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# Economic Valuation of Ecosystem Services of Selected Interventions in Agriculture in India

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**ABSTRACT**

Agriculture is multi-functional, producing economic goods including food, feed, fibre, and fuel, as well as providing several intangible or non-tradable services to society free of cost. Non-tradable services, unlike economic goods, remain unpriced; as a result, farmers are not compensated monetarily for the benefits of the several non-tradable services they provide through agriculture. Recognizing the monetary value of non-tradable ecosystem services is crucial to incentivize farmers to adopt eco-friendly technologies and practices for the sustainable development of agriculture. Through a meta-analysis of the existing evidence on ecosystem services, this study attempts to estimate the value of ecosystem services by using direct and indirect valuation methods—for example, carbon sequestration, methane emission, nutrient availability, biological nitrogen fixation, and water saving—generated by several important technological and agronomic interventions, namely the direct seeding of rice (DSR), zero-tillage in wheat, leguminous crops, organic manure, integrated nutrient management, and agroforestry, based on studies conducted in India. It also explores the trade-offs between the non-tradable and tradable ecosystem services attributable to these interventions. The monetary value of the non-tradable services resulting from most of these interventions is quite large, 34–77% of the total value of all the ecosystem services.

However, not all interventions result in a win-win situation that yields improvements in both tradable and non-tradable outcomes. While no-till wheat, legumes, and integrated nutrient management result in a win-win outcome, there are trade-offs between the tradable and non-tradable ecosystem services in the cases of directed seed rice, organic manure, and agroforestry. This evidence suggests that not all agricultural technologies and practices are beneficial for farmers, despite their higher environmental benefits. Thus, the findings of this study imply that agricultural policy should provide incentives for the adoption of technologies and practices to conserve ecosystems and natural resources.

**Keywords:** ecosystem services; agriculture; improved farm practices; economic value; trade-offs; meta-analysis

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## 1. Introduction

Bio-chemical and mechanical innovations in agriculture along with investment in irrigation and infrastructure, institutions, and incentives have played a crucial role in the transformation of India's agri-food production system. This has led to a dramatic increase in the production of food and non-food commodities, and consequently, higher farm incomes, affordable access to food, and a reduction in poverty. This progress, however, has come at a cost (NAAS, 2020). The intensification of agriculture has resulted in the deterioration of natural resources (e.g., decline in soil and groundwater and its quality), the environment (e.g., air pollution and greenhouse gas emissions), and agrobiodiversity (Foley et al., 2011). Current agricultural policies do not support sustainable production and consumption patterns (WRI, 2019; Gautam et al., 2022), necessitating a reconsideration of the current agricultural incentive structure and its alignment with principles of sustainability to ensure agriculture efficiency and resilience. Incentivizing farmers to adopt technologies and practices that help preserve non-tradeable ecosystem services is one possibility (Costanza, 2006; FAO, 2007; NAAS, 2020).

Agriculture is one of the largest land-based ecosystems. It provides food, feed, fibre, and fuel, and performs several intangible functions essential to environmental preservation and the sustenance of human life on Earth. Therefore, the primary focus of this study is to assess the intangible services including carbon sequestration, soil fertility, biological nitrogen fixation (BNF), and greenhouse gas emissions resulting from improved agricultural practices.

The impact of agriculture on ecosystem services is largely determined by farm input use and crop management practices (Wossink and Swinton, 2007; Ma et al., 2012). The intensive use of inputs and unsustainable agricultural practices can disturb ecological balance, leading to the deterioration of ecosystem services, especially supporting and regulatory services. For instance, conventional tillage, although it increases yield in the short run, has adverse effect on soil health and leads to higher greenhouse emissions, increased soil erosion, disrupts the natural habitat of soil microorganisms and beneficial organisms (Ji et al., 2015; Schneider and Smith, 2009). Similarly, conventional methods of rice production causes severe air pollution, nutrient loss, and adverse effects on human health (Chaudhary et al., 2023). Further, exclusive application of chemical fertilizer without any organic inputs tends to increase more greenhouse emissions and effects quality of both surface and groundwater (Zhang et al., 2012; Wu and Ma, 2015). On the other hand, the adoption of improved agricultural practices tends to have positive influence on soil health, biodiversity, soil organic carbon, and reduction of external inputs.

Farmers and farm policies play a crucial role in managing agricultural landscapes through actions that determine the quantity and quality of ecosystem services. Farm incomes are derived from the provisioning services. Several other intangible or non-tradable services are also generated, which depending on the quantity and quality of the inputs used and the type and intensity of the agronomic practices, may be termed as either positive or negative externalities. Unfortunately, the economic contribution of such practices to the conservation of ecosystems has either not been accounted for or remains undervalued due to a lack of markets for intangible services. To reward farmers for their contribution towards environmental preservation and well-being of the present and future generations, it is imperative to establish the value of non-provisioning ecosystem services resulting from the adoption of good agricultural practices (De Groot et al., 2010).

Valuation of ecosystem services has been attracting considerable attention in academic and policy debates, mainly as a means to reduce the negative effects of excessive and intensive use of agrochemicals. Economic valuation is an attempt to assign monetary values to goods and services provided by environmental resources, regardless of whether a market exists for them (Lambert, 2003). The valuation of ecosystem services is a complex process. It involves an assessment of the contributions of an ecosystem to sustainable human well-being as well as the rational distribution and efficient allocation of services (Costanza and Folke, 1997; Liu et al., 2010). It provides a clear understanding of the degradation of natural resources and its costs to society. When such costs are not accounted for, resources are misallocated social welfare decreases. Moreover, valuation provides an economic rationale for the investment in natural resource management for their efficient and sustainable use.

In India, a few studies have attempted to assign monetary values to agricultural ecosystem services such as soil fertility, water savings, soil retention, aquifer recharge, and carbon retention (Palsaniya et al., 2012; Mondal et al., 2018; MoSPI, 2021). However, these studies focused primarily on the overall valuation of agroecosystem services using the benefits transfer approach. While many studies investigated agronomic and environmental benefits associated with improved farming practices, valuation of the ecosystem services generated by these improved farm practices has been rarely conducted. This study attempts to synthesize the evidence of various studies on the potential ecosystem services in the Indian agricultural landscape. Using a meta-analysis framework, this study aims to assess the economic worth of ecosystem services provided by some good agricultural practices: (i) direct-seeded rice (DSR), (ii) no-till wheat, (iii) legumes, (iv) organic manure (i.e., farm yard manure), (v) integrated nutrient management (INM), and (vi) agroforestry.

Provisioning services have been quantified as the contribution of these practices to the crop yields; supporting services in terms of their contribution to soil fertility, nutrient retention, and biological nitrogen fixation; and regulating services in terms of their contribution to carbon flow and water holding capacity.

## 2. Data and Methods

*2.1 Data*

An extensive literature search was undertaken following the PRISMA framework (Fig.1) to compile research studies on key ecosystem services relevant to the improved agricultural practices using online search engines, namely Google Scholar, Scopus, and Science Direct, from 1983 to December 2022. The combination of search keywords used to identify research studies include "crop yield", "carbon sequestration", "soil health", "greenhouse gas emission", "water use", "biological nitrogen fixation", "nutrient availability", "direct seeded rice", "organic manure", "no/zero-till wheat", "agroforestry", "legumes", "integrated nutrient management", and "India".

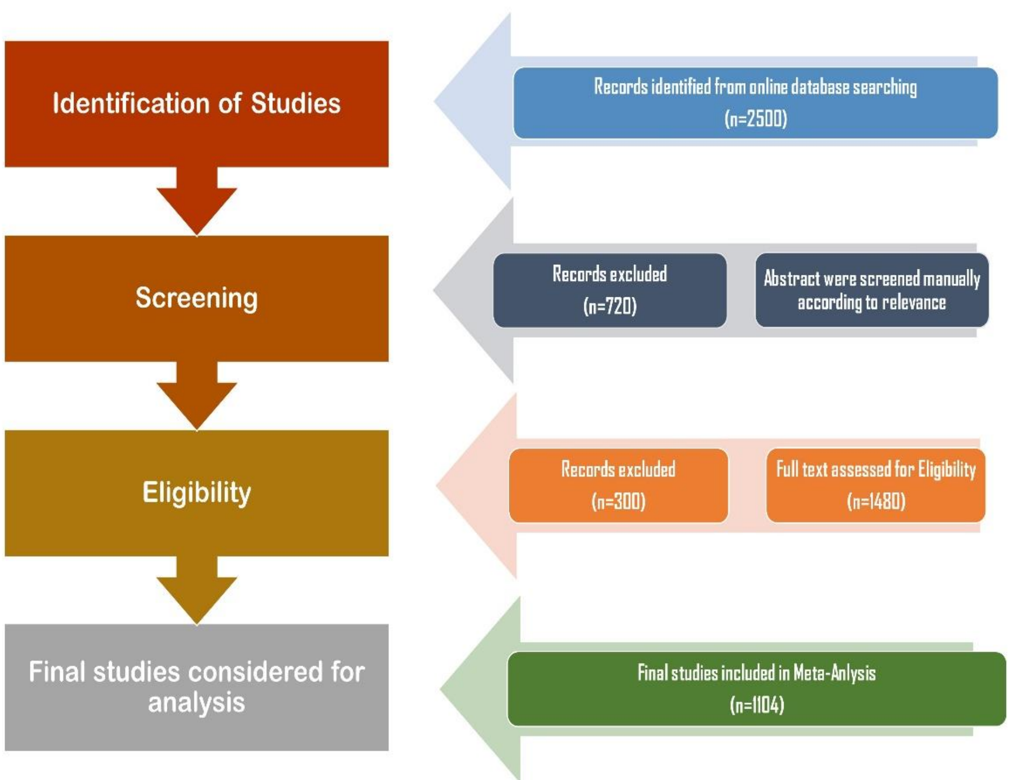


Fig.1 PRISMA framework showing the workflow and the number of studies included in the analysis.

