.92 (decreasing)	29.04 (increasing)
CN165	7926 ±285	1404 ± 96	9626 ± 962	Heading to flowering stag	-26.93 (decreasing)	32.34 (increasing)
IN110	6323 ±173	1973 ± 122	7131 ± 801	Ripening stage	-18.51 (increasing)	22.91 (decreasing)
1N165	7628±211cd	2243 ± 113	6757 ± 998	Harvesting stage	-13.29 (increasing)	15.78 (decreasing)

Static chamber-gas chromatography (Conservation Tillage) (42)		
Treatment	**Net ecosystem CO_2 exchange (NEE) μ mol m^{-2} s^{-1}**	**NECB kg C ha^{-1}**
RR-ZTR	**23937.2±870.9**	1523 (37.1%)
RR-ZTNR	**22651.7±812.4**	
RR-RTR	**26765.2±946.1**	
RR-RTNR	**25313.1±908.5**	
RR-CTR	**24915.4±872.5**	
RR-CTNR	**23624.4±852.6**	

Static closed-chamber method (Two Irrigation methods) (44) **Gas sampling and analyses (Two Cropping methods)** (37)				
Treatment			**NPP**	**NECB kg C ha^{-1}**
B. Biomass application (Mg ha^{-1}, dw) (B)	**Continuous flooding (CF)**	0	5859	-275
		3	8315	1008
		6	7614	1251
		12	7317	2959
	Intermittent drainage (ID)	0	5680	-402
		3	8154	572
		6	7564	965
		12	7225	2799
Biomass application (Mg ha^{-1}, DW)	**Cover Cropping**	0	5618	- 1435
		3	5750	- 1448
		6	5841	- 1439
		12	6017	- 1402
	Rice Cropping	0	5852	- 56
		3	8584	1154
		6	7654	1273
		12	7397	2649

saving irrigation represented, the NECB values from 1151 ± 134 to 2243 ± 113 kg C ha^{-1}. This suggested that all treatments resulted in net carbon sequestration, had positive NECB values which indicated more carbon uptake than release. In Static chamber gas chromatography under conservation tillage, the NECB value was 1523 kg C ha^{-1} (37.1 %), which was lower than the water-saving irrigation treatments (37). This implies that water-saving irrigation method may be more effective for carbon sequestration. The NECB values for A. Static closed-chamber method vary widely depending on the treatment and the lowest value was -1448 kg C ha^{-1} (0 N fertilizer, cover cropping) and the highest value was 2649 kg C ha^{-1} (12 N fertilizer, rice cropping) (37) and in B. Gas sampling and analyses (Two Cropping methods) the NECB value was lowest of -402 kg C^{-1}(0 N fertilizer, intermittent irrigation) and the highest value of 2959 kg C ha^{-1} (12 N fertilizer, continuous flooding). Most of the treatments resulted positive NECB, which indicated net carbon sequestration exhausted in that ecosystem (44). However, there has been limited focus on the effect of practice on the sustainability of the soil's Annual Net Carbon Balance (ANCB) in continuous flooding systems (i.e., NECB of 2959 kg C ha^{-1}) on paddy soil.

NECB of wheat

Wheat (*Triticum aestivum* L.) is the world's most traded and cultivated crop, covering 216 million hectares with an average yield of 3.5 t ha^{-1} with the global production of 765 million tons (FAOSTAT 2019). More over half of the world's wheat harvest is consumed by humans and the remainder utilized for animal feed and processing (45). Wheat demand has risen globally in recent years for food, seed, industrial and feed as animal. Agriculture has a number of challenges due to increased environmental concerns by over use of irrigation water fertilizer and pesticide (46, 47). Furthermore, agriculture is likely to be one of the industries hardest hit by climate change in the future (48, 49). The atmospheric CO_2 level for the historical baseline (baseline level) was set at 362 ppm, which corresponds to the 30-year average of the baseline period (1980-2010). Crop models for future scenarios were developed using an expected elevated atmospheric CO_2 level of 572 ppm (2041-2070) to study the combined effects of temperature, rainfall and elevated CO_2.

The study focused on SAFY-CO_2, a research initiative near Toulouse in southwest France, encompassing two monitored agricultural sites: Auradé (FR-Aur) and Lamasquère (FR-Lam) and diagnostic regional modelling approach that integrates High Spatial and Temporal Resolution (HSTR) optical remote sensing data into a simplified crop model. The study assessed the model's effectiveness in estimating crop yield and key components of the annual carbon budget for winter wheat (50). The SAFY-CO_2 model (Fig. 3) was modified from the SAFY model (Simple Algorithm for Yield Estimates (51) for estimating the components of net CO_2 fluxes and cropland annual carbon budget. SAFY is a daily time step crop model that replicates the temporal evolution of green area index (GAI), dry aboveground mass (DAM) and final grain yield (YLD) using two climatic input variables, incoming global radiation and average temperature.

