THE EFFECT OF REGENERATIVE COTTON CULTIVATION ON ITS ECOSYSTEM SERVICES IN INDIA

MASTER THESIS

Claire Kooiman
MSc Environmental Sciences

Solen Le Clech'
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INDEX

LIST OF ABBREVIATIONS AND TERMINOLOGY

Abbreviation	Explanation
ACRE	Alliance of Cotton stakeholders on Regenerative Agriculture
BAU	Business-as-Usual
CICES	Common International Classification of Ecosystem Services
CT	Conservation tillage
EEA	European Environmental Agency
ES	Ecosystem Services
ESA	Ecosystem Service Assessment
EU	European Union
GDP	Gross Domestic Product
GWP	Global Warming Potential
IPM	Integrated Pest Management
IR	Infiltration Rate
MCA	Multi-Criteria Analysis
NGO	Non-Governmental Organisation
OCA	Organic Cotton Accelerator
OM	Organic Matter
PBB	Permanent Broad Beds
PPP	Plant Protection Products
RF	Regenerative Farming
RFM	Regenerative Farming Measures
RQ	Research question
SCY	Seed Cotton Yield
TOC	Total Organic Carbon Stock
US	United States
WUE	Water Use Efficiency
WP	Water Productivity

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ABSTRACT

This research investigates the potential of regenerative farming measures in enhancing ecosystem services within the Indian cotton industry, a sector facing significant environmental and economic challenges. With cotton cultivation contributing to the livelihoods of approximately 1 billion people globally, the research addresses the pressing issues of the high water demand, reliance on agrochemicals, and soil degradation exacerbated by climate change. Through literature review, expert interviews, and a systematic analysis, this study identifies eight applicable regenerative farming measures tailored to India's cotton agroecosystems. It evaluates their impacts on key ecosystem services, including cotton production, water conservation, soil quality, and biodiversity. The findings reveal that regenerative farming measures, such as conservation tillage, crop rotations, intercropping and cover cropping, can significantly improve soil health and reduce dependence on synthetic inputs, leading to enhanced agricultural resilience and sustainability. A multi-criteria analysis compares regenerative cotton scenarios against a conventional cotton scenario and expert interviews highlight the sociopolitical benefits and barriers of implementation from farmers perspectives. This research underscores the importance of context specific adaptations of regenerative measures and advocates for supportive policies and financial incentives to facilitate their adoption, as well as further research and context specific economic analysis.

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1.INTRODUCTION

1.1 THE COTTON INDUSTRY

Cotton is the most globally significant non-food crop with widespread cultivation and economic impact, used in the textile industry (WWF, 2024). In 2018, cotton made up 81% of global natural fibre production by weight (FAO, 2021), and the current global production estimates around 25 million tonnes annually, using approximately 2.5% of the world's arable land (Fair Trade India, 2020). About 80% of cotton is processed into apparel (FAO, 2021) and provides the main source of income for up to 1 billion people globally, including 100 million farmers (Fair Trade India, 2020).

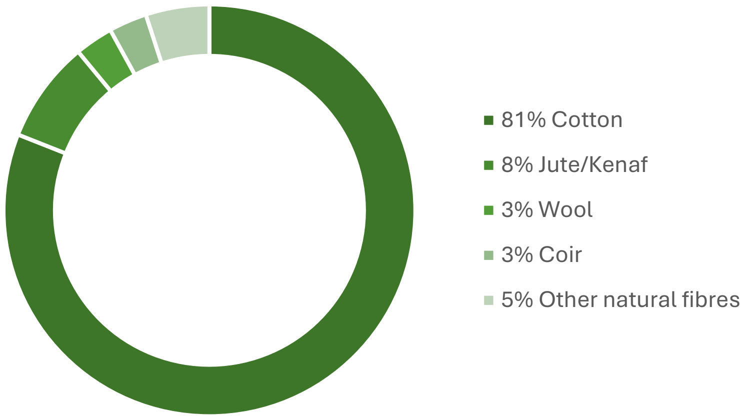

Figure 1 *Global natural fibre production 2018, adapted from FAO (2021).*

Cotton's cultivation, however, is highly vulnerable to global environmental changes caused by climate change. It is estimated that by 2040, all cotton-growing regions will be exposed to increased risk of climate hazards such as heat stress, water availability issues, and extreme weather events (Farooq et al., 2023; WTW, 2021). Cotton's vulnerability to changes in heat and humidity, affects farmers through unpredictable weather patterns and more frequent and severe pest infestations (Looney, 2024; Solidaridad, 2024). Intensified rainfall and hurricanes increase risks of flooding, waterlogging, and wind damage, as seen by the 2022 floods in Pakistan that destroyed 40% of its cotton harvest (Solidaridad, 2024; WTW, 2021).

1.2 ENVIRONMENTAL CHALLENGES

While cotton is highly vulnerable to climate change, the textile industry is also among those with the highest environmental footprint, with 70% of the environmental impact coming from the upstream process including raw material production (McKinsey & Company, 2020). To keep up with accelerated demand, cotton production has increased more than threefold since 1950, which has been achieved through intense input application and unsustainable practises, of which the environmental impacts have been overlooked, this is called the Green Revolution (Jena, 2013; Suresh et al., 2014). Conventional agricultural practices in the cultivation of cotton have increasingly come under scrutiny and the increased pressure from the European Union for sustainable textile production, creates a need for the production countries to follow (Jena, 2013).

Conventional cotton cultivation faces significant environmental challenges, including high water demand, vulnerability to pests and diseases, and soil fertility depletion (National Food Security Mission, 2017; NEXTIAS, 2024). Long-term frequent tillage, combined with excessive reliance on the use of synthetic fertilisers and pesticides, causes soil degradation (Blaise et al., 2021). The application of synthetic fertilisers in cotton farming increased from 44 kg per hectare in 1978 to 158 kg per hectare in 2010 (Suresh et al., 2014). This degradation leaves soils more vulnerable to erosion caused by extreme weather events, such as drought, wind or heavy rainfalls which can wash away top soil, intensified by climate change (J. Singh et al., 2023). Furthermore, water loss through evaporation, run off and bad water retention contributes to further erosion and depletion of organic matter and nutrients (Blaise et al., 2021). More (inefficient) irrigation will be needed in naturally rainfed cotton fields, worsening global freshwater scarcity (Jena, 2013).

Over the past few decades, cotton crops have also become more susceptible to different pests, especially bollworms, due to the indiscriminate use of pesticides, which disrupts natural pest control mechanisms (Shambharkar et al., 2018). In India, more than 55% of all agricultural pesticides are used on cotton alone (Shambharkar et al., 2018), yet the crop remains vulnerable to 166 recorded insect pests (Prajapati & Kulkarni, 2024). Finally, poor care of cotton-growing agroecosystems prompts agricultural expansion into new, previously undisturbed areas, leading to land-use change, habitat loss, and increased global emissions (RegenCottonIndia, 2024).