The studies included for the final analysis were selected based on the criteria that the (i) the study should be based on field experiments, (ii) at least any one of the key ecosystem services is reported therein along with controls, and (iii) detailed information on the experiment, including the location, duration, and other agronomic practices, are reported. The studies included in the final analysis represented all the agro-climatic zones of the country (Fig.2).

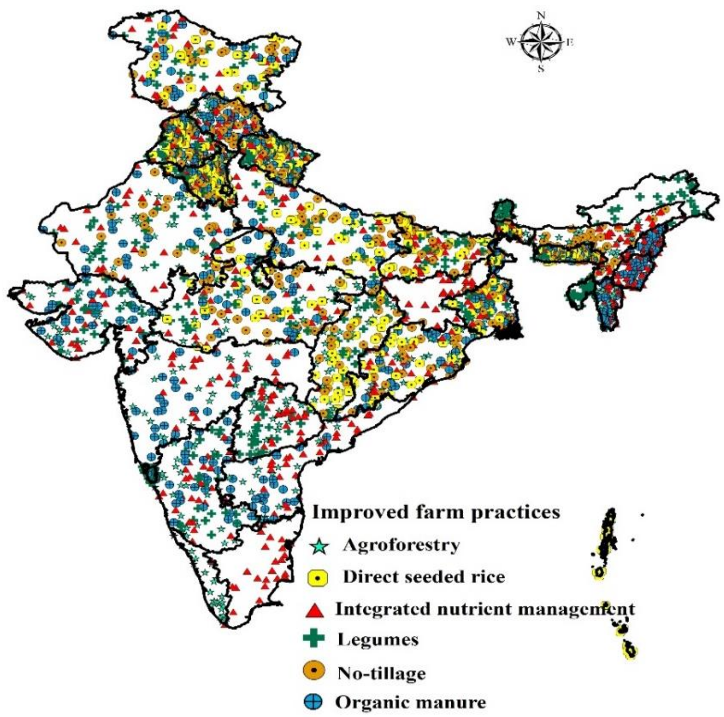


Fig.2 Geographical distribution of the studies considered for the analysis.(Source: Authors)

A summary of the studies used for meta-analysis is presented in Table 1. Excluding outliers, a total of 4,726 pair-wise observations from 1,104 studies were considered. The highest number of observations were for DSR (30%), followed by no-till wheat (26%), agroforestry (13%), legumes (12%), integrated nutrient management (11%), and organic manure (9%). Further, amongst ecosystem services, crop yield (42%), carbon sequestration (24%), soil fertility (15%), and water use (6%) were studied. The average duration of on-station experiments on ecosystem services related to improved agricultural practices ranges from 2.4 to 15.9 years.

Table 1. Summary statistics of studies

| Category | No. of Studies | Observations | Duration |
|---|---|---|---|
| **Direct Seeded Rice** | | | |
| Yield | 83 | 710 | 4.3±2.2 |
| C sequestration | 18 | 246 | 5.4±2.4 |
| Water use | 30 | 307 | 4.6±2.4 |
| GHG emission | 10 | 82 | 7.5±6.5 |
| Soil fertility | 6 | 55 | 7.3±2.6 |
| **No-till Wheat** | | | |
| Yield | 70 | 810 | 2.7±1.9 |
| C sequestration | 19 | 119 | 4.3±3.4 |
| Water use | 25 | 181 | 3.2±1.8 |
| GHG emission | 7 | 47 | 3.2±1.5 |
| Soil fertility | 10 | 64 | 4.7±2.7 |
| **Agroforestry** | | | |
| Yield | 9 | 107 | 5.9±2.0 |
| Soil fertility | 6 | 92 | 13.4±8.0 |
| C sequestration | 46 | 423 | 15.9±13.1 |
| **Legumes** | | | |
| Biological Nitrogen Fixation(BNF) | 26 | 118 | 2.4±1.2 |
| Soil fertility | 41 | 162 | 2.4±3.1 |
| C sequestration | 24 | 84 | 5.6±4.1 |
| Water use | 5 | 18 | 5.5±3.4 |
| GHG emissions | 12 | 50 | 2.3±0.7 |
| Yield | 26 | 123 | 2.5±2.6 |
| **Organic Manure** | | | |
| Yield | 75 | 82 | 7.3±9.9 |
| C Sequestration | 83 | 90 | 8.3±9.4 |
| Soil fertility | 69 | 212 | 8.3±8.5 |
| GHG emission | 13 | 18 | 6.9±11.8 |
| Water use | 8 | 11 | 6.6±9.0 |
| **Integrated Nutrient Management** | | | |
| Yield | 118 | 173 | 14.7±15.7 |
| C Sequestration | 127 | 172 | 15.7±15.3 |
| Soil fertility | 99 | 113 | 11.2±13.6 |
| GHG emission | 21 | 36 | 7.5±13.5 |
| Water use | 18 | 21 | 7.4±8.9 |
| **Total** | **1104** | **4726** | - |

[a] Note: Mean ± Standard Deviation

## 2.2 Methods

### *2.2.1 Quantification of ecosystem services*

Primary ecosystem services, including provisioning services (food), regulating services (carbon flow, nitrogen fixation, and water holding services), and supporting services (soil fertility and nutrient cycling) were considered for valuation. However, due to the unavailability of information, we have studied only key ecosystem services; hence, the total value of the ecosystem services provided by an improved agricultural practice may still be underestimated.

Ecosystem services have been quantified in a meta-analysis framework. The weighted average and the effect size of each study have been estimated as the response ratio (RR), i.e., ratio of the outcome variable of an improved agricultural practice and its counterfactual or control (Hedges and Gurevitch, 1999).

$$\text{Effect size} = RR = (X_T/X_C)$$

where $X_T$ and $X_C$ are the ecosystem services of improved and conventional practices, respectively. The observations are weighted by the number of replications. For a study where the number of observations is more than one, weights are divided by the total number of observations in that study. The weights have been estimated as:

$$\text{Weights (w)} \; \frac{N_T \text{ X } N_C}{N_T + N_C}$$

where $N_T$ and $N_C$ are the number of replicates of the treatment and control groups, respectively (Lam et al., 2013; Kumara et al., 2023). The paired t-test was performed to show the significance of the mean difference of different ecosystem services of improved agricultural practices.

*2.2.2 Valuation of ecosystem services*

We used the monetary approach, the most widely used approach for policy communication purposes (Christie et al., 2012). Moreover, direct and indirect valuation methods, such as market price, replacement cost, and benefit transfer methods, can be used to assign a value to an ecosystem service. It is important to note that estimated value represents indirect indicators of the society's willingness to pay for an ecosystem service (Costanza et al., 1997).

The total value of the ecosystem service provided by an improved agricultural practice is estimated as:

$$TVE = \sum VTE + \sum VNE$$

where TVE is the total value of the ecosystem service; and VTE and VNE are the values of its tradable and non-tradable components, respectively. Provisioning ecosystem services are directly traded in the market and are valued at their market prices. Non-marketed ecosystem services are estimated using an indirect valuation approach following Sandhu et al. (2008). The details of the coefficients used for monetization of different ecosystem services are shown in Table 2.

Table 2. Coefficients used in the valuation of ecosystem services

| **Ecosystem service** | **Response** | **Estimating formula** | **Price** | **Source** |
|---|---|---|---|---|
| **Provisioning services** | | | | |
| Food | Yield | Yield (t $ha^{-1}$) x Price(Rs $ton^{-1}$) | Minimum support price of crops, 2022/23 | Directorate of Economics and Statistics, Ministry of Agriculture & Farmers' Welfare |
| **Supporting services** | | | | |

| | | | | |
|---|---|---|---|---|
| Soil fertility | Nutrient (NPK) availability in soil (net soil contribution) | Economic price of fertilizers 2022/23 | Rs.110.9 $Kg^{-1}$ of N<br>Rs.132.2 $Kg^{-1}$ of P<br>Rs. 86.6 $Kg^{-1}$ of K | Sandhu et al. (2008) |
| Nitrogen fixation | Amount of nitrogen fixed | Amount of N fixed (kg $ha^{-1}$) x Price of N fertilizer (Rs. $kg^{-1}$) | Rs.110.9 $Kg^{-1}$ of N | Sandhu et al. (2008); Nayak et al. (2019); Rasheed et al. (2021) |
| Soil erosion control | Amount of NPK retained in soil | Economic price of fertilizers 2022/23 | Rs.110.9 $Kg^{-1}$ of N<br>Rs.132.2 $Kg^{-1}$ of P<br>Rs. 86.6 $Kg^{-1}$ of K | Sandhu et al. (2008) |
| **Regulating services** | | | | |
| Carbon Sequestration | Net carbon change after accounting emission | Amount of soil carbon sequestered (t $ha^{-1}$) x Price of carbon (Rs. $ton^{-1}$ of $CO_2e$) | Voluntary carbon market price of carbon credit Rs.726 $ton^{-1}$, 2022 | Nayak et al. (2019); Sandhu et al. (2008); Donofrio et al. (2022) |
| Water holding services | Irrigation water saved | Irrigation water saved ($m^3$ $ha^{-1}$) x Cost of irrigation water (Rs. $m^3$ $ha^{-1}$) | Rs.0.8 per $m^3$ | Pathak et al. (2017) |

### *2.2.3 Assessing trade-offs*

An agricultural practice generating ecosystem services need not necessarily synergistic effect on crop yields. There could be a trade-off between yield and other ecosystem services. Therefore, we conducted a trade-off analysis to examine the relationship between crop yield and at least one non-tradable ecosystem service. The win-win, lose-lose, and trade-off observations were identified and then plotted on a Cartesian plane for comparison (Tamburini et al., 2020). Additionally, Spearman's rank correlation was also calculated.