This method is based on Monteith and Moss' (1977) light -use efficiency theory, which connects the production of total daily assimilation of matter (DAM) to the photosynthetically active part of solar radiation (PAR) absorbed by plants. The SAFY-CO_2 model predicts daily crop growth (biomass, leaf partitioning, etc.), net ecosystem CO_2 flow components, annual yield and NECB. SAFY model results for LAM 2007 (for the site-year 2007 at Lamasquère), indicated that the NECB value is -

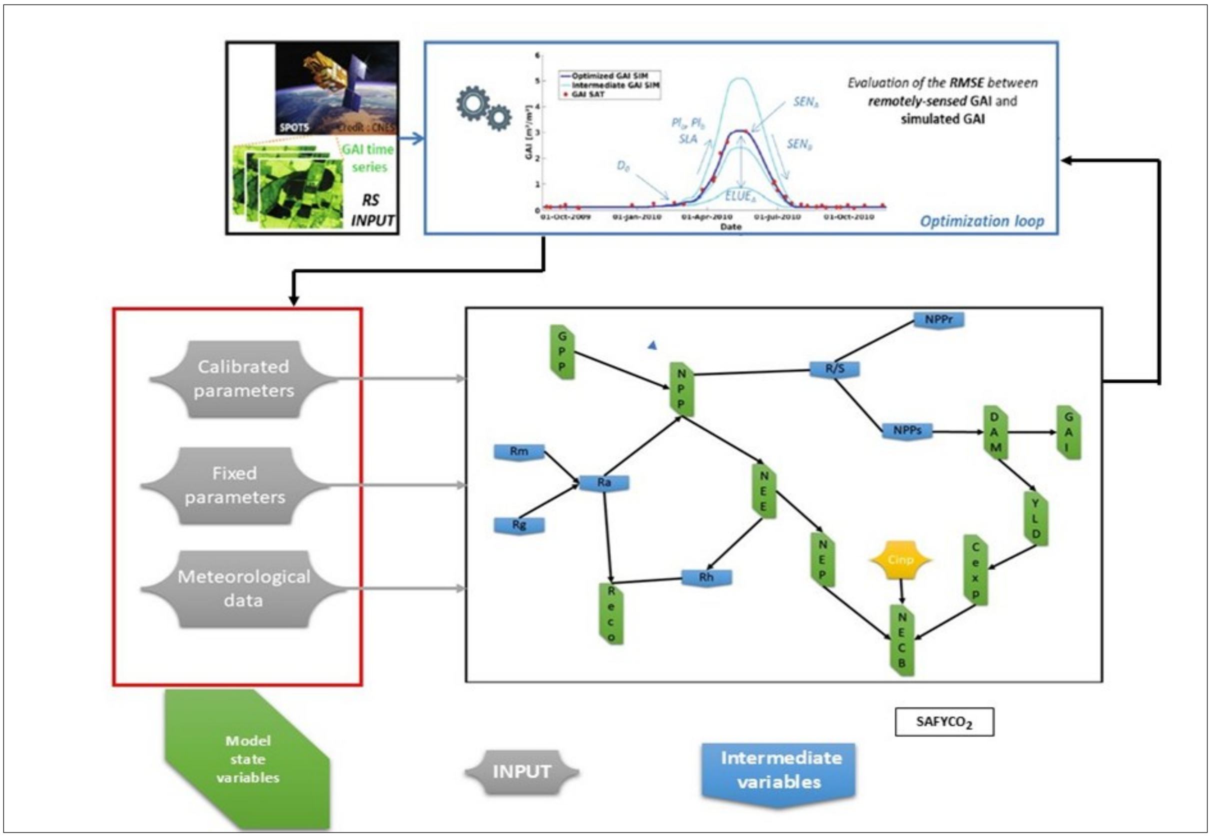

Fig. 3. Schematic representation of the assimilation procedure of GAI derived from high resolution satellite optical images for the calibration of the agro-meteorological model SAFY-CO_2 by minimizing difference between satellite derived (SAT) and simulated (SIM) GAI.

4390 ±1050 kgC^{-1}, indicating a net carbon loss from the ecosystem (52) AUR 2014 (for the site-year 2014 at Auradé). The NECB value of -290 ±750 kg C^{-1}observed suggesting a carbon loss, was much smaller than LAM 2007.

A three-year field experiment on a wheat-maize rotation system in the southern Loess Plateau, China, assessed the effects of different mulching practices on crop yield, soil respiration (R_S), ecosystem respiration (R_E) and the NECB with four mulching methods *viz.*, conventional flat planting without mulching (CK), flat planting with plastic film mulching (PM), flat planting with straw mulching (SM) and ridge-furrow planting with plastic film and straw mulching (RFPS). The NECB varied significantly among the mulching methods, demonstrating their impact on carbon sequestration and emissions. During the wheat season, CK and PM acted as carbon sources, with NECB values of -390 kg C ha^{-1} yr^{-1} and -320 kg C ha^{-1} yr^{-1}, respectively, indicating net carbon losses (53). In contrast, SM and RFPS functioned as carbon sinks, with NECB values of 1180 kg C ha^{-1} yr^{-1}and 1360 kg C ha^{-1} yr^{-1}, respectively, showcasing their superior ability to enhance soil carbon sequestration.