1.3 REGENERATIVE FARMING & ECOSYSTEM SERVICES

A solution to these environmental challenges could be regenerative farming. Regenerative farming is a conservation and rehabilitation approach to farming systems, aimed at restoring soil fertility and enhancing biodiversity, to maintain the health of the ecosystem (Diwan et al., 2021). It generally follows the following 5 core principles: minimise soil disturbance, protect soil surface, maintain living roots in the soil, maximise diversity and livestock integration (Ahmad & Hasanuzzaman, 2020; Giller, 2022; Newton et al., 2020; Ritz, 2021), which are displayed in figure 2. It encompasses a set of possible farming practices that can be used in isolation or in combination.

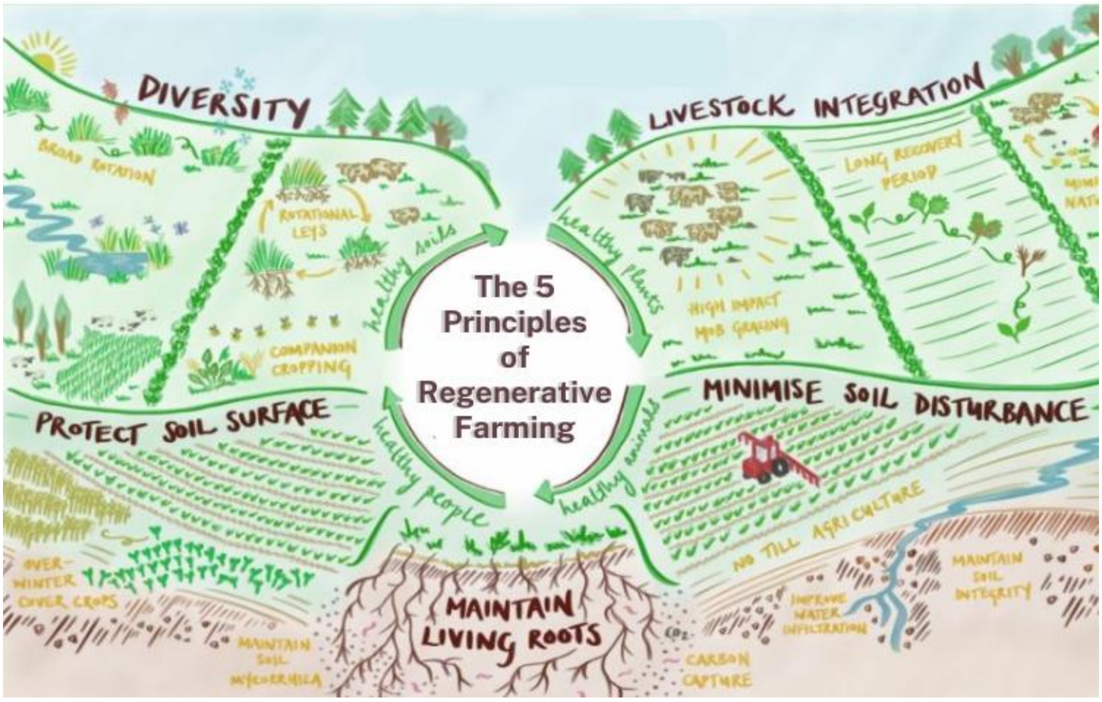

Figure 2 *Visualisation of the 5 core principles of regenerative farming and possible measures, adapted from (Groundswell, 2024)*.

Ecosystem Services (ES) is a robust framework that enables to look at the effects of these regenerative farming measures in a holistic way. ES are defined as the goods and services provided by ecosystems to humans (Ministry of Environment Protection, 2010). The European Environmental Agency (EEA) developed the Common International Classification of Ecosystem Services (CICES) that separates 3 categories; Provisioning (e.g. timber, water), Regulating & Maintenance (e.g. biodiversity, soil quality), and Cultural (e.g. aesthetics, cultural heritage) (Haines-Young & Potschin-Young, 2018).

1.4 KNOWLEDGE GAPS

Despite the growing interest in regenerative farming as a sustainable alternative to conventional agricultural practices, there is limited understanding of its practical application and effectiveness in specific agroecosystems. Past research has extensively documented the environmental impacts of conventional cotton cultivation, including high water demand, soil degradation, and reliance on agrochemicals, as well as its vulnerability to climate change (Begam et al., 2024; Farooq et al., 2023; Jena, 2013; Mohanasundaram, 2015; Pimentel, 2006; Suresh et al., 2014). Studies have highlighted the principles of regenerative agriculture and their potential benefits, such as improved soil health, increased biodiversity and water retention, and natural pest control (Alexanderson et al., 2023; Pimentel, 2006). However, there are significant differences in how these measures are defined, implemented, and evaluated across different contexts. This research intents to fill this gap by providing a well-defined and context-sensitive assessment to evaluate regenerative farming measures specifically tailored to Indian cotton cultivation.

Regenerative farming practices are often implemented as a combination of measures rather than as isolated techniques, complicating the assessment of individual contributions to ecosystem services (Alexanderson et al., 2023; Maskell et al., 2023; Venugopalan et al., 2021). The Indian government has established policies to promote more sustainable practises, however there is no direct crop-specific policies for cotton (Jena, 2013). There is also limited assessment on how these measures effect different ecosystem services. Without a clear understanding of their impacts, it is difficult to quantify the benefits and trade-offs associated with regenerative practices, hindering evidence-based policy-making and adoption. This knowledge gap may also result in missed opportunities to optimise practices for greater ecological and socioeconomic benefits. Therefore, this research will assess the ecosystem service outcomes of regenerative farming measures in comparison to conventional practices through scenario-based approaches. As well as, identifying the sociopolitical benefits and barriers of its implementation to create a better understanding.

1.5 OBJECTIVE AND RESEARCH QUESTIONS

This study aims to evaluate the impact of selected regenerative farming measures on ecosystem services within cotton farms. Specifically, the objective is to identify the most applicable regenerative farming measures for cotton cultivation and what are the sociopolitical benefits and barriers of the implementation of regenerative cotton for farmers. Further, the aim is to assess their effects on ecosystem services and develop scenario-based insights compared to conventional practices, to support more sustainable cotton farming practices adapted to its agroecological conditions.

The above mentioned problem statement, knowledge gap and objective translates into the following research questions:

1. What **regenerative farming measures** are best suited for cotton cultivation?
2. What **ecosystem services** do these regenerative cotton cultivation measures provide?
3. How does regenerative cotton cultivation compare to **conventional cotton** cultivation?
4. What are the sociopolitical **benefits and barriers** of the implementation of regenerative cotton cultivation for farmers?

The thesis is part of the Wageningen University & Research investment theme “Transformative Bioeconomies: Towards a materials transition”. This program focuses on phasing out fossil feedstocks by transitioning to renewable materials. The textiles sector is a key focus area, exploring pathways like bio-based materials, recycling and CO_2 capture, utilisation and dematerialisation. These approaches align closely with regenerative cotton cultivation, which promotes soil health and reduces reliance on fossil-based inputs, contributing to the larger vision of a sustainable textile industry.