## 3. Results and Discussion

### *3.1 Direct Seeded Rice (DSR)*

Rice is one of the predominant staple food crops, providing energy and nutrition to more than half of the world's population (Ainsworth, 2008; Shiferaw et al., 2013). India is second largest producer of rice, after China. In 2022/23, India produced 122.2 million tonnes from an area of 45.07 million hectares. However, the sustainability of rice-based production systems is threatened by several factors, including water scarcity, rising cost of inputs, and climate change (Ladha et al., 2009; Chaudhary et al., 2023).

Traditionally, rice is cultivated as a puddled transplanted crop. Although puddling helps crop establishment, it affects soil quality through clod formation and poor permeability (Chaudhary et al., 2023). Moreover, puddling is a labour- and water-intensive activity. Between 3,000 and 5,000 litres of water is required to produce one kilogram of rice (Bouman and Tuong, 2001; Kirchhof et al., 2011). Direct seeding of rice (DSR) purportedly solves the limitations of traditional transplantation method. As its name connotes, DSR seeds are directly sown in the field unlike conventional puddled transplantation.

We evaluate the key ecosystem services provided by DSR. These include food provision, water use, carbon sequestration, nitrogen fixation, and soil fertility (available NPK). A comparative analysis of the farm-level impacts of DSR, particularly of traditional puddled transplanted rice, on these ecosystem services is presented below.

#### *3.1.1 Impacts of DSR on ecosystem services*

Switching to DSR from the traditional puddled method of transplanting causes reduction in crop yield by 11% (Table 3). The lower yield associated with direct seeding is attributed to higher weed infestation and fewer spikelets per panicle compared to transplanted rice (Xu et al., 2019; Singh et al., 2016; Rao et al., 2007;

Jat et al., 2019). Weed infestation is reportedly significantly higher during the early growth stages (Rao et al., 2007; Kumar et al., 2008). Effective management of weeds is, therefore, crucial to avoid crop loss and to improve input-use efficiency (Singh et al., 2008; Sims et al., 2018).

Despite the yield disadvantage, direct seeding has significant environmental benefits, using 18% less water than transplanted rice (Table 3) and reducing the need for nursery raising and puddling (Jat et al., 2019). It is important to note that the extent of water saving depends on several the factors, including irrigation scheduling, and the rate of evapotranspiration.

DSR has a conspicuous effect on soil organic carbon stock. Compared to puddled rice, sequestered carbon is 15% higher with DSR (Table 3). Slower decomposition, reduced oxidation, increased macro-aggregate associate carbon, and better physical protection of particulate matter result in higher soil organic carbon stock (Parihar et al., 2018; Bhattacharyya et al., 2012; Page et al., 2020). Additionally, DSR causes a significant reduction in GHGs—38% over the transplanted rice. Moreover, it leads to an improvement of over 20% in soil nutrients (NPK). Several studies have demonstrated that DSR helps improve soil health, enzymatic and microbial activities, and soil carbon content (Singh et al., 2022; Chaudhary et al., 2023; Kumar et al., 2021).

Table 3. Impacts of direct seeded rice (DSR) on ecosystem services

| Ecosystem service | DSR | TPR | Net change* | Response ratio |
|---|---|---|---|---|
| Yield(t $ha^{-1}$) | 4.79 | 5.37 | -0.58(10.80) | 0.89 |
| Water use (mm $ha^{-1}$) | 1519 | 1853 | -334(18.02) | 0.82 |
| Carbon sequestration(t $ha^{-1}$ $CO_2$ eq) | 10.95 | 9.75 | 1.20(12.30) | 1.12 |
| GHG emission(Kg $ha^{-1}$) | 280 | 450 | -170(37.77) | 0.62 |
| Nutrient availability | | | | |
| ▪ N(Kg $ha^{-1}$) | 160 | 149 | 11(7.38) | 1.07 |
| ▪ P(Kg $ha^{-1}$) | 35 | 27 | 8(29.62) | 1.31 |
| ▪ K(Kg $ha^{-1}$) | 277 | 216 | 60(27.77) | 1.28 |
| Total NPK(Kg $ha^{-1}$) | 472 | 392 | 80(20.40) | 1.20 |

Note: * indicates 1 percent-level of significance; DSR: Direct Seeded Rice; TPR: Transplanted Rice; values in parenthesis indicate percent change

### *3.1.2. Valuation of ecosystem services*

The monetized values of ecosystem services provided by DSR are shown in Table 4. Despite a decline in its provisioning function, i.e., yield, the total economic value of the ecosystem services of DSR remains positive, estimated at Rs1,503/ha. The value of the non-traded services (i.e., climate regulation, water saving, soil fertility, and nitrogen fixation) is estimated at Rs13,335/ha, comprising almost half of the total value of ecosystem services (Fig.3). DSR is practiced on 0.96 million ha (approximately 26% of total rice area) in the country (Ravi et al., 2010), and the total economic value of non-marketed ecosystem services associated with DSR is estimated at Rs128,170 million per year. This represents the value of the benefits of DSR accrued by society, but the value of this positive externality is not realized by the farmers.

These estimates of the ecosystem services attributable to DSR are conservative. We valued only a small number of ecosystem services because of lack of data and studies on other services such as biodiversity, biocontrol of pests, soil formation, groundwater recharge, and mineralization of plant nutrients.

Table 4. Economic value of ecosystem services of DSR

| Ecosystem service | Physical magnitude | Economic value ($Rs.ha^{-1}year^{-1}$) |
|---|---|---|
| Food ($t\ ha^{-1}$) | -0.58 | -11,832 |
| Water saving ($m^3\ ha^{-1}$) | 3340 | 2,672 |
| Carbon sequestration ($t\ ha^{-1}CO_2$ eq) | 1.37 | 994 |
| Soil fertility | | |
| ▪ N($Kg\ ha^{-1}$) | 11.06 | 1,226 |
| ▪ P($Kg\ ha^{-1}$) | 8.41 | 1,111 |
| ▪ K($Kg\ ha^{-1}$) | 60.33 | 5,225 |
| Total NPK ($Kg\ ha^{-1}$) | 79.79 | 7,562 |
| Nitrogen fixation($Kg\ ha^{-1}$) | 19.00 | 2,107 |
| Value of traded services | | -11,832 |
| Value of non-traded services | | 13,335 |
| Total value of ecosystem services | | 1,503 |
| Value of externality | | 13,335 |

Note: Value of food and carbon sequestration is estimated using direct market price method; Soil fertility, nitrogen fixation and water saving estimated using replacement cost and benefit transfer approach respectively.

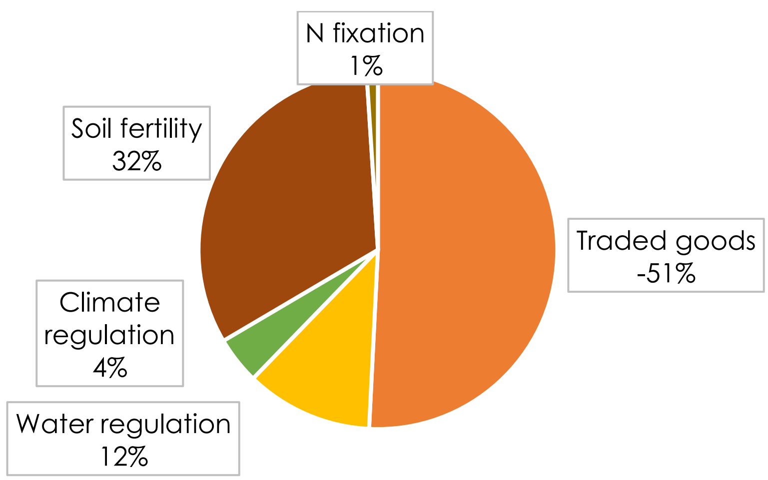


Fig. 3 Contribution of ecosystem services of DSR (% share in their total value)

### *3.2. No-till Wheat*

Wheat is the second-largest staple food crop in India in terms of both production and consumption after rice. In 2022/23, the country produced 112.18 million tonnes of wheat from 31.86 million ha of land (Press Information Bureau, GoI, 2023).

About 56% of the total wheat area is concentrated in the Indo-Gangetic plains, followed by Madhya Pradesh (22%), Rajasthan (9%), and other states.

Although conventional tillage practices help improve crop yields, they also impose negative externalities on natural resources and the environment in terms of the reduction in soil microbial activities, biodiversity, and GHG emissions. Several studies have shown deceleration in yield growth due to the adoption of these farm practices (Sekar and Pal, 2012; Kumar et al., 2002; Kandpal et al., 2023). Conservation practices, including no/zero tillage, residue retention, and crop rotation, are advocated to restore the ecological balance, rejuvenate soil biodiversity, help carbon sequestration, and reduce water requirements and GHG emissions. We looked into the impacts of no-tillage on food provision, water use, carbon sequestration, and soil fertility in physical and monetary terms.

### *3.2.1 Impact of no-till wheat*

Compared to conventional practices, no-tillage marginally improves crop yield (Table 5) because of early sowing, which reduces weed infestation at early stages of the crop and helps the crop escape heat stress at anthesis and grain-filling stages (Mehlka et al., 2000; Kumara et al., 2023; Jat et al., 2019; Sidhu et al., 2007; Erenstein et al., 2008).

With no-tillage, irrigation water use is reduced by 8% due to the reduction in evaporation, minimal soil disturbance, and conservation of soil moisture (Jat et al., 2013; Parihar et al., 2016; Siddique et al., 2012). Further, by sequestering more carbon, no-tillage helps mitigate climate change. Our results indicate that no-tillage sequesters 6% more carbon and reduces GHG emission by 14% (Table 5). It also enhances soil nutrients by 15% (Table 5).