However, the effect of flat planting with plastic film mulching (PM) showed fluctuated NECB across years. During 2018-2019 and 2020-2021, the NECB was -410 kg C ha^{-1} yr^{-1}, indicating significant carbon loss, whereas, it was improved to -140 kg C ha^{-1}yr^{-1}, showing reduced in emissions during 2019-2020. This variation suggested that plastic mulching influenced carbon dynamics and NECB remains inconsistent. In contrast, the higher NECB values observed in SM and RFPS mulching highlight the positive role of straw incorporation and combined mulching practices in enhancing soil carbon sequestration, making them effective strategies for improving carbon balance in wheat-maize cropping systems (53). In CropSyst model for winter wheat fields (2011-2015), the NECB ranged from 920 to -170 kg C ha^{-1}, indicating potential for carbon sequestration and loss (54). Most of the mulching methods resulted in negative NECB values, suggesting these agricultural systems are generally net carbon sources rather than sinks. The magnitude of carbon loss varies significantly between treatments and years, with LAM 2007 model due to loss.

NECB of maize

Maize (*Zea mays* L.) is the third most important crop of country after rice and wheat and used as feed, food and industrial raw material and cultivated round the year, though more than 80 % is grown in rainy or kharif season (July to October). Depletion of natural resources, low organic carbon from soil, resulted declining in factor productivity (55), decreasing farm land due to more land under non-agricultural uses in future and profitability due to escalating input prices in agricultural production will further aggravate the problem of sustaining maize production systems (56). China is the second-largest producer of maize in the world, with an estimated maize output of 261 million tons, in 2021 comprising 22 % of the global maize yield (57).

Nutrient management on the NECB value for maize was 2879 kg C ha^{-1} year^{-1} (Table 3) indicating significant net carbon sequestration were highly effective in promoting carbon storage in the ecosystem (50, 52). The mean NECB of PPP-LSF (Combing public-private partnership and large-scale farming) were 22.5 Mg C ha^{-1} which increased by 15.3 % (19050.75 kg C ha^{-1}) and 23.9 % (17122.5 kg C ha^{-1}) compared to LSF (Large scale farming) and SHF (Smallholder Farming) (58). The NECB of maize production varied across four straw-tillage management systems of conventional tillage (CT), no-tillage (NT), conventional tillage with straw retention (CT-SR) and no-tillage with straw retention (NT-SR). The NT-SR and CT-SR systems recorded the highest NECB values, of 15746 kg C ha^{-1} and 15700 kg C ha^{-1}, respectively. The CT system had a lower NECB, of 14000-14500 kg C ha^{-1} and op par with CT-SR. Meanwhile, the NT system had the lowest NECB, of 13,917 kg C ha^{-1}, which was 13 % lower than NT-SR and 12.9 % lower than CT -SR. On average, NECB was 10 % lower in systems without straw retention (CT, NT) compared to those with straw retention (CT-SR, NT-SR), emphasizing the benefits of integrating straw retention into both tillage and no-tillage practices (59). Continuous observations using eddy correlation techniques showed that the maize farmland ecosystems acted as carbon (C) sinks. In the north-central USA, C budgets of -7334.0 kg C ha^{-1}, -8804.0 kg C ha^{-1} and -7024.0 kg C ha^{-1} was recorded during the growing seasons of maize during 1997, 1999 and 2001 (60).

Similarly, in Nebraska, the C budget of maize farmland under both irrigated and non-irrigated conditions was approximately -7000.0 kg C ha^{-1} (61). In Jinzhou, South Northeast China, maize farmland ecosystems exhibited strong C sinks, with an average C budget of -5295.2 kg C ha^{-1} between 2005 and 2008-2011 (62-64). In this study, the 2019 growing season C budget of typical maize ecosystems in the Songnen Plain of China was -8085.7 kg C ha^{-1}, while the non-growing season C budget was 1250.4 kg C ha^{-1}, resulting in a total annual C budget of -6835.3 kg C ha^{-1}. Considering that maize grain yield (-3534.4 kg C ha^{-1}) was removed from the farmland at harvest, the NECB was calculated as -3300.9 kg C ha^{-1}, confirmed that the maize agroecosystem acted as a C sink in 2019 (34). However, the NECB values observed were lower than those reported for maize farmlands in the USA and Jinzhou, likely due to the exclusion of maize grain removal effects in previous studies. Additionally, during 2018-2019 it was -800 kg C ha^{-1}, 2019-2020 was -920 kg C ha^{-1} and 2020-2021 was -470 kg C ha^{-1} examined the NECB under a plastic film-mulched ridge and straw-mulched furrow system (53). These findings suggested that mulching practices can influence carbon sequestration, with potential variations depending on climatic conditions and management strategies.