1.6 SCOPE AND IMPLICATIONS

This research focuses on evaluating the impact of regenerative farming measures on ecosystem services in cotton cultivation, within the scope of India. India is the world’s second-largest cotton producer, has large cotton-growing regions, and a heavy reliance on rainfed agriculture, which makes it highly vulnerable to climate change. Additionally, India's average cotton production was 480 kg per hectare last season, while the global average lies at 800 kg per hectare (Aglawe et al., 2022; Preetha, 2024), making it an important context for assessing the potential benefits of regenerative farming.

This research aids in broader insights applicable to other cotton producing regions facing similar challenges. The implications of this research provide evidence to support more sustainable farming practices that enhance soil health, water retention, and biodiversity. Furthermore, it informs policymakers, industry stakeholders, and farmers about the potential environmental and socio-political benefits and challenges of adopting regenerative cotton farming. These insights can help shape policies that encourage the transition toward more sustainable agricultural practices, align with international sustainability goals, and reduce the environmental footprint of the textile industry.

2. METHODOLOGY

2.1 OVERALL RESEARCH APPROACH

This study aims to evaluate the impact of selected regenerative farming measures on ecosystem services within Indian cotton agroecosystems. To achieve this, a mixed-methods approach was employed, integrating **literature review, expert interviews, and data analysis**. The research is structured around four sub-research questions (RQs), each contributing to the overall assessment. Literature reviews provided empirical evidence and expert interviews enabled context-specific validation. Data analysis is done through an Ecosystem Service Assessment (ESA) and a scenario-based Multi-Criteria Analysis (MCA) to facilitate structured comparison and evaluation. The integration of these methods ensures a comprehensive evaluation of RFMs, addressing both ecological impacts and practical feasibility within Indian cotton farming systems. AI will be used for improving the scientific English writing of the report, a statement on this can be found in the appendix.

2.2 CONCEPTUAL FRAMEWORK

REGENERATIVE FARMING

Regenerative farming can be defined as a conservation and rehabilitation approach to farming systems, aimed at restoring soil fertility, enhancing biodiversity and maintaining ecosystem health (Diwan et al., 2021). There is a lack of an agreed definition and can be interpreted in many different ways (Newton et al., 2020). However, available reports generally centre their general agreement around the following principles (Ahmad & Hasanuzzaman, 2020; Giller, 2022; Newton et al., 2020; Ritz, 2021):

Minimising soil disturbance refers to the reduction of mechanical, chemical and biological disruptions to protect soil surface and microbiology. The goal of keeping the **soil surface covered** is to ensure the soil is not left bare to prevent erosion, retain moisture and protect soil life, primarily through the use of organic matter inputs such as covering soil with crop residue or green manure. **Always maintain living roots in the soil** refers to having plants growing year-round to enhance soil microbiology and carbon sequestration and prevent erosion. The regenerative farming principle of **maximising biodiversity** refers to enhancing diversity above and below ground to create resilient ecosystems. **Livestock integration** refers to introducing animals into farming systems to recycle nutrients and improve soil health and overall productivity. (CottonToday, 2024; FAO, 2015; Pimentel, 2006; Yemadje et al., 2025)

These principles encompass a set of farming practices that can be applied individually or in combination depending on local conditions, which generally focus on maintaining soil health and enhancing biodiversity. Organic matter in healthy soil, such as living plant roots and microorganisms naturally provides essential nutrients, reducing the need for chemical fertiliser, and improves water retention, reducing erosion, runoff, and drought impacts. Additionally, healthy soils capture atmospheric carbon dioxide, supporting climate change mitigation efforts. They also support a rich variety of organisms, such as bacteria, fungi, insects, and earthworms, that aid in nutrient cycling, pest control, and organic matter decomposition. (CottonToday, 2024; FAO, 2015; Giller, 2022; Pimentel, 2006; Yemadje et al., 2025) These benefits can be assessed using the ES framework.

The terminology surrounding regenerative farming is often inconsistent in the literature. Terms such as ‘crop diversification’ , ‘natural farming’, ‘FAB (Functional-Agro Biodiversity) measures’ (Maskell et al., 2023) and ‘organic farming’ are often used interchangeably, making assessment more complex (Newton et al., 2020). However, all these approaches fall under the broader umbrella of regenerative farming.

ECOSYSTEM SERVICES

Ecosystem Services (ES) is a robust structured framework that enables to look at the benefits of regenerative farming in a holistic way. The Common International Classification of Ecosystem Services (CICES) framework separates 3 categories; Provisioning, Regulating & Maintenance, and Cultural (Haines-Young & Potschin-Young, 2018).

Provisioning ES are biotic or abiotic tangible, material or energetic outputs form the ecosystem, which can be exchanged, traded or consumed, such as timber, fish (biotic) or water (abiotic). **Regulating & Maintenance ES** are biotic and abiotic factors that control the performance and maintain the natural cycle of the ecosystem, such as capturing carbon (abiotic) or biodiversity (biotic). Cultural ES are non-material outputs, which are either symbolic, intellectual, or experiential, such as education, aesthetics or cultural heritage. (Haines-Young & Potschin-Young, 2018)

Using this ecosystem services framework eases the transfer of knowledge among disciplines and improves communication and measurement of the importance of ecosystems to society, due to its structured approach and robustness (Finisdore et al., 2020). This study specifically focuses on Provisioning ES and Regulating & Maintenance ES, because they offer tangible and measurable benefits directly linked to regenerative farming practices, such as improved soil fertility, water retention, and carbon sequestration. These categories provide a clear basis for evaluation, aligning with existing indicators and literature, making them more applicable to assessing the environmental and agricultural impacts of regenerative farming.

2.3 STUDY AREA

Agriculture accounts for 22% of India's GDP, with 70% of its population living in rural areas with agriculture as the main source of livelihood (Mohanasundaram, 2015; Soni et al., 2023). As one of the world's largest countries, India encompasses various climatic zones (Figure 3). India is the world's second-largest cotton producer, it has the biggest cotton covered land area globally which historically played an important role in connecting the country with the rest of the world through trade and commerce (Aglawe et al., 2022). Approximately 60 million people in India are estimated to be dependent on the cotton industry, of which about 6,5 million farmers (Ministry of Agriculture and Farmers Welfare, 2017).