Table 5. Impacts of no-till wheat on ecosystem services

| Ecosystem service | No-tillage | Conventional tillage | Net change* | Response Ratio |
|---|---|---|---|---|
| Yield (t $ha^{-1}$) | 4.26 | 4.18 | 0.08(1.91) | 1.02 |
| Water use (mm $ha^{-1}$) | 608 | 664 | -55.81(8.4) | 0.92 |
| C sequestration (t $ha^{-1}$ $CO_2$ eq) | 13.51 | 12.75 | 0.76(6.0) | 1.06 |
| GHG emission(kg $ha^{-1}$) | 193 | 225 | -31.80(14.12) | 0.86 |
| Nutrient availability | | | | |
| ▪ N(Kg $ha^{-1}$) | 151 | 139 | 11.90 (8.58) | 1.09 |
| ▪ P(Kg $ha^{-1}$) | 21 | 19 | 2.84(15.23) | 1.15 |
| ▪ K(Kg $ha^{-1}$) | 227 | 190 | 37.00 (19.47) | 1.19 |
| Total NPK(Kg $ha^{-1}$) | 399 | 348 | 51.74(14.86) | 1.14 |

Note: * indicate 1 percent-level of significance; values in parenthesis indicate percent change

### *3.2.2 Valuation of no-till wheat ecosystem services*

Table 6 shows the estimated monetary values of ecosystem services of no-till wheat. The total value of the additional ecosystem services of no-till is estimated to be Rs7,685/ha, of which the non-tradables account for as much as 78%.

Wheat cultivation is confined to India's northwestern states (Punjab and Haryana) where the implementation of no-tillage has the potential to generate ecosystem services worth Rs. 45,112 million every year.

Table 6. Economic value of ecosystem services due to no-tillage in wheat

| **Ecosystem service** | **Physical magnitude** | **Economic value (Rs. $ha^{-1}year^{-1}$)** |
|---|---|---|
| Food (t $ha^{-1}$) | 0.08 | 1,700 |
| Water Saving ($m^3$ $ha^{-1}$) | 558 | 446 |
| Carbon sequestration (t $ha^{-1}$ $CO_2$ eq) | 0.88 | 639 |
| Soil fertility | | |
| ▪ N(Kg $ha^{-1}$) | 11.90 | 1,320 |
| ▪ P(Kg $ha^{-1}$) | 2.84 | 375 |
| ▪ K(Kg $ha^{-1}$) | 37 | 3,205 |
| Total NPK (Kg $ha^{-1}$) | 51.74 | 4,899 |
| Value of traded services | | 1,700 |
| Value of non-traded services | | 5,985 |
| Total value of ecosystem services | | 7,685 |
| Value of externality | | 5,985 |

Note: Value of food and carbon sequestration is estimated using direct market price method; Soil fertility and water saving estimated using replacement cost and benefit transfer approach respectively.

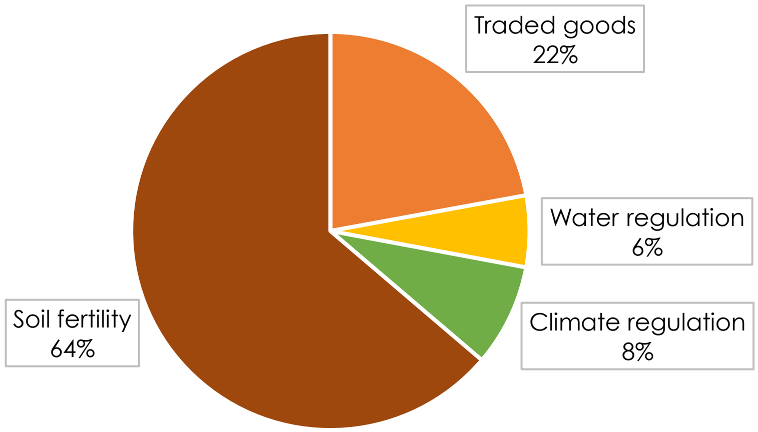


Fig. 4. Share of each service in the total value of ecosystem services due to no-till wheat

### 3.3. *Legumes*

Legume crops play an important role in improving human nutrition due to their higher protein content, dietary fibre, and essential vitamins (Maphosa and Jideani, 2017). The consumption of pulses also helps prevent chronic diseases like type 2 diabetes, cardiovascular diseases, obesity, and cancer (Burstin et al., 2011).

Leguminous crops provide several non-tradable services such as biological nitrogen fixation (BNF), carbon sequestration, and water conservation. BNF is their most important service. Legumes naturally fix nitrogen in the soil through enzyme reactions between prokaryotes and plants, thus reducing requirements of external nitrogen (Dequiedt and Moran, 2015) and resulting in lower $N_2O$ emissions.

Rotating and inter-cropping legumes is considered one of the most efficient, climate-resilient paths to sustainable agricultural production (Fig. 5).

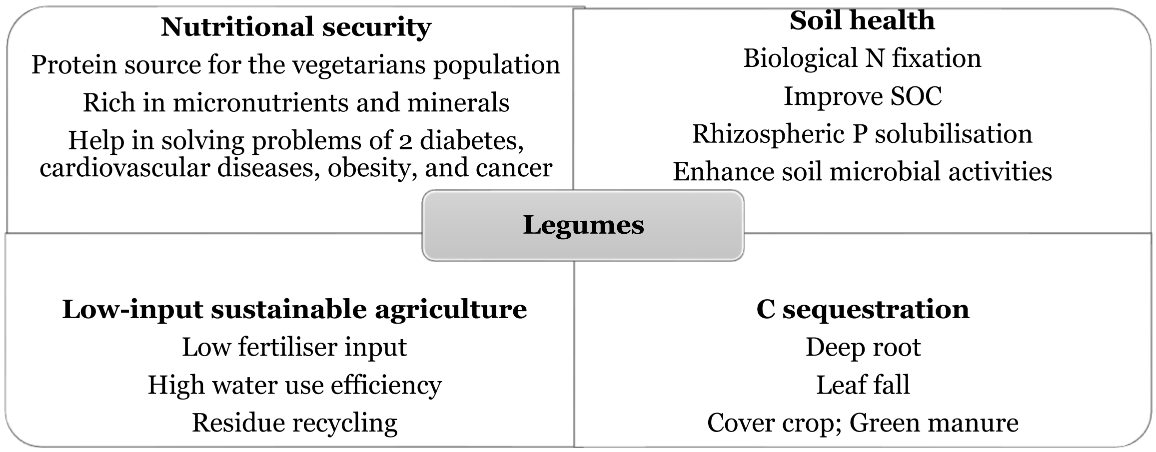


Fig. 5. Legumes for sustainable agriculture

India is the largest producer of pulses, but the production is insufficient to meet the expanding domestic demand. Leguminous crops, including pulses and oilseeds (i.e., groundnut and soybean), occupy more than one-fifth (45 million ha) of the gross cropped area. The Government of India has been implementing several programs to increase their production; however, these programs have rarely focussed on providing incentives to legume cultivators for non-marketed environment benefits.

Although, legumes provide several non-tradable ecosystem services, we assess the economic contribution of biological nitrogen fixation (BNF), carbon sequestration, GHG emissions, soil health, and water conservation of legume-based systems over conventional cereal-based systems.

*3.3.1. Impact of legume-based systems on ecosystem services*

Leguminous crops an average fix 70.03 kg/ha of nitrogen from the atmosphere (Table 7). Groundnut has the highest nitrogen fixation potential (124.2 kg/ha), followed by soybean, green gram, and black gram. The BNF potential of different legumes, however, varies depending on the Rhizobial strain, species or varieties; above and below ground biomass; and soil pH, moisture, nutrients, and temperature (Aranjuelo et al., 2007). The symbiotic associations resulting from BNF represent the most significant ecosystem service, providing several benefits for agroecosystems: replenishing of the soil organic nitrogen reservoirs, improving in soil nitrogen availability, and reducing negative environmental externalities by reducing use of inorganic nitrogen fertilizer. Pulses also contribute to soil health by improving the soil organic carbon and nutrient availability (Hazra et al., 2020). Our meta-analysis shows that legume crops sequester 17% more carbon ($CO_2$ equivalent) than non-leguminous crops such as cereals (Table 7), resulting from higher crop biomass and leaf fall, expansive carbon-rich root systems, and their symbiotic associations of nitrogen-fixation (Bayer et al., 2016; Hazra et al., 2018).

Reducing the use of nitrogenous fertilizers on legumes reduces GHG emissions. Additionally, legumes enhance soil fertility by increasing soil nutrients. Moreover, leguminous crops require on average 25% less water compared to several other crops.

Table 7 Impact of legumes on ecosystem services

| Ecosystem services | Legume based system | Control | Net change* | Response ratio |
|---|---|---|---|---|
| Yield (t $ha^{-1}$)# | 4.55 | 3.68 | 0.87(23.64) | 1.24 |
| Biological nitrogen fixation (kg $ha^{-1}$) | 70.03 | 0.00 | 70.03 | - |
| Carbon sequestration (t $ha^{-1}$ $CO_2$ eq) | 15.99 | 13.69 | 2.31(16.84) | 1.17 |
| GHG emission (kg $ha^{-1}$) | 1,237 | 1,833 | -596(32.52) | 0.67 |
| Nutrient availability | | | | |
| ▪ N(kg $ha^{-1}$) | 231 | 219 | 12(5.38) | 1.05 |
| ▪ P(kg $ha^{-1}$) | 22 | 20 | 2(10) | 1.10 |
| ▪ K(kg $ha^{-1}$) | 182 | 168 | 14(8.33) | 1.08 |
| Total NPK(kg $ha^{-1}$) | 435 | 407 | 28(6.83) | 1.07 |
| Water use (mm $ha^{-1}$) | 897 | 1,194 | -297(24.87) | 0.75 |

Note: * indicate 1 percent level of significance; #indicate wheat equivalent yield; values in parenthesis indicate percent change

### *3.3.2. Valuation of legume ecosystem services*

The estimated economic values of tradable and non-tradable ecosystem services of legume-based cropping systems are presented in Table 8. Legumes provide additional benefits of Rs32,672/ha/year, 47% of which comes from non-tradable ecosystem services. BNF accounts for the highest share (24%) of the total value of the ecosystem services, followed by the soil fertility (9%), water saving (7%), carbon sequestration (5%), and GHG emissions (Fig.6).