By fully utilizing climate resources and improving agricultural managements, carbon sink is increased in farmland ecosystems. Soil respiration rate and composition were influenced and controlled by the synergistic effect of soil temperature and water content under the maize farmland ecosystem which is carbon sink. In this study, the influence of biological factors on soil respiration rate was not considered and soil respiration assessment has certain limitations. In future, this aspect of research should be developed to adapt the needs of soil carbon budget assessment.

NECB of sugarcane

Approximately two thirds of the sugar produced worldwide comes from the sugarcane crop (*Saccharum officinarum L.*) (65). It is a plant with a C_4 metabolism with high CO_2 uptake capacity (66). The net exchange of CO_2 between the ecosystem (soil and vegetation) and the atmosphere (NEE) can be used to calculate the amount of CO_2 assimilated by a crop's canopy (67, 68).

In Table 3 the year 2016-2017 shows a big decrease in NECB of -7221.8 ±1252.2 kg C $ha^{-1}yr^{-1}$. This indicates the ecosystem had a strong carbon sink during this period, absorbing significantly more carbon than it released. Year 2 (2017-2018) had a smaller negative NECB of -1699.1 ± 959.1 kg C $ha^{-1}yr^{-1}$ (69). While still a carbon sink, the ecosystem's carbon uptake decreased substantially compared to Year 1. Both years show the ecosystem acting as a net carbon sink, which is generally positive from a climate change mitigation perspective. The substantial decrease in carbon uptake from Year 1 to Year 2 warrants further investigation to understand the causes and whether this represents a long-term trend or natural variability. The GHG balance closely mirrors the CO_2 flux, indicating that CO_2 is the dominant greenhouse gas in this system's carbon budget. The negative values (-7569.0 ± 129.0 and -4552.0 ± 124.0 g CO_2 eq m^{-2} yr^{-1}) confirm the ecosystem's role as a net GHG sink. The small positive N_2O emissions observed (62.4 ± 1.3 and 52.3 ± 1.8 g CO_2eq m^{-2} yr^{-1}) slightly offset the CO_2 sink effect. N_2O emissions decreased from Year 1 to Year 2 and follows the trend of reduced GHG fluxes. Fertilizer-based agriculture data gives annual soil GHG fluxes show CO_2 emissions (17.6 ± 0.0 Mg C $^{-1}yr^{-1}$) and small CH_4 uptake (-1.1 ± 0.0 kg C $^{-1}yr^{-1}$). These values suggest that the soil emits CO_2, it slightly mitigates this by absorbing some methane. Net C loss gives the strong CO_2 sink in the eddy covariance measurements, the fertilizer-based agriculture data shows a net C loss of –760 kg C $ha^{-1}yr^{-1}$, indicating complex carbon dynamics in the agricultural system (70). Cumulative carbon fluxes show the negative Cumulative Net Ecosystem Exchange (-923.04 g C $^{-2}$) further supports the ecosystem's role as a carbon sink (71). The Gross Primary Productivity (3316.65 g C m^{-2}) exceeds the ecosystem respiration (2433.18 g C m^{-2}), explaining the net carbon uptake. Ecosystem Efficiency carbon use efficiency (CUE) of the ecosystem is calculated as:

CUE = (GPP - Reco)/GPP = (3316.65 - 2433.18)/3316.65 ≈ 0.27 or 27 %

This suggests that about 27 % of the carbon fixed by photosynthesis is retained in the ecosystem.

Thus, between 2016-2017 and 2017-2018, NECB declined from -7221.8 ± 1252.2 to –1699.1 ± 959.1 kg C ha^{-1} yr^{-1} and GHG balance from -7569.0 to -4552.0 g CO_2 eq $m^{-2}yr^{-1}$, indicating reduced carbon sink strength. In contrast, fertilizer-based agriculture showed a net carbon loss of -760 kg C $ha^{-1}yr^{-1}$, highlighting the role of natural ecosystems in carbon sequestration.

NECB of cotton

Cotton (*Gossypium hirsutum* L.) is cultivated in 76 countries for fiber and ranks first as a commodity of global agricultural trade (72). Cotton accounts for about 25-35 % of world's total fiber uses (73). In India, cotton is cultivated on nearly 9.5 million ha area (74) covering about 30% of global cultivated area, with 60 % of total cotton production. Although India ranked second only next to China in cotton production (75), with average national cotton productivity of 516 kg ha^{-1} which is much lower than USA (943 kg ha^{-1}), China (1301 kg ha^{-1}), Brazil (1480 kg ha^{-1}) and Australia (1579 kg ha^{-1}) (76). It is estimated that cotton cultivation contributes about 0.3-1.0 % towards total global greenhouse gases emissions (77). The NECB of cotton cultivation varies based on different factors such as nutrient management, energy flow and tillage practices (21). Therefore, efficient management practices and energy optimization play crucial roles in determining the NECB under cotton cultivation.