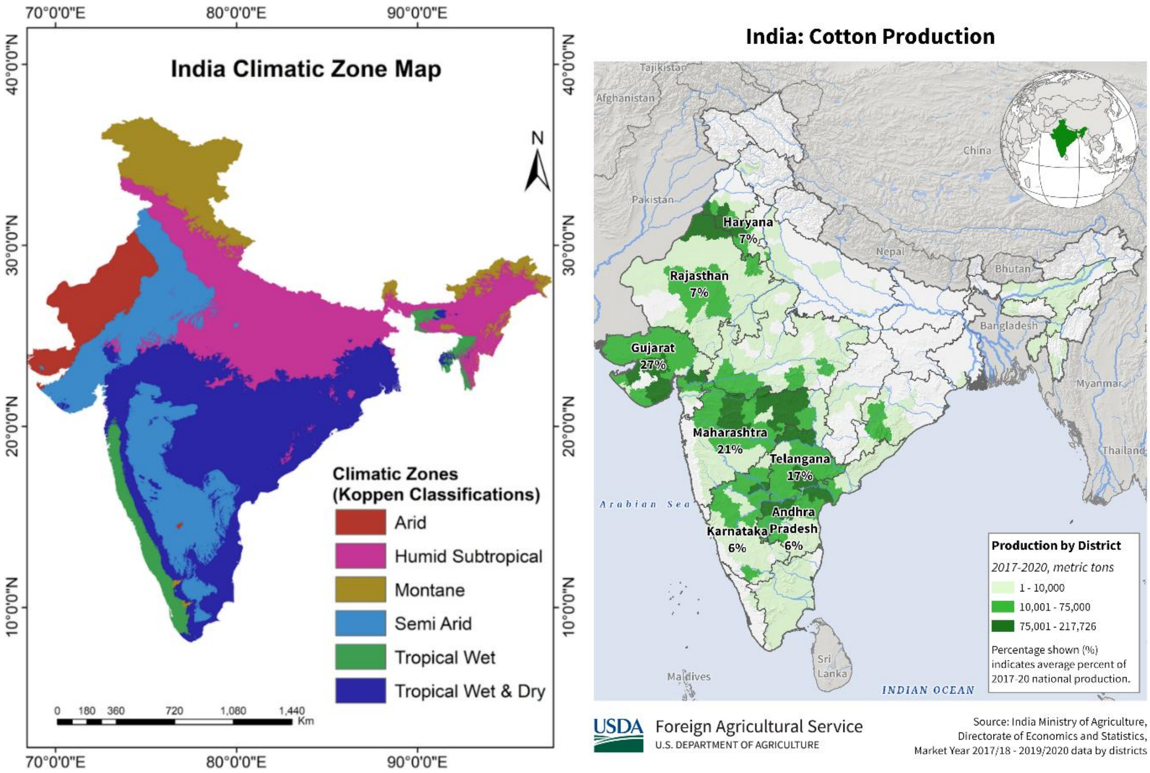

Figure 3 *Side by side of map of Indian climatic zones (Jain et al., 2022) and cotton production in India (USDA, 2023).*

Cotton is largely grown in states like Maharashtra, Gujarat, Karnataka, Rajasthan, Andhra Pradesh and Haryana (Mohanasundaram, 2015). In 2023, India produced 23% of the global production, about 25.800 lb bales of cotton, which is the equivalent of 4.386.000 kg (USDA, 2023). Most of this is cultivated on the clay or loamy regur black soils of the central southern region, called the Deccan plateau, surrounded by three mountain ranges. The climate of this area is mainly semi-arid and tropical wet & dry (Figure 3) (Jain et al., 2022). Here cotton grows in temperatures between 23 - 32°C and is typically sown from May to July and harvested from November to February (Aglawe et al., 2022; Prajapati & Kulkarni, 2024). This is called the kharif rainy monsoon season.

About 65% of India's cotton fields are rainfed or partially irrigated, particularly in these central and southern regions, which makes them highly vulnerable to soil erosion and extreme weather events (National Food Security Mission, 2017). Cotton yield is lower in rainfed areas, especially Maharashtra which is 95% rainfed, compared to the mainly irrigated fields in northern India (Mukherjee, 2024). With Indian agriculture largely dependent on monsoon rains, failure due to climate change can reduce or destroy yields, while excessive rainfall can wash away top soil (Mohanasundaram, 2015). This however, also makes this the region where regenerative farming measures can have the biggest impact.

The majority of Indian cotton farmers often own small and fragmented pieces of land, value indigenous farming practises and lack the capital for advanced irrigation techniques commonly used in the US (Aglawe et al., 2022). Additionally, around 70% of India's cotton is mono-cropped or strip-cropped, limiting biodiversity and resilience, and increasing environmental risks (Venugopalan et al., 2021). In many developing countries, including India, cotton farmers are facing decreasing marginal returns due to stagnating yields coupled with high input costs (Eyhorn et al., 2007; Preetha, 2024). While the global average yield is 800 kg per hectare, India's average was only 480 kg per hectare last season, accompanied by reductions in crop size (Aglawe et al., 2022; Preetha, 2024). These factors highlight the need for more holistic approaches to sustainable cotton cultivation adapted to India.

2.4 RESEARCH DESIGN AND METHODS

This research follows a structured, multi-method approach to assess the suitability, impact, and implementation challenges of regenerative cotton cultivation in India. The study is organised around four interrelated sub-research questions (SRQs), as visualised in Figure 4, which outlines the logical flow and inputs used for each question. This allows for an iterative process, where there is built on findings from earlier research questions.

First, RQ1 identifies regenerative farming measures (RFMs) through a literature review determining which practices are best suited for cotton cultivation in India, validated by the experts. RQ2 builds on this by evaluating the ecosystem services (ES) these selected RFMs provide, using Ecosystem Services Assessment (ESA) to classify and measure their benefits. RQ3 integrates these measures into regenerative cotton scenarios, based on findings from RQ1 and using a Multi-Criteria Analysis (MCA) to compare these to conventional cotton cultivation, using the output from RQ2 as input. Finally, RQ4 explores the sociopolitical benefits and barriers influencing implementation, based on insights from the interviews with the experts.