At the all-India level, legume-based systems have the potential to generate non-tradable ecosystem services worth Rs623,080 million annually from 41.15 million hectares of land. Expanding legume cropping area can further improve their environmental and nutritional benefits. However, legume crops lack a comparative advantage over other crops, especially rice and wheat. It is, therefore, imperative to incentivize farmers to grow leguminous crops to conserve the environment, maintain soil health, and improve human nutrition and health, and to reduce import dependence.

Table 8 Economic value of ecosystem services from legumes

| **Ecosystem services** | **Physical magnitude** | **Economic value (Rs. $ha^{-1}year^{-1}$)** |
|---|---|---|
| Food(t $ha^{-1}$) | 0.87 | 17,531 |
| Water saving ($m^3$ $ha^{-1}$) | 2,970 | 2,376 |
| Biological nitrogen fixation (kg $ha^{-1}$) | 70.03 | 7,766 |
| Carbon sequestration (t $ha^{-1}$ $CO_2$ eq) | 2.31 | 1,759 |
| Soil fertility | | |
| ▪ N(kg $ha^{-1}$) | 12 | 1,330 |
| ▪ P(kg $ha^{-1}$) | 2 | 264 |
| ▪ K(kg $ha^{-1}$) | 14 | 1,212 |
| Total NPK(kg $ha^{-1}$) | 28 | 2,806 |
| Reduced GHG emission (kg $ha^{-1}$ $CO_2$ eq) | 597 | 456 |
| Value of traded services | | 17,531 |
| Value of non-traded services | | 15,142 |
| Total value of ecosystem services | | 32,672 |
| Value of externality | | 15,142 |

Note: Value of food, carbon sequestration, and GHG emission is estimated using direct market price method; Soil fertility, BNF and water saving estimated using replacement cost and benefit transfer approach respectively.

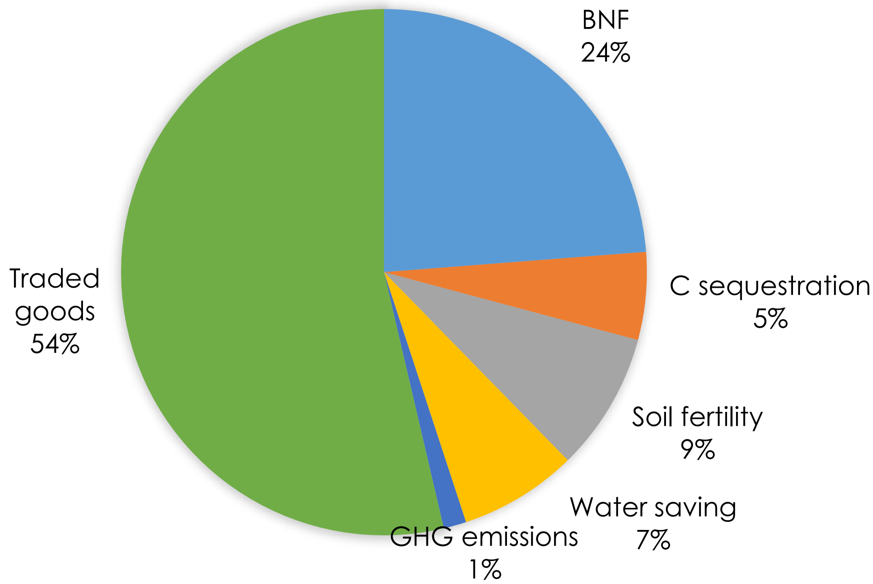


Fig. 6 Share of each ecosystem service in the total value of legume ecosystem services

*3.4 Organic manures*

Manures enhance soil organic carbon and nutrient supply, and by replacing chemical fertilizers, contribute to soil and environmental health (Gregorich et al., 2001). Their use also contributes to sustainable improvements in crop yields (Manna et al., 2005; Bayu et al., 2006). Therefore, organic manures have the potential to alleviate the harmful impacts of intensive agriculture (Reganold and Wachter, 2016). Among different types of manures, farmyard manure (FYM) is the most widely used in Indian agriculture.

*3.4.1 Impact of FYM on ecosystem services*

Crop response to FYM is relatively poor. The wheat-equivalent yield of crops is about 6% less with sole use of FYM rather than chemical fertilizers (Table 9). This is attributable to its slow release of nutrients, whereas nutrients from inorganics are readily available to crops (Zhang et al., 2019). In order to make the required amounts of nutrients available to crops, high rates of FYM are recommended but are costlier than chemical fertilizers.

Compared to inorganic fertilizers, FYM enhances soil nutrients by about 5% , but over a longer period. Organic manures are rich in nutrients and act as a binding agent that helps improve microbial and enzymatic activities (Wang et al., 2017). Further, FYM improves water holding capacity and reduces evaporation-transpiration (Zhang et al., 1998), thereby helping conserve soil moisture and reduce crops' water requirement by 8%.

FYM, as a nutrient- and nitrogen-rich organic matter, increase plant biomass (Gregorich et al., 2001), which in turn significantly enhances carbon sequestration by about 15% (Table 9). FYM also causes an increase in earthworm populations, which support internal ecosystem processes. However, because the contribution of earthworms, is integrated into other ecosystem services (Fu et al., 2010), we do not consider their contribution separately.

FYM also emits GHGs, mainly nitrous oxide (Shakoor et al., 2021), by increasing labile carbon in the soil, accelerating soil microbial activity, and increasing nitrification and denitrification rates (Jones et al. 2005). Our analysis shows that sole application of FYM emits about 6% more GHGs than inorganic fertilizers. Yet, when accounting for GHG emissions, FYM improves net carbon sequestration.

Table 9 Impact of FYM application on ecosystem services

| Ecosystem services | FYM | NPK | Net change | Response ratio |
|---|---|---|---|---|
| Yield (t $ha^{-1}$)# | 4.82 | 5.13 | -0.31** | 0.94 |
| Carbon sequestration (t $ha^{-1}$ $CO_2$ eq) | 16.80 | 14.64 | 2.16** | 1.15 |
| GHG emission (kg $ha^{-1}$) | 676 | 635 | 40** | 1.06 |
| Water use (mm $ha^{-1}$) | 577 | 626 | -49.25 | 0.92 |
| Nutrient availability | | | | |
| ▪ N(kg/ha) | 213 | 200 | 13 ** | 1.07 |
| ▪ P(kg/ha) | 28 | 27 | 1 * | 1.04 |
| ▪ K(kg/ha) | 211 | 204 | 7* | 1.03 |
| Total NPK | 452 | 431 | 21** | 1.05 |

Note: **&*Indicate 1% & 5% level of significance; # wheat equivalent yield

### *3.4.2 Valuation of ecosystem services from FYM*

The estimates of the economic contribution of ecosystem services of FYM are presented in Table 10. The total economic value of tradable and non-tradable ecosystem services, is negative to the tune of Rs2,001/ha. This is mainly due to the lower value of the tradable services, i.e., crop yields (Rs6,247/ha). However, the contribution of the non-tradable services is estimated at Rs4,245/ha, (40% of the total value of ecosystem services) (Fig. 7). It appears that FYM is not a practical replacement for inorganic fertilizers. The primary function of FYM is to improve soil fertility, but the monetary value of enhanced soil nutrients only accounts for 21% of the total economic value.

Table 10. Economic value of ecosystem services from FYM application

| Ecosystem services | Physical magnitude | Economic value (Rs. $ha^{-1}year^{-1}$) |
|---|---|---|
| Food (t $ha^{-1}$) | -0.31 | -6,247 |
| Water saving ($m^3$ $ha^{-1}$) | 492 | 394 |
| Carbon sequestration (t $ha^{-1}$ $CO_2$ eq) | 2.11 | 1,616 |
| Soil fertility | | |
| ▪ N (kg/ha) | 13 | 1,466 |
| ▪ P(kg/ha) | 1 | 150 |
| ▪ K (kg/ha) | 7 | 619 |
| Total NPK (kg/ha) | 21 | 2,235 |
| Value of traded services | | -6,247 |
| Value of non-traded services | | 4,245 |
| Total value of ecosystem services | | -2,001 |
| Value of externality | | 8,248 |

Note: Value of food and carbon sequestration is estimated using direct market price method; Soil fertility and water saving estimated using replacement cost and benefit transfer approach respectively.

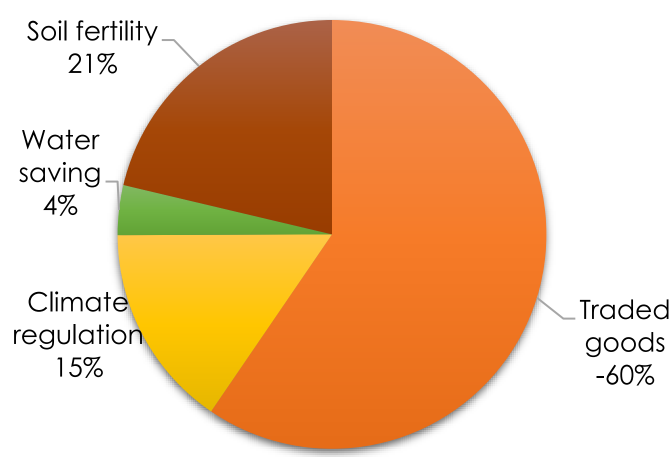


Fig. 7. Share of each service in the total value of ecosystem services under organic manure

### *3.5 Integrated nutrient management (INM)*

While the application of only organic manures causes trade-offs between crop yields and ecosystem services, integrated nutrient management (INM)—the joint use of organic manures and inorganic fertilizers has the potential to sustain crop yields while reducing the negative externalities to the environment (Darjee et al.,2022). INM is, thus, a promising option to balance agricultural productivity and natural resource management (Zhang et al., 2019).