The NECB is 1801 kg C ha^{-1}, (Table 3) indicating a significant net carbon gain in the ecosystem under the nutrient management practice (52). On plastic film mulching and drip irrigation (PFMDI) the NECB values are consistently negative from -950 to -300 kg C ha^{-1} from 2012 to 2016 (Fig. 4) (67). This suggest that the ecosystem was a carbon sink throughout these years. There is a general trend of decreasing carbon sequestration over time (from -950 in 2012 to -300 in 2016). The average NECB for the PFMDI field is -670 ± 370 kg C ha^{-1} yr^{-1}, confirming the overall carbon sink status. In the Charnes-Cooper-Rhodes model for inefficient DMUs, the net ecosystem C budget is -4940 ± 150 kg C ha^{-1} (1). For efficient DMUs, it's -4040 ± 180 kg C ha^{-1} (21). Both models indicate carbon sequestration, with inefficient DMUs showing slightly higher sequestration. The study doesn't provide NECB values directly, but the Cumulative NEEs (Net Ecosystem Exchanges) suggest varying carbon sink/source behaviour across different periods of the year (78).

The NEE represents the carbon budget with an account of carbon release and captured by an ecosystem through assimilation and respiratory processes (79, 80). The negative values of net ecosystem C budget for efficient and inefficient

Table 3. NECB for different cropland system with different measurements

Crops	Metric Type	Value (kg C ha^{-1} yr^{-1})	Treatment
Wheat	NECB - Highest	+1360	Ridge-furrow with plastic film and straw mulching (RFPS) (53)
	NECB - Lowest	-4390 ± 1050	SAFY Model (OBS) (50, 86, 87)
Maize	NECB - Highest	+22,500	Public-private partnership & large-scale farming - Different scale of farming (58)
	NECB - Lowest	-8804	North-central USA (2000, Growing season) (34)
Sugarcane	Max CO_2 Absorption (Annual)	–32,661	Modelling (71)
	Gross Primary Productivity (GPP)	33,166.5	Modelling (71)
	NECB - Least Negative	-1699.1 ± 959.1	Eddy covariance (69)
	NECB - Most Negative	-7221.8 ± 1252.2	Eddy covariance (69)
	CH_4 Flux - Lowest	-1.1	Fertilizer-based system (70)
	CH_4 Soil GWP - Lowest	-30	Fertilizer-based system (70)
Cotton	NECB - Highest	+1801	Nutrient management (52)
	NECB - Lowest	-4940 ± 150	Inefficient DMUs (21)
	NEE - Highest	+1940	Treatment C1 - Automatic Chamber (78)
	NEE - Lowest	-1510	Treatment C3 - Eddy Covariance (78)
Sunflower	NECB - Highest	+2650.6	2019, SB (straw-derived biochar) (84)
	NECB - Lowest	-19.9	2018, CK (control without straw return) (84)
	NEE - Highest	3175.5 (from R^2 = 0.87)	HSTR method, 2007-2016 (82)
	NEE - Lowest	2956.5 (from RMSE = 0.81)	HSTR method, 2007-2016 (82)

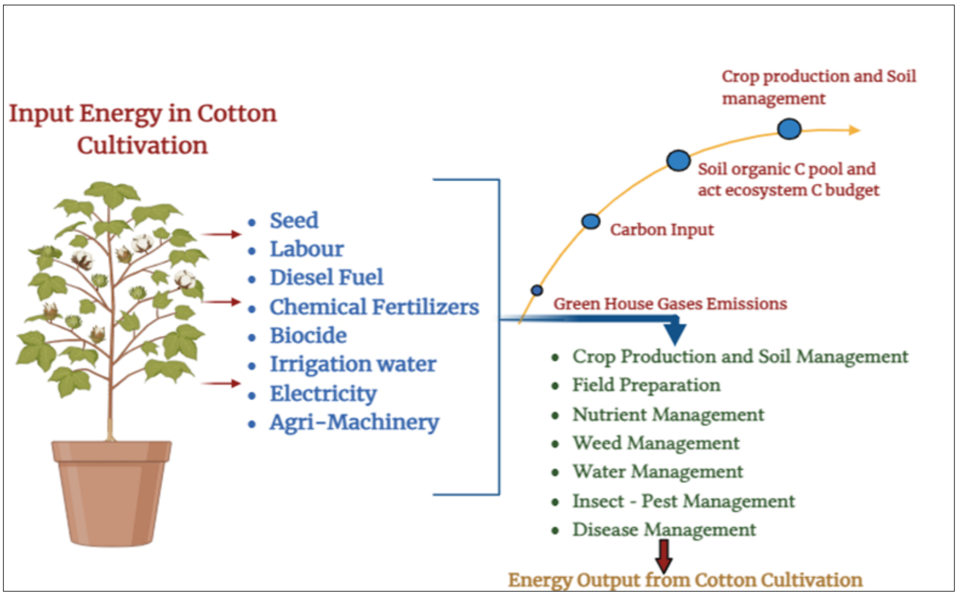

Fig. 4. Flow chart describing the system boundary for different processes involved in cotton (*Gossypium hirsutum* L.) cultivation in north-western India (67).