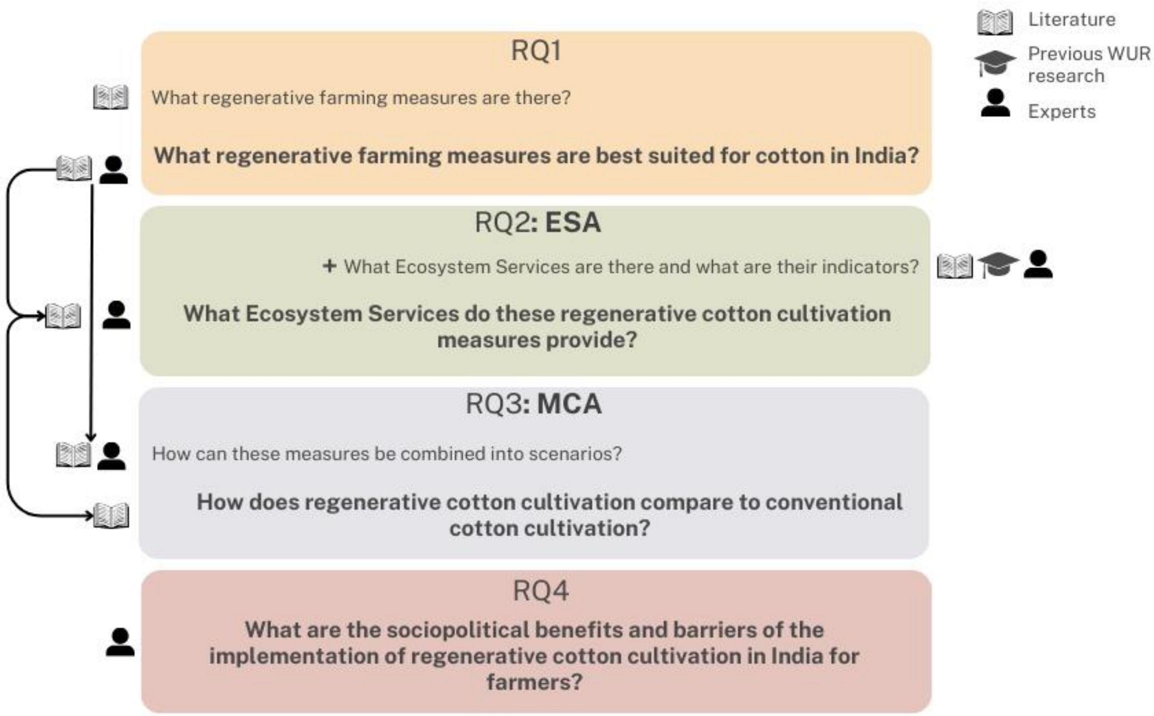

Figure 4 *Methodological approach used to answer the four sub-research questions.(ESA = Ecosystem Service Assessment, MCA = Multi-Criteria Analysis, ES = Ecosystem Services, BAU = Business-as-Usual) The arrows suggest where output from one RQ is used as input for the next.*

RQ1: REGENERATIVE FARMING MEASURES

The objective of the first research question is to identify the most applicable regenerative farming measures (RFMs) for cotton cultivation in India. The first step is to provide an overview of the possible measures of regenerative farming. The second step is to tailor it to cotton in India, as RFMs are very context dependent.

First, a comprehensive literature review was conducted to identify existing RFMs. Data was collected from peer-reviewed scientific papers published on the topic of regenerative farming measures for cotton. Google Scholar and Scopus were used to search using the queries 'Regenerative farming' and synonyms of farming, such as agriculture or cultivation, in title, abstract and keywords and using the snowball method to find more specific RFMs. The collected data was organised in Excel and Word, and categorised based on their respective regenerative farming principle.

Next, using the same methods, Google Scholar and Scopus were used to search the queries on the 8 specific RFM in the context of cotton in India, for example 'Mulch tillage AND cotton AND India' or 'Intercropping AND cotton AND India' and synonyms. Collected papers were screened on title, abstract and key words, and excluded when not applicable to the context of this research. This means all papers found had to be English written official peer-reviewed publications on regenerative farming measures mentioning cotton crop and India or parts of India, unless otherwise stated. When nothing was found on a specific RFM using this method, it was assumed not applicable to cotton in India. There was decided which measures were most relevant based on frequency of mention in the context of rainfed cotton in India, on similar soils as the mentioned study area. This yielded 15 relevant studies concerning 8 RFMs applicable to cotton in India.

Experts were contacted to evaluate and validate the suitability of these RFMs specifically for cotton cultivation in India. This included relevant WUR researchers, companies, organisations, NGO's and farmers. A table of the four respondents, their expertise and justifications can be found in the interview section of this methodology below (Table 2). They were asked where they agreed or disagreed with the eight selected RFMs, if the RFMs that were not selected were also not seen in real-life in the context of cotton agroecosystems in India, if they had any additions and if they agreed with the methods used.

RQ2: ECOSYSTEM SERVICE ASSESSMENT

The objective of the second research question is to identify how these RFMs can affect the Ecosystem Services (ES) the cotton agroecosystem provides. The first step is to identify what ES this cotton agroecosystem could possibly provide and what would serve as their indicators. Next, an Ecosystem Service Assessment (ESA) was done to analyse and evaluate the ES these RFMs could enhance or decrease.

This stage builds on prior research, existing of a previous master thesis done on the subject of Ecosystem Services (ES) and its indicators specific to regenerative cotton cultivation. This thesis and the papers from the literature research of RQ1 were analysed on potential benefits, their indicators and their respective units of measurement, laid the foundation for the selection of ES. These benefits were classified using the Common International Classification of Ecosystem Services (CICES) and can be found in figure 8 of the results. 2 Provisioning ES and 7 Regulating & Maintenance ES were defined in the context of cotton agroecosystems in India. Sometimes, articles additional to the ones from RQ1 were used to complement missing data or strengthen an argument, by searching for the very specific relation or effect or cotton in other contexts than India.

Data on the effect of the selected RFMs on the ES a cotton agroecosystem can provide was mainly collected from the 15 articles found in the literature research from RQ1. These papers were scanned on the mentioning of any of the 9 ES or their indicators and the impact of the RFMs were evaluated based on the quantitative data collected for their indicators compared to their control measurement of conventional cotton cultivation. These findings were translated into a +/- matrix table, with the RFMs on the y-axis and ES on the x-axis. A distinction was made between strong scientific evidence, such as direct measurements and weaker scientific evidence, such as qualitative arguments. And a distinction was made between a positive effect (+) and a strong positive effect (++), approximately more than 10% improvement compared to conventional cotton. The amount of scientific literature found to support a specific relation or effect was not taken into account in the +/- matrix, meaning if there were multiple sources found on a relation of effect, this wasn't automatically counted as a strong positive effect. The same four experts were interviewed to evaluate and validate the findings through literature and help answer RQ2, more on this can be found in the interview section of this chapter. They were asked if they agreed or disagreed with the selection of the ES and the selection of the indicators for the ES, their thoughts on the +/- matrix findings and the methods used.

RQ3: MULTI-CRITERIA ANALYSIS

The objective of the third research question is to compare regenerative cotton cultivation to conventional cotton cultivation in a Multi-Criteria Analysis (MCA). The first step is to identify two regenerative cotton cultivation scenarios, combining RFMs. A Business-as-Usual scenario was defined to serve as a control, which can be found in the methodology below. Then the ES from regenerative cotton agroecosystems were compared to conventional cotton agroecosystems.

First, a Business as Usual (BAU) scenario, reflecting conventional cotton cultivation, was defined as a baseline for comparison using literature. Data was collected from peer-reviewed scientific papers published on the topic of conventional cotton cultivation. Google Scholar and Scopus were used to search using the query 'Conventional cotton cultivation' and synonyms of cultivation, such as agriculture or farming, using the snowball method. Collected papers were screened on title, abstract and key words, and excluded when not applicable to the context of this research. The selected papers were analysed to form a general consensus on what conventional cotton cultivation in India looks like.