#### *3.5.1 Impact of INM on ecosystem services*

INM has a positive effect on crop yields—16% more compared to the sole application of chemical fertilizers (Table 11)—notably improving nutrient mobilization, soil enzyme activity, and root development, and providing nutrients to the crops in balanced proportions (Darjee et al., 2022). INM also helps preserve water and soil fertility. INM application enhances NPK availability by 13%, reduces crops' water requirement by 11%, and sequesters 22% more carbon over sole application of chemical fertilizers. In addition, it reduces crops' water requirement by 11% and sequesters 22% more carbon (Table 11). Despite these benefits, however, INM results in 37% more GHG emissions (Table 11).

Table 11 Impact of INM application on ecosystem services

| **Ecosystem services** | **INM** | **NPK** | **Net change** | **Response ratio** |
|---|---|---|---|---|
| Yield (t ha$^{-1}$)# | 5.57 | 4.81 | 0.76 (15.80)** | 1.16 |
| Water use (mm ha$^{-1}$) | 447 | 504 | -57.53 (11.40)* | 0.89 |
| Carbon sequestration (t ha$^{-1}$ $CO_2$ eq) | 11.46 | 9.41 | 2.09 (21.79)* | 1.22 |
| GHG emission (kg ha$^{-1}$) | 1,100 | 805 | 295 (36.05)** | 1.37 |
| Nutrient availability | | | | |
| ▪ N(kg ha$^{-1}$) | 233 | 205 | 27 (13.66)** | 1.14 |
| ▪ P(kg ha$^{-1}$) | 42 | 35 | 7 (20.00)** | 1.20 |
| ▪ K(kg ha$^{-1}$) | 253 | 227 | 26 (11.45)** | 1.11 |
| Total NPK(kg ha$^{-1}$) | 528 | 467 | 60 (13.06) | 1.13 |

Note: **&*Indicate 1% & 5% level of significance; #wheat equivalent yield; values in parenthesis indicate percentage change

### *3.5.2 Valuation of ecosystem services of INM*

The value of ecosystem services of INM is estimated at Rs23,312/ha. Of this, non-tradable services comprise 34%. Soil fertility offers the highest benefits, followed by carbon sequestration and water saving (Fig. 8).

Table 12. Economic value of ecosystem services from INM

| Ecosystem services | Physical magnitude | Economic value (Rs. $ha^{-1}year^{-1}$) |
|---|---|---|
| Food (t $ha^{-1}$) | 0.76 | 15314 |
| Water saving ($m^3$ $ha^{-1}$) | 575 | 460 |
| C sequestration (t $ha^{-1}$ $CO_2$ eq) | 1.79 | 1369 |
| Soil fertility | | |
| ▪ N (kg $ha^{-1}$) | 27 | 2994 |
| ▪ P(kg $ha^{-1}$) | 7 | 925 |
| ▪ K (kg $ha^{-1}$) | 26 | 2252 |
| Total NPK (kg $ha^{-1}$) | 60 | 6171 |
| Value of traded services | | 15314 |
| Value of non-traded services | | 7998 |
| Total value of ecosystem services | | 23312 |
| Value of externality | | 7998 |

Note: Value of food and carbon sequestration is estimated using direct market price method; Soil fertility and water saving estimated using replacement cost and benefit transfer approach respectively.

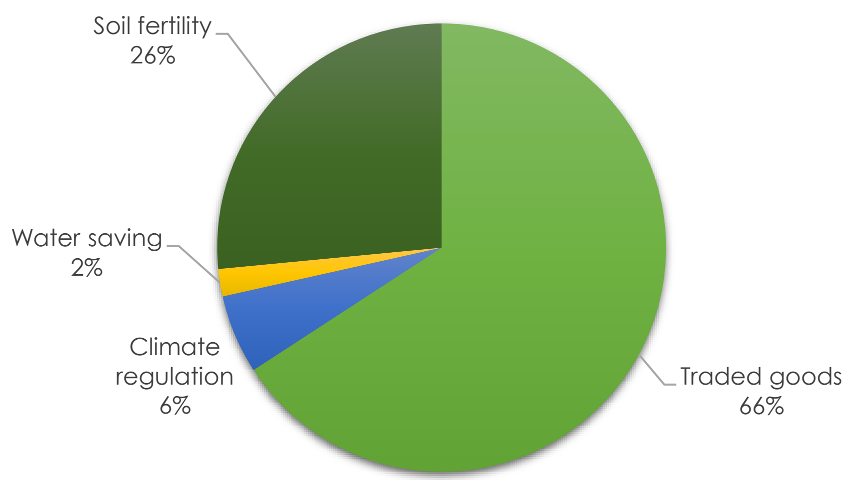


Fig. 8. Share of each service in total value of economic services under INM

### *3.6. Agroforestry*

Agroforestry is recognized, nature-based food production system and sustainable land management practice that addresses climate change far better than conventional farming (IPCC, 2019; Torralba, 2016). Agroforestry effectively utilizes agricultural land and rehabilitates degraded and waste lands (Röhrig et al., 2020). The key ecosystem benefits of agroforestry include additional income, biodiversity conservation, prevention of soil erosion, nutrient loss aversion, and climate regulation through carbon sequestration (Foster and Neufeldt, 2014; MEA, 2005; Oteros-Rozas et al., 2018; Crous-Duran et al., 2020). The ecosystem benefits of agroforestry, however, depend on the cropping intensity, tree species, and land cover (Rolo et al., 2021).

In India, agroforestry is an age-old practice where trees are intentionally incorporated into the cropping systems to provide fodder, fuel, and food (Chavan et al., 2015). Currently, agroforestry is practiced on 25.32 million hectares of land (8.2% of the total geographical area) in India (Dhyani et al., 2014).

#### *3.6.1 Impact of agroforestry*

Crop yields under agroforestry are 12% lower than conventional farming (Table 13). This is attributed to the reduction in light intensity due to tree canopies, competition between tree and crops, and presence of allelopathic effects (Newaj et al., 2003; Sarvade et al., 2014). Other studies have also reported similar findings (Newaj et al., 2003; Bijalwan, 2011; Dhanya et al., 2013; Adhikari et al., 2019). Nevertheless, the yield disadvantage can be offset by the direct and indirect benefits derived from the products and byproducts of the trees (Adhikari et al., 2019; Dhanya et al., 2013).

The findings show that agroforestry sequesters about 10% more carbon than conventional cropping systems (Table 13). Higher rates of carbon sequestration are mainly due to the increase in the quantity and quality of biomass as well as optimal use of inputs (Jobba'gy and Jackson, 2000; Lal, 2001; Nair et al., 2010). Nevertheless, the rate of carbon sequestration depends on the tree species and agroecological conditions (Albrecht and Kandji, 2003).

Agroforestry enhances availability of soil nutrients by 19% due to integration of leaf litter, in situ decomposition of roots, and favourable soil moisture (Patel et al., 2010; Lodhiyal et al., 2017; Singh et al., 2017). In addition, agroforestry reduces soil erosion by 49%, a significant impact.

Table 13 Impacts of agroforestry on ecosystem services

| **Ecosystem service** | **Agroforestry** | **Control** | **Net change** | **Response Ratio** |
|---|---|---|---|---|
| Yield ($t\ ha^{-1}$)# | 2.93 | 3.34 | -0.41(-12.27)* | 0.88 |
| Carbon sequestration ($t\ ha^{-1}\ CO_2$ eq) | 13.28 | 12.11 | 1.17 (9.66)** | 1.10 |
| Nutrient availability | | | | |
| ▪ N($kg\ ha^{-1}$) | 217 | 188 | 29.00(15.43)** | 1.15 |
| ▪ P($kg\ ha^{-1}$) | 17 | 14 | 2.81(20.22)** | 1.20 |
| ▪ K($kg\ ha^{-1}$) | 180 | 147 | 33.27(22.69)** | 1.23 |
| Total NPK($kg\ ha^{-1}$) | 414 | 349 | 65(18.67)** | 1.18 |
| Soil erosion ($t\ ha^{-1}$) | 4.97 | 9.70 | -4.73(-48.74)** | 0.51 |

Note: **&* indicate 1% & 5% level of significance; #wheat equivalent yield; values in parenthesis indicate percent change

### *3.6.2 Valuation of agroforestry ecosystem services*

Table 14 summarizes the monetary value of non-tradable ecosystem services of agroforestry. It is estimated at Rs7,759/ha/year, primarily due to improvements in soil fertility, higher rates of carbon sequestration, and nutrient retention in soil due to reduction in soil erosion.

Table 14 Value of non-traded ecosystem services under agroforestry

| Ecosystem service | Physical magnitude | Economic value (Rs. $ha^{-1}year^{-1}$) |
|---|---|---|
| Carbon sequestration (t $ha^{-1}$) | 1.17 | 849 |
| Soil fertility | | |
| ▪ N(kg $ha^{-1}$) | 29.00 | 3,216 |
| ▪ P(kg $ha^{-1}$) | 2.81 | 371 |
| ▪ K(kg $ha^{-1}$) | 33.27 | 2,882 |
| Total NPK (kg $ha^{-1}$) | 65.08 | 6,468 |
| Nutrient retention (NPK kg $ha^{-1}$) | 4.00 | 441 |
| Value of non-traded services | | 7,759 |
| Value of externality | | 7,759 |

Note: Value of carbon sequestration is estimated using direct market price method; Soil fertility and nutrient retention is estimated using replacement cost approach.

## 4. Win-win effects and trade-offs between tradable and non-tradable ecosystem services

We identified win-win, lose-lose, and trade-off relationships between crop yield and ecosystem services by estimating the effect sizes. The relationship of improved agricultural practices' impacts on yield and at least one concomitant ecosystem service have been analysed simultaneously (Iverson et al. 2014; Tamburini et al., 2020).

### *4.1 Direct seeded rice (DSR)*

With DSR, there is a potential trade-off between yield and ecosystem services (Fig. 9). Over two-thirds of the paired observations show a trade-off or lose-lose relationship of yield with carbon sequestration (75%), water use (82%), soil fertility (83%), and GHG emissions (76%). The trade-off is commonly observed when competition for resources such as nutrients, light, and other inputs outweighs the improvement in ecosystem services. Nevertheless, a few studies have shown a win-win (20%) outcome.