DMUs revealed that these ecosystems act as a C source. These results corroborate the earlier findings of negative net ecosystem C budget for cotton cultivation in a cotton-wheat cropping system (80).

The ecosystems behave as net carbon source if crops fail to produce net biome production to offset C emissions (81). The amount of C added to soil organic C pool was significantly higher under efficient DMUs, compared with the inefficient DMUs (Fig. 5). The ΔSOC pool was also significantly higher by ~22.4 % for efficient DMUs, compared with the inefficient DMUs. These results are in conformity with those reported by showing a loss of 817 kg C ha^{-1} in a cotton-wheat cropping system (80). The comparison of NECB values highlights distinct carbon dynamics across management practices. Plastic film mulching and drip irrigation (PFMDI) and the Charnes-Cooper-Rhodes (CCR) model practices consistently act as carbon sinks, with NECB values averaging -670 kg C ha^{-1} and reaching up to -4940 kg C ha^{-1} in inefficient DMUs. In contrast, nutrient management shows a positive NECB of +1801 kg C ha^{-1}, indicating a net carbon release. These results suggest that the nutrient management may enhance crop productivity whereas PFMDI and efficient system designs are more effective in promoting long-term carbon sequestration.

NECB of sunflower

Sunflower (*Helianthus annuus* L.) was introduced to Europe by Spaniards during the 16th century as an ornamental plant species, before its oil began to be used for food during the 19th century. Currently, sunflower is cultivated on more than five continents, with Ukraine and Russia being the largest producers, followed by the European Union (EU) (82). The CO_2 implications of NGWP (Net Global Warming Potential) represents CO_2 equivalent negative values which indicate net CO_2 sequestration (Table 3). All treatments show negative NGWP values shows all sequester CO_2 overall. Straw-derived biochar (SB) consistently shows the highest CO_2 sequestration across all years. Straw return with rotary tillage (SR) also shows significant CO_2 sequestration, though less than biochar. All treatments show positive NECB values, indicating carbon accumulation in the soil. Straw-derived biochar (SB) treatments show the highest NECB values each year. Straw return

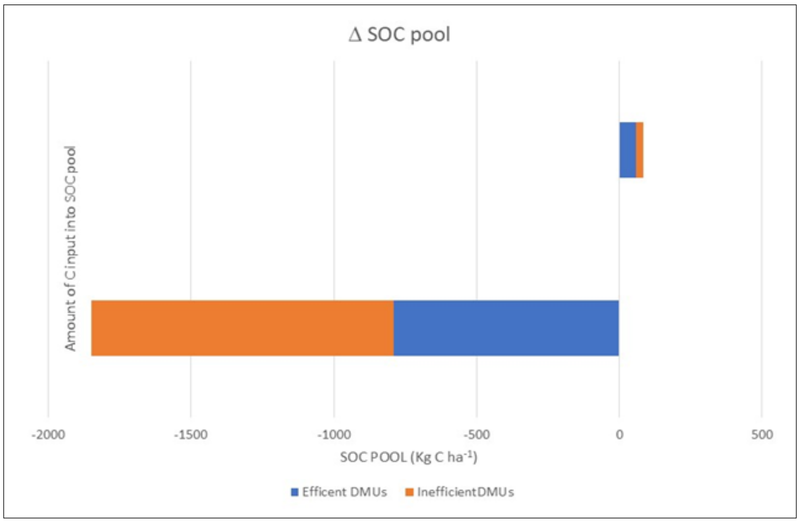

Fig. 5. Amount of C added into soil organic C pool and the change in soil organic C (ΔSOC) pool in soils under cotton (Gossypium hirsutum L.) cultivation in an intensively cultivated north-western India. Mean values followed by different letters are significantly different ($p < 0.05$) by Students' t-test. Line bars indicate standard error from mean (S.E.M). Note: B - Reviewer - Highlighted in blue colour; C- Reviewer - Highlighted in red colour; Grammar and other corrections - Highlighted in violet colour.