Next, based on findings from RQ1, the RFMs were combined into viable, real-world scenarios using expert insights and literature, acknowledging that RFMs are typically applied in combination rather than on its own. There was focussed on the RFMs occurring mostly in combination with each other in literature and there was made sure there was no overlap in RFMs and no bare soils in winter or mono-cropping, to ensure the scenarios remained logical and applicable. This was evaluated and validated by the same four experts. They were asked what combinations they often saw implemented and which could not be combined.

Then, MCA criteria were derived from the identified ES and its indicators. The output from the ESA from RQ2 was used as input for the MCA scoring. The +/- matrix from the ESA output was translated into scores. A point system was used, where every '+' yields a point and every '-' deducts a point for each criteria, with double values for the bolded symbols, signifying strong scientific evidence (Table 1). All the values from the ESA from literature are normalised against a control of conventional cotton cultivation. The score of the BAU scenario will logically be 0. The scoring was visualised in spider web graphs based on Figure 9. The criteria were weighted by the hands of the experts. They were asked to divide a total of 100 points over the nine criteria (ES), ranking their importance. More points assigned to a criteria, indicates a higher importance. Their weights of the criteria was displayed in a table and the standard deviation (σ) was calculated. The average of all the weights assigned by the experts was taken and applied to the scoring table of the MCA, yielding scores on each criteria and a total score per scenario.

Table 1 *Point system for translating the +/- matrix to MCA scores.*

Scoring

++	++	**+**	+	**+/-**	-	**-**	--	**--**
4 points	2 points	2 points	1 point	0 points	-1 point	-2 points	-2 points	-4 points

Lastly, a sensitivity analysis was performed on the weighting, to do so the changes in the scores of the scenarios were assessed when using equal weights for all criteria, to see how the scores would change when there was no influence from the weighting. The same was done using only the weights from the local farmer's initiatives perspective (Expert 4), to see how the score would change as this is the only person whose opinion influences implementation most.

BUSINESS-AS-USUAL SCENARIO

The Business-as-Usual (BAU) scenario of conventional cotton cultivation in India consists of mono-cropping, extensive tillage and extensive fertiliser and pesticide use. In central and southern India cotton (*Gossypium hirsutum L.*) is mainly rainfed or partially irrigated, typically sown in May during the Kharif monsoon season and harvested by October – November. Extensive tillage includes deep ploughing before sowing to prepare a seedbed, multiple passes of harrowing and removal or burning of crop residues, which, while efficient, emits GHG emissions. (Blaise et al., 2021; Choudhary et al., 2016; Soni et al., 2023) Fertilisation relies heavily on synthetic inputs like urea, diammonium phosphate (DAP), and potash, applied based on general recommendations (60:30:30 kg $N:P_2O_5:K_2O\ ha^{-1}$ (Gabhane et al., 2023)) rather than soil testing (Badikheti, 2022; Getfarms, 2024). Extensive pesticide use includes regular application of synthetic insecticides to control pests such as bollworms, aphids, and whiteflies, herbicide application for weed control and limited to no use of biological pest control or trap crops (Aglawe et al., 2022).

REGENERATIVE COTTON SCENARIO 1

The first regenerative cotton scenario, based on Blaise et al. (2021) and J. Singh et al. (2023), integrates intercropping, mulching and cover cropping. Cotton is intercropped with sesame, whose residue is used as in situ mulch and a legume cover crop is grown during the winter Rabi season.

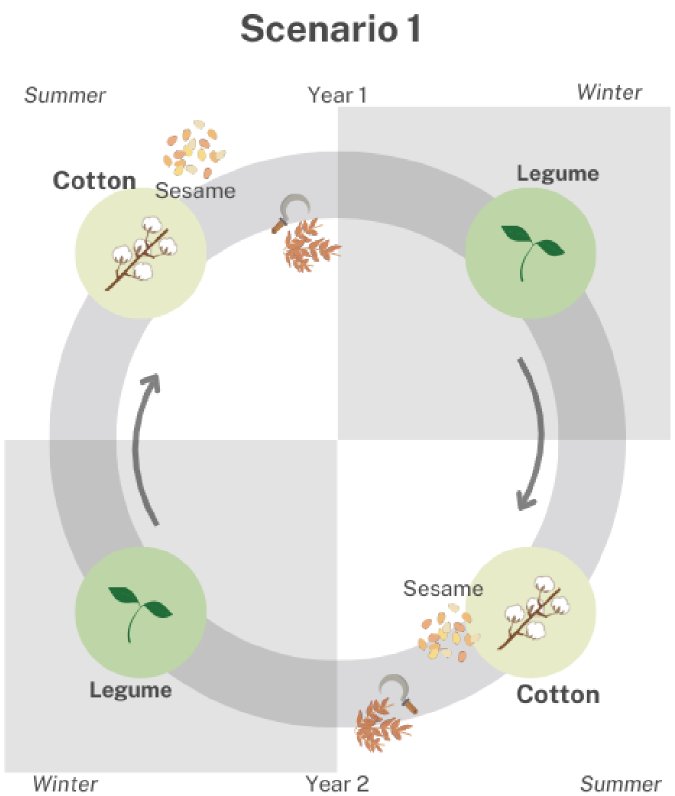

Figure 5 *Regenerative cotton scenario 1: Cotton with sesame intercrop residue mulching and legume cover crop* (Blaise et al., 2021; J. Singh et al., 2023; Yemadje et al., 2025).

Cotton (*Gossypium hirsutum L.*) is sown in May during the Kharif monsoon season in India and 30 days later, sesame (*Sesamum indicum*) is sown between cotton rows. Sesame is harvested 45-50 days after sowing and its residues are placed on the soil surface as mulch. (Blaise et al., 2021) During the Rabi season, legume cover crops, either Austrian winter pea (*Pisum sativum L.*) or hairy vetch (*Vicia villosa L.*), are sown using a no-till drill after cotton harvest in late October. The cover crops are chemically terminated and left to decompose in mid-to-late April. The entire system is not or minimally tilled. (J. Singh et al., 2023)

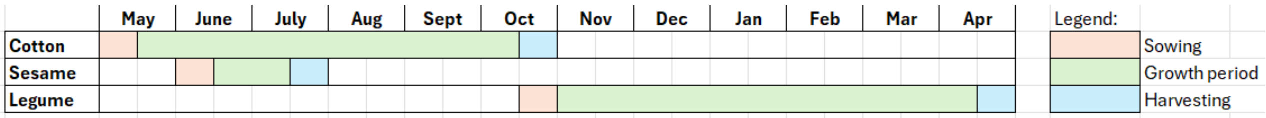

Figure 6 *Cropping calendar regenerative cotton scenario 1: Cotton with sesame intercrop residue mulching and legume cover crop* (Blaise et al., 2021; J. Singh et al., 2023).