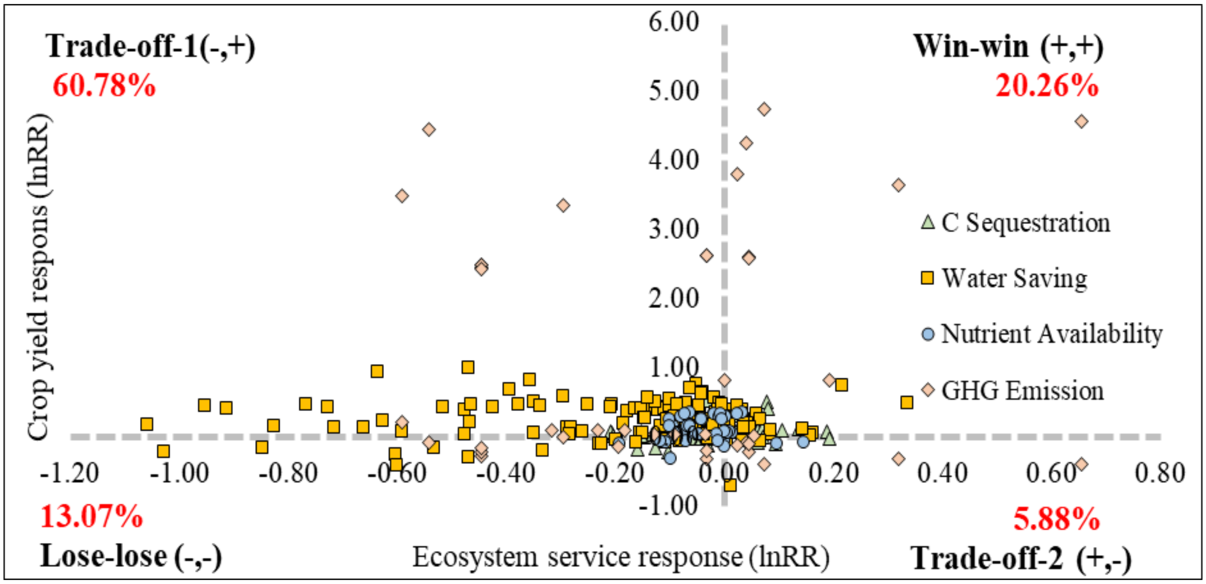


Fig. 9 Win-win and trade-off scenarios between ecosystem services under DSR.

Note: The percentages indicate the percentage of studies in each scenario

*4.2 No-till wheat*

No-tillage leads to a win-win outcome. Several studies have shown that no-tillage not only improves crop yield but helps sequester carbon (61%), save water (78%), improve soil nutrients (75%), and reduce GHG emissions (52%) (Fig. 10). This win-win outcome is attributed to improvements in soil fertility, resource-use efficiency, and soil moisture. Nonetheless, some studies have also reported a trade-off (26% of cases) and lose-lose outcome (4% of cases).

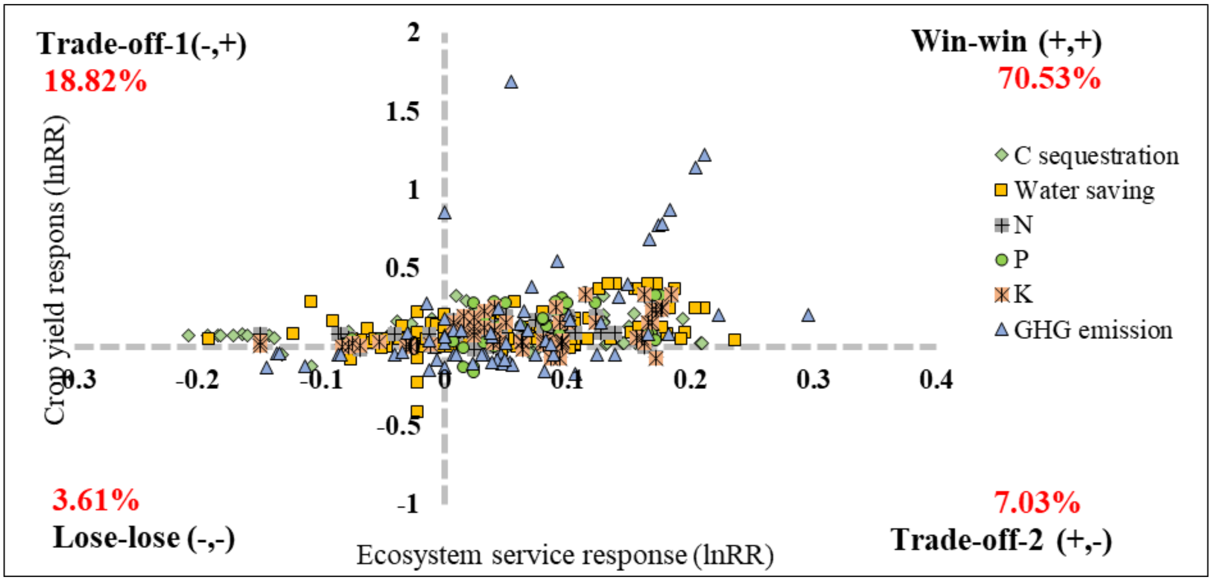


Fig. 10 Win-win and trade-off scenarios between ecosystem services under no-till wheat.
Note: The percentages indicate the percentage of studies in each scenario

*4.3. Legumes*

Three-fourths of the studies reported a positive association between crop yield and ecosystem services (Fig. 11). Climate regulation exhibits the highest win-win outcomes, with 90% of combinations showing an increase in both yield and carbon sequestration. Similarly, 76% of combinations show an increase in yield as well as nutrient availability.

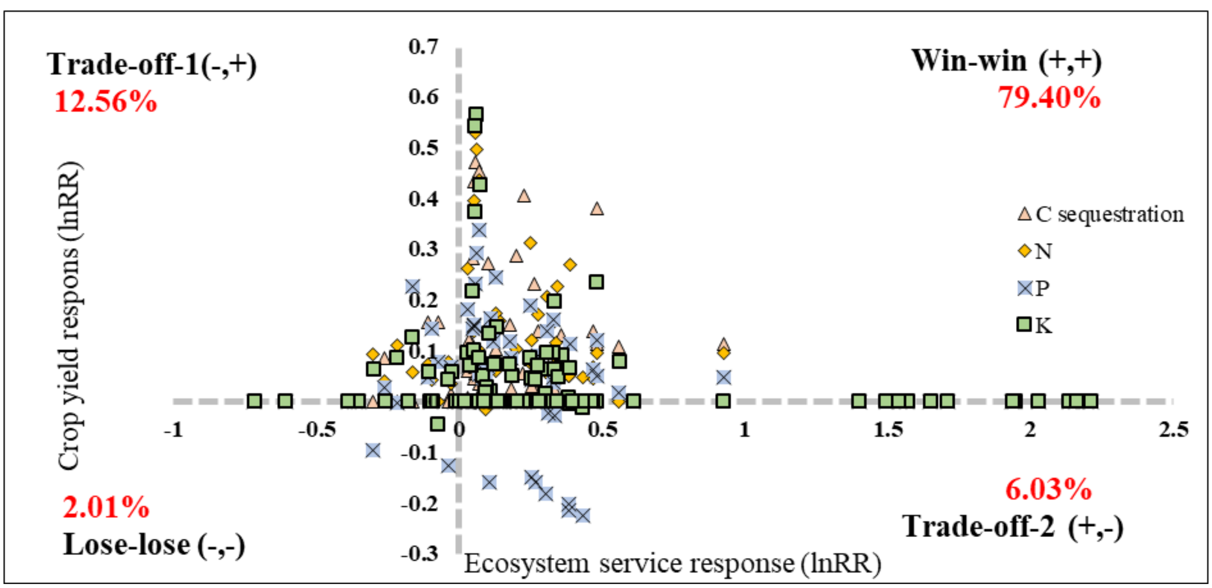


Fig. 11 Win-win and trade-off scenarios between ecosystem services under legumes.
Note: The percentages indicate the percentage of studies in each scenario

*4.4. Farm yard manure (FYM)*

The sole application of organic manure, or FYM, results in trade-offs between ecosystem services and crop yields (Fig. 12). Approximately half of the observations demonstrate trade-offs and 28% indicate lose-lose outcomes. Nonetheless, there are also potential win-win outcome in 29% of the cases.

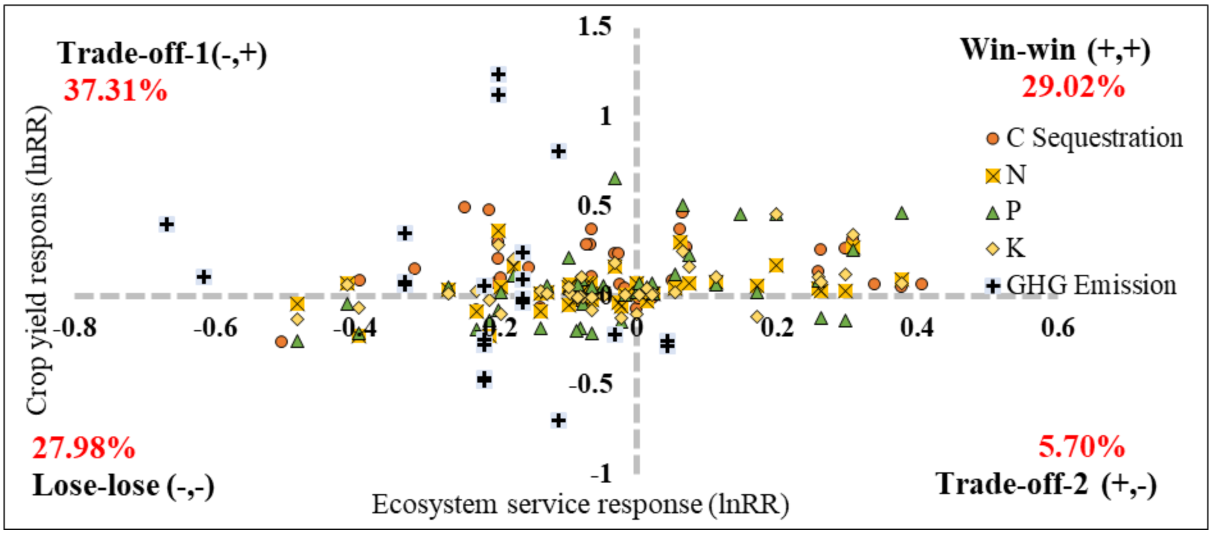


Fig. 12 Win-win and trade-off scenarios among ecosystem services under FYM
Note: The percentages indicate the percentage of studies in each scenario.