treatments (SP and SR) also show high NECB values, but generally lower than biochar. Consistently show that control treatments (CK) exhibit the lowest CO_2sequestration and carbon accumulation. Biochar amendments perform best for both CO_2 sequestration and soil carbon accumulation. Straw return methods (with ploughing or rotary tillage) are more effective than control but less effective than biochar. Data from multiple studies indicate that NECB varies significantly depending on land management practices and straw return treatments. The NECB values in the Garonne River region fluctuated between 640 and 3000 kg C ha^{-1} yr^{-1} over the years 2007 and 2016, highlighting both carbon sink and source dynamics (83). In contrast, the different straw return treatments in saline-alkali farmlands under arid conditions significantly influenced NECB (84). In 2017, the control treatment (CK) without straw return had the lowest NECB (191.5 ± 5.5 kg C ha^{-1}), whereas straw-derived biochar (SB) exhibited the highest NECB (11,570.9 ± 334.0 kg C ha^{-1}), indicating enhanced carbon sequestration. A similar trend was observed in 2018 and 2019, with biochar consistently outperforming other treatments, while CK showed a negative NECB (-19.9 ± 0.6 kg C ha^{-1}) in 2019, suggesting carbon loss. Additionally, the NECB of 88.9 kg C ha^{-1} in ploughed fields with mineral fertilization, reinforcing the importance of management practices in carbon balance regulation.

NECB values vary widely with land management, ranging from 640 to 3000 kg C ha^{-1} yr^{-1} in the Garonne region and just 88.9 kg C ha^{-1} in ploughed, fertilized fields. Straw-derived biochar showed the highest sequestration of 11570.9 kg C ha^{-1}, while control plots represented as low as -19.9 kg C ha^{-1}, indicating carbon loss. These findings underscore that practices like biochar application significantly enhance ecosystem carbon storage compared to conventional methods.

Management strategies for NECB in croplands

Irrigation management

Water-saving irrigation is recognized as an effective agricultural management due to water security and environmental protection problems with IN165 (intermittent irrigation along with Nitrogen -165 kg N ha^{-1}) with NECB value as 2243± 113 kg C ha^{-1} (Table 2). In Northeast China, an increasing number of paddy fields are shifting from conventional irrigation to water-saving irrigation (40). The highest NECB values were observed under high nitrogen fertilization and intensive water or crop management practices. Using the static closed-chamber method, the maximum NECB was recorded (2649 kg C ha^{-1}) with 12 N fertilizer and rice cropping. Similarly, gas sampling and analyses showed the highest NECB of 2959 kg C ha^{-1} under 12 N fertilizer with continuous flooding (44). These practices likely enhanced biomass production and carbon input to the soil, contributing to a positive carbon balance. Thus, high N input combined with effective water and crop management supports greater soil carbon sequestration. The plastic film mulching and drip irrigation (PFMDI), irrigation management resulted in consistently negative NECB values, indicating a carbon sink (Table 3). NECB ranged from -950 to -300 kg C ha^{-1}, with an average of -670 ± 370 kg C ha^{-1} yr^{-1} from 2012 to 2016. Despite being a carbon sink, the carbon sequestration potential decreased over time, highlighting the need to optimize irrigation practices for long-term sustainability (67).

Mulching

Mulching management plays a crucial role in influencing the NECB in agricultural systems. In wheat, the straw mulching (SM) and ridge-furrow planting combined with plastic film and straw mulching (RFPS) showed the most positive impact, acting as carbon sinks with NECB values of +1180 and +1360 kg C ha^{-1} yr^{-1}, respectively. These practices enhance soil carbon sequestration by improving soil structure and organic matter retention. In contrast, flat planting with plastic film mulching (PM) resulted inconsistent carbon sink, ranging from -410 to -140 kg C ha^{-1} yr^{-1}, indicating fluctuating carbon losses. The variability in PM's effectiveness suggests that plastic mulch alone may not reliably support carbon balance goals. Conventional flat planting without mulching (CK) consistently acted as a carbon source, with an NECB of -390 kg C ha^{-1} yr^{-1}. In an overall, mulching strategies that incorporate organic materials like straw are more effective in reducing carbon emissions. These findings support the adoption of integrated mulching techniques for sustainable carbon management in cropping systems. During 2018-2019, 2019-2020 and 2020-2021, the NECB under a plastic film-mulched ridge and straw-mulched furrow system was -800, -920 and -470 kg C ha^{-1}, respectively in maize, indicating continued carbon loss (53). Comparatively, the RFPS treatment in wheat, with an NECB of +1360 kg C ha^{-1} yr^{-1}, proved to be the most effective mulching practice for enhancing soil carbon sequestration.