REGENERATIVE COTTON SCENARIO 2

The second regenerative cotton scenario, based on Choudhary et al. (2016) and Matloob et al. (2020), involves intercropping cotton with mung bean and rotation with wheat on Permanent Broad Beds (PBB).

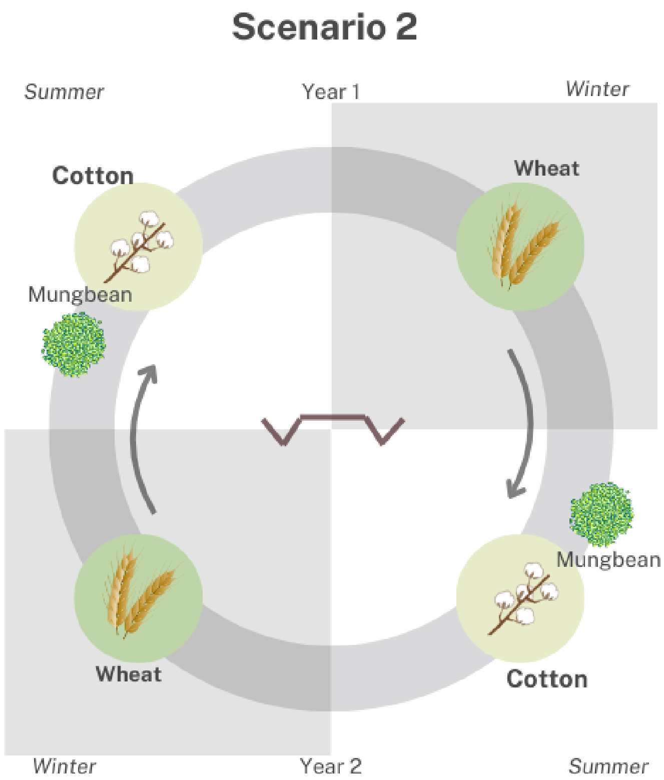

Figure 7 *Regenerative cotton scenario 2: Cotton-wheat rotation on PBBs with relay mung bean intercropping in wheat* (Choudhary et al., 2016) .

Cotton (*Gossypium hirsutum L.)* is sown at the end of May during the Kharif monsoon season in India on alternate sides of the 102 cm wide PBB, which require seasonal reshaping after harvest. The cotton is planted using a high clearance tractor-operated relay seeder. Wheat (*Triticum aestivum L.)* is sown in three rows on alternate side of the cotton row during the Rabi winter season in November and harvested in April. The legume mung bean (*Vigna radiata)* is sown in the last week of April, before cotton and after wheat harvest in the same rows as wheat. Matloob et al. (2020) advised the use of nitrogen fixing legumes in cotton-wheat rotations to overcome the low cotton yield issue, which was expected to be due to nitrogen depletion.

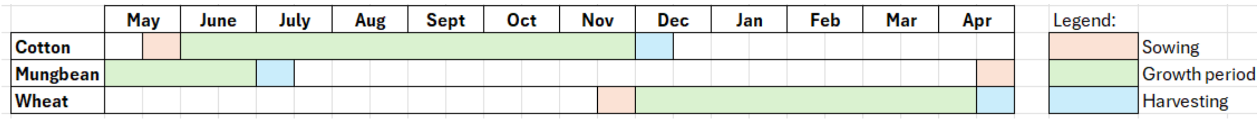

Figure 8 *Cropping Calendar regenerative cotton scenario 2: Cotton-wheat rotation on PBBs with relay mung bean intercropping in wheat* (Choudhary et al., 2016).

RQ4: BARRIERS AND BENEFITS

The objective of the fourth research question is to understand the sociopolitical benefits and barriers of regenerative cotton farming from a farmer's perspective.

To answer this question in-depth discussions were held with the same four experts, about their experiences with the social-political and economic challenges and opportunities.

INTERVIEWS

Four experts were interviewed to evaluate, validate and enhance the research. The experts were approached through email with a brief explanation of the research topic along with the specific expertise they were needed for. The interviews were done at the hand of a semi-structured interview guide, online in Teams, however not recorded. This data collection was done simultaneously for all RQs. The interview guide took them through all the steps of the research, leaving room for exploratory insights, comments or additions. Based on their expertise there was focused on different parts of the research and thus different parts of the interview guide.

Table 2 *List of experts, their organisations and expertise.*

	Organisation	**Expertise**
1.	Wageningen University & Research	PhD on Regenerative Farming and its Implementation and Measurability
2.	Wageningen University & Research	Senior Researcher on Ecosystem Services, Soil-plant relations and Biodiversity
3.	Wageningen University & Research	Researcher on Regenerative Agriculture and Circular textiles
4.	ACRE (Alliance of Cotton stakeholders on Regenerative Agriculture)	Regen Cotton India - Stakeholder Platform to embrace Regenerative Cotton

As the expert panel WUR researchers from different principles were contacted, alongside a representative from a relevant farmer organisation in India that focuses on regenerative cotton. This ensures a well-rounded, context-specific perspective. Expert 1 was selected for his expertise on ES, their indicators, their trade-offs and synergies, as well as his expertise on soil-plant relations and biodiversity. Expert 2 was contacted for his expertise and collaboration on multiple projects on the implementation and measurability of regenerative farming measures. Expert 3 was selected for her research on a 1,5 year project on regenerative cotton in India and cotton specific expertise. RegenCottonIndia is an farmer's initiative under the more international ACRE. Expert 4 was selected to provide local insights and a more practical and less scientific point of view on this research.

4. RESULTS

4.1 **RQ1**: REGENERATIVE FARMING MEASURES

The literature review revealed inconsistencies in the definitions and categorisation of regenerative farming measures (RFMs), leading to overlapping interpretations. Certain measures, such as cover cropping, crop rotations and intercropping are often used interchangeably, especially when referring to legumes. While cover crops and crop rotations are planted for the same reason; to avoid bare soils, cover crops are left to decompose on the field and crop rotations are harvested. Intercropping refers to growing alternating rows of crops in the same field at the same time. Legumes are a family of plants, known for their ability to fix nitrogen in the soil. However, some legumes such as chickpea, lentils, mung beans are harvested for sale and some legumes, such as clover or vetch are used as cover crops.

Similarly, crop residue mulching, green manure application, and agropasture incorporating cover crops require clearer differentiation. Crop residue mulching incorporates crop residue into the soil after its harvest. Green manuring involves planting crops along the field specifically for soil enrichment by incorporating some leaves into the soil while still green. The integration of livestock grazing (agropasture) with cover or forage crops is yet another variation that needs distinct classification. These nuanced differences are often overlooked or blended in discussions of regenerative farming, leading to misinterpretations in research and practice.

A review of 15 different studies identified eight RFMs most suited for cotton in India. Among these, conservation tillage emerged as the measure dominating literature, whereas semi-natural landscape elements and livestock integration were barely mentioned in the context of cotton in India. Table 3 outlines these measures, listing them alongside their respective regenerative farming principle (minimising soil disturbance, keeping soil surface covered, always maintaining living roots in the soil, maximising diversity and livestock integration), including descriptions and specifications along with their references for Indian cotton cultivation.

Table 3 *Regenerative farming measures descriptions along their respective principle.* (Diwan et al., 2021; Maskell et al., 2023; Riar et al., 2020; US EPA, 2015; Vogeler et al., 2019; Yemadje et al., 2025) *Different variations of measures are bolded in the description and the specifications are in the context of cotton in India.*

RF Principle	RFMs	Description	Specifications	Source
1. Minimise soil disturbance	**Conservation Tillage (CT):**	*No disturbance of the soil of the cropland by heavy machinery or ploughing.* ***Direct seeding, strip-/ridge-tillage.***	Permanent Broad Beds (PBB)	(Choudhary et al., 2016; Das et al., 2024; Singh et al., 2023)
	Reduced PPP use:	*Reduced Plant Protection Products (PPP) use, such as pesticides and herbicides, and replacing synthetic with biological inputs.*	IPM (Integrated Pest Management)	(Aglawe et al., 2022; Prajapati & Kulkarni, 2024; Shambharkar et al., 2018)
	Replacing synthetic fertilisers:	*Replacing synthetic fertilisers with* ***composted organic solid waste, manure or biochar.***	Biochar	(Han et al., 2017*; Soni et al., 2023)
2. Keep soil surface covered	**Mulch till systems:**	*Shallow tillage that incorporates mulch residues into the soil.* ***Organic (woods, straw) or inorganic (plastic or gravel).***	Intercrop residue mulch	(Blaise et al., 2021)
	Organic matter input:	*Incorporating harvested leaves into the soil while still green during the growing season.*	Legume green manure	(Gabhane et al., 2023)
3. Maintain living roots in the soil	**Crop rotations:**	*Rotating different types of crops in time, alternating winter and summer crops or alternating years.*	Cotton-Wheat	(Blaise et al., 2021; Choudhary et al., 2016; Das et al., 2024; Feng et al., 2017*; Matloob et al., 2020; K. Singh et al., 2023; Yemadje et al., 2025*)
	Catch & cover crops:	*Grown quickly between two main cash crops to capture nutrients, prevent soil erosion, supresses weeds and not harvested.*	Legume cover	(Matloob et al., 2020; J. Singh et al., 2023*; Yemadje et al., 2025*)
4. Maximise diversity	**Semi-natural landscape elements:**	*Bordering cropland with alternative vegetation to enhance nutrient cycling, water movement, and biodiversity on the land.* ***Hedgerows, wildflower margins, ponds & ditches and agroforestry.***	-	
	Mixed crops:	*Diverse species cultivation in the field at the same time.* ***Intercropping, strip-cropping.***	Mung bean intercropping	(Blaise et al., 2021; Choudhary et al., 2016; Jayakumar & Surendran, 2017; Matloob et al., 2020)
5. Livestock integration	**Agropasture:**	*Livestock grazing on (forage) crops, such as wheat, barley, oats, canary and triticale (in winter).*	-	

*Source is specific to cotton agroecosystems, but not exclusively to Indian conditions.

MINIMISE SOIL DISTURBANCE

The first regenerative farming (RF) principle is to minimise soil disturbance. The aim is to reduce mechanical, chemical and biological disruptions to protect the soil structure and microbiology. This can be done by conservation tillage (CT). Unlike conventional ploughing or tilling for the purpose of weed control, CT leaves residue from previous crops on the soil surface. CT practises are generally classified into direct seeding and strip-/ridge- tillage. Direct seeding is a no-tillage approach, where drills are used to plant crops into the completely undisturbed field. Strip-tillage involves tilling only narrow strips of soil are for planting rows, leaving the rest of the field undisturbed (Maskell et al., 2023). A ridge-tillage approach is **Permanent Broad Beds (PBB)**, where crops are planted on wide raised beds, separated by furrows (Choudhary et al., 2016). Studies on CT in cotton cultivation in India consistently show that PBB often delivers higher yields compared to other CT practises and conventional tillage (Choudhary et al., 2016; Das et al., 2024). CT also integrates easily with other regenerative farming methods and is an extensively researched RF practise.

Minimising soil disturbance also entails chemical soil disturbance by minimising the use of aggressive Plant Protection Products (PPP). Cotton is highly susceptible to pests and experiencing significant yield losses in India (Eyhorn et al., 2007; Jayakumar & Surendran, 2017; Preetha, 2024). Only 3% of India's cotton is organic due to high labour demands and lower economic viability (Dogra, 2020). **Integrated Pest Management (IPM)** offers a sustainable alternative to traditional pest control by reducing dependency on PPPs while addressing pest resistance and environmental degradation (Prajapati & Kulkarni, 2024). IPM is a pesticide approach that combines pest control strategies to minimise damage and soil disturbance. It is based on key principles such as prevention, monitoring and identification, thresholds, and control (US EPA, 2015). The pests most common in cotton fields are; grasshoppers, thrips, aphids, and jassids and most importantly various types of bollworms. Effective IPM practices for cotton in India include; removing and destroying cotton stalks, deep ploughing, avoiding mono-cropping, using certified seeds and seed treatments, applying recommended fertiliser doses, employing trap crops, setting up yellow sticky traps, using biological insecticides, and thoroughly cleaning fields after the final harvest (Shambharkar et al., 2018).

Chemical fertilisers, which contribute to soil degradation, can be replaced with bio-based alternatives such as from composted organic solid waste. In farming systems that integrate livestock, livestock manure offers significant potential. Farmers then could consider incorporating biomanures like vermicompost, neem cake, and vermiwash into their regular farming practices to reduce reliance on chemical inputs and improve sustainable soil health (Jadhav et al., 2024). Organic farming, which excludes the use of synthetic fertilisers, pesticides and GMO's completely, is a form of regenerative farming. 97% of India's cotton is the bollworm-resistant transgenic Bt hybrid, which saved them from bollworm infestations in 2002. Organic cotton in India is generally considered to have reduced yields, efficiency and revenue, fails to meet cotton demand and uses more resources, time and labour. (Dogra, 2020; Gutierrez et al., 2023) Therefore in this research there is looked into additional methods to help replace chemical fertilisers. **Biochar**, a charcoal-like material produced by pyrolyzing agricultural biomass at 400–500°C, is another promising soil amendment. Biochar enhances soil fertility, contributes to carbon sequestration and has shown potential to aid in pest and disease management (Han et al., 2017; Srinivasarao et al., 2014).

KEEP SOIL SURFACE COVERED

The second RF principle is to keep the soil surface covered, to ensure soil is not left bare to prevent erosion and retain moisture, primarily through the use of organic matter inputs. A distinct approach within CT is mulch till systems, which involves shallow tillage that incorporates residue into the soil. This can be done using organic residues, such as wood and straw or inorganic residues, such as plastic and gravel.

Blaise et al. (2