*4.5. Integrated nutrient management (INM)*

INM has significant potential to improve yield and ecosystem services. About 87% of observations indicate a win-win outcome between yield and carbon sequestration, and 80% between yield and soil fertility (Fig. 13). However, over 72% of the studies report a trade-off between yield and GHG emissions.

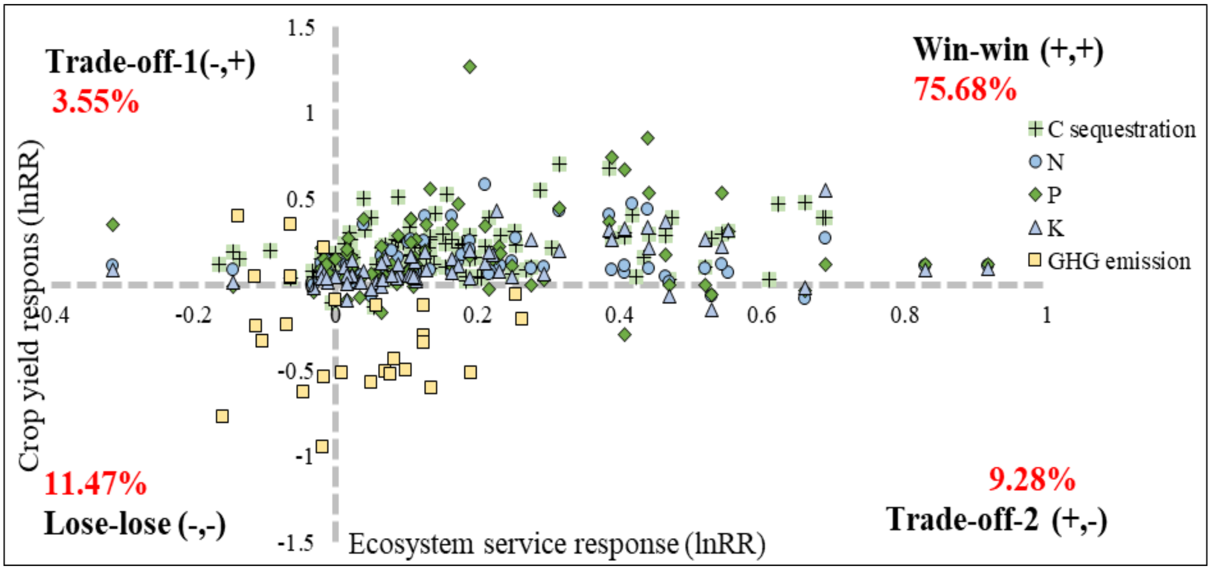


Fig. 13 Win-win and trade-off scenarios between ecosystem services under INM.
Note: The percentages indicate the percentage of studies in each scenario

## *4.6. Agroforestry*

In the case of agroforestry, trade-off and lose-lose outcomes are present (Fig. 14). Most studies (81%) indicate a trade-off between crop yield and carbon sequestration. However, win-win outcomes are also possible when trees are appropriately managed to minimize the competition and improve soil fertility.

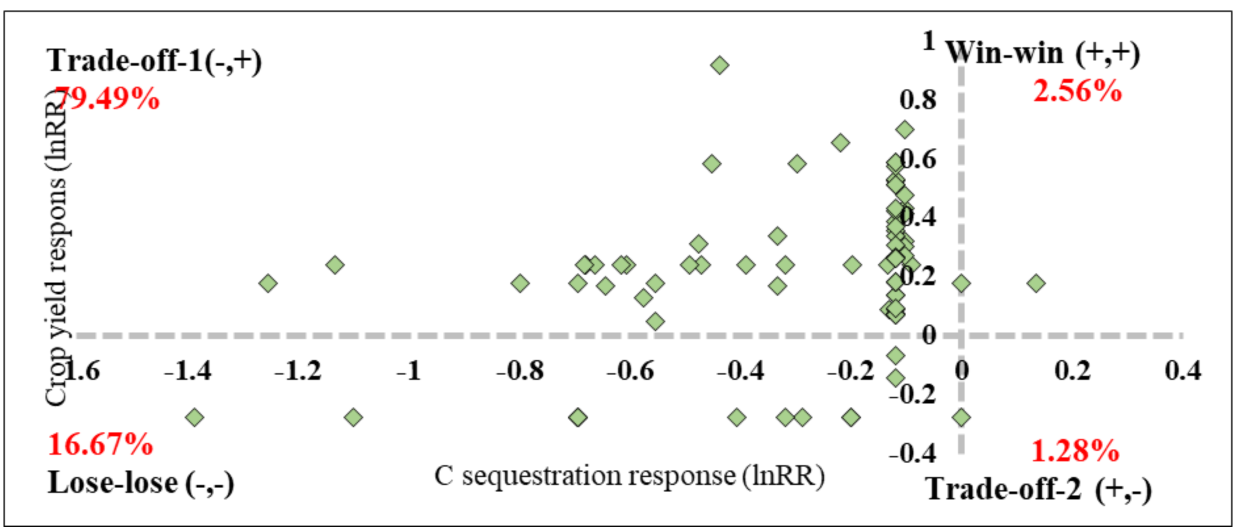


Fig. 14. Win-win and trade-off scenarios between yield and carbon sequestration under agroforestry.

Note: The percentages indicate the percentage of studies in each scenario

Furthermore, Spearman's rank correlation reveals a mixed relationship between yield and concomitant ecosystem services. In the case of direct-seeded rice, integrated nutrient management, and agroforestry, a positive and significant relationship between crop yield and carbon sequestration was observed. Similarly, a positive and significant correlation was found between crop yield and soil fertility. However, we did not find any significant relationship between crop yield and GHG emissions.

*4.7. Limitations of the study*

To the best of our knowledge, we conducted a comprehensive survey of existing literature on the valuation of ecosystem services arising from improved agricultural practices in India. Nevertheless, certain limitations of this study must be highlighted. One of the limitations is due to paucity of data on all types of non-tradable ecosystem services: we could assess the economic worth of only some important ecosystem services. Hence, the values reported for non-tradable ecosystem services in this study may be underestimated. Another limitation is that we could not account for the effects of the complementarity and competition among the non-tradable ecosystem services while quantifying the values of different ecosystem services provided by an agricultural practice. This is because most studies have investigated ecosystem services independently, making it difficult to account for their complex interactions. Also, the temporal distribution of the ecosystem service could not be factored in due to the lack of data.

In addition, it is essential to recognize that the extent of services provided by ecosystems depends not only on the scale and functions of the ecosystems but also on the condition of the particular ecosystems. Hence, the actual values reported in this study may vary depending on the agroecological conditions and biodiversity in the ecosystems. Finally, our estimates are derived solely from studies that utilize experimental data. For comprehensive and realistic estimates of ecosystem services, sufficient data from farmer's fields are needed.

## 5. Conclusions and Implications

This study quantified and monetized the ecosystem services provided by some improved agricultural practices, namely direct seeded rice, no-till wheat, legumes, organic manure, integrated nutrient management, and agroforestry, in a meta-analysis framework. By employing direct and indirect valuation methods, we were able to determine the economic worth of important ecosystem services such as yield, soil fertility, biological nitrogen fixation, nutrient retention, carbon flow, and water holding services.

Our findings show that not all the agricultural practices generate win-win outcomes. There are trade-offs between the tradable and non-tradable ecosystem services. While no-till wheat, legumes, and integrated nutrient management generate win-win outcomes, with an improvement of both tradable and non-tradable ecosystem services, trade-offs are present in the cases of direct-seeded rice, organic manure, and agroforestry.

Nevertheless, all the improved practices provide more environmental benefits than their conventional counterparts. Therefore, it is imperative to incentivize farmers to adopt environmentally friendly technologies and practices. This can be achieved by repurposing existing agricultural incentives that currently support unsustainable patterns of production. In this context, repurposing fertilizer subsidies merits attention. The excessive and indiscriminate use of nitrogenous fertilizers has resulted in quantitative and qualitative damages to natural resources, including, land, water, and in terms of the greenhouse gas emissions. In 2022/23, the huge sum of Rs1750 billionswas spent on fertilizer subsidies. The gradual phasing out or reduction of fertilizer subsidies while providing income support that encourages farmers to adopt nature-based farming practices can be part of the repurposing strategy. It is important to note that the Government of India has announced several schemes like (i) soil health cards for application of nutrients as prescribed or recommended, (ii) incentives to reduce the use of chemical fertilizers to restore the health of natural resources, (ii) promotion of natural farming, and (iv) establishment and strengthening of manufacturing of bio-based inputs for agriculture (Union Budget, 2023-24).

Further, to compensate farmers for contribution towards non-tradable ecosystem services, scientifically sound methodologies are necessary to estimate magnitude (coefficient) of ecosystem services. This is essential to design frameworks that compensate farmers for their contribution towards the preservation of natural resources and the environment. These are also important for creating a market for ecosystem services. Recently, in the Union budget of 2023-24, the Government of India has announced a Green Credit Programme to provide market-based incentives for the adoption of eco-friendly farming practices.

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