Nutrient management

The nutrient management in maize represented the NECB value of 2879 kg C ha^{-1} yr^{-1} (Table 3), indicating a significant net carbon sequestration (50). The negative values of net ecosystem C budget for efficient (-4040 kg C ha^{-1}) and inefficient (-4940 kg C ha^{-1}) decision making units revealed that these ecosystems act as net C source. The average efficiency of 870 ± 20 revealed that ~13 % of total energy input could be saved without any impact on cotton productivity and environment. These results underpin the overwhelming significance of intensified extension efforts for efficient use of chemical fertilizers and discouraging farmers from unwarranted use of biocides in cotton in the north-western India (21). Data presented in Table. 3 compares soil GHG fluxes and (WFPS, temperature, mineral N) between forest and sugarcane plantations under different fertilizer management of monthly intervals (forest) and intensively (sugarcane) from May 2019 to June 2020. Four forest plots and 12 sugarcane plots across three fertilization levels (low, standard, high) were studied. Despite improved SOC sequestration and lower N_2O emissions under sugarcane with fertilizer management, conversion led to a net soil C loss. This loss (-760 kg C ha^{-1} yr^{-1}) was mainly due to increased CO_2 efflux and reduced CH_4 uptake (70). Compared to maize, where nutrient management led to significant carbon sequestration (NECB: 2879 kg C $ha^{-1}yr^{-1}$), sugarcane under fertilizer management still showed a net carbon loss (-760 kg C $ha^{-1}yr^{-1}$). This highlights the greater potential of optimized nutrient management in maize for enhancing ecosystem carbon balance.

Conservation tillage and reduced soil disturbance

The nutrient management practices in maize employed in 2010 were highly effective in promoting carbon storage in the ecosystem (Table 3). The effect of best management practices like conservation tillage on soil carbon sequestration remains unclear. The No-Tillage with Straw Retention (NT-SR) and

Conventional Tillage with Straw Retention (CT-SR) systems recorded the highest NECB values, of 15746 kg C ha^{-1} and 15700 kg C ha^{-1}, respectively. An integrated straw-tillage management is therefore an efficient and feasible way to maintain high maize productivity and carbon sustainability (59). The data presented suggests that sunflower crop incorporated organic matter through tillage (either ploughing or rotary tillage) is beneficial. However, the differences between ploughing and rotary tillage are relatively small, indicating that either method can be effective. Straw-derived biochar showed the highest sequestration at 11570.9 kg C ha^{-1} (2017) in SB (straw-derived biochar), while control plots dropped as low as -19.9 kg C ha^{-1} (2019), indicating carbon loss (84).

Organic amendments and residue management

The use of organic amendments clearly demonstrates their positive impact on soil carbon dynamics and productivity (Table 3). Application organic inputs, especially straw-derived biochar (SB), showed the highest NECB (11570.9 kg C ha^{-1}) and the lowest NGWP (-50189.8 ± 1627.3 kg CO_2 eq ha^{-1}) in 2017, along with high NPP values ranging from 13743.2 ± 346.7 to 16180.4 ± 427.5 kg ha^{-1}. If biochar application is not feasible, straw return with ploughing (SP) or straw return with rotary tillage (SR) still improved NECB and NPP over the control (84). These practices showed consistent benefits from 2017 to 2019, highlighting the value of regular organic matter inputs. Balancing carbon sequestration with NPP ensures soil improvement without compromising yield, especially under saline-alkali, arid conditions.

Conclusion

The NECB across various croplands reveals significant variability in carbon dynamics, emphasizing the complex interplay between crop types, management practices and environmental factors. Rice, maize, cotton and sunflower cropland systems usually act as carbon sinks, meaning they absorb more carbon than they release. In contrast, wheat and sugarcane fields often show mixed results and can sometimes release more carbon. Farming methods play a key role in these techniques like water-saving irrigation in rice, conservation tillage in maize and using organic materials like biochar in different crops can help increase carbon storage in the soil. The study highlights the importance of balancing productivity with carbon storage, as exemplified by the positive impacts of nutrient management strategies on both yield and net ecosystem carbon balance (NECB). Methodological approaches, including eddy covariance techniques, chamber methods and crop models provide complementary insights though standardization of NECB calculations would improve cross-study comparability. Year-to-year variations in NECB underscore the necessity for long-term studies to capture the full spectrum of cropland carbon dynamics. The research suggests that optimizing NECB can contribute substantially to climate change mitigation while maintaining agricultural productivity. However, the wide range of NECB values observed across different crops and management scenarios ranging from -26460 ± 4587 to 22500 kg C ha^{-1} emphasizes the need for site-specific strategies. The potential for croplands to serve as carbon sinks is evident, but realizing this potential requires tailored approaches that consider local climate conditions, soil properties and farming practices. As agriculture faces the dual challenges of feeding a growing population and mitigating climate change, the insights gained from this NECB analysis provide valuable guidance for developing sustainable farming practices. Future research should focus on refining our understanding on the mechanisms driving NECB variations and developing innovative management techniques to optimize carbon sequestration across diverse agricultural ecosystems.

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Authors' contributions

RR wrote the manuscript. PC provided guidance in writing the manuscript. PS, KS and TS reviewed the manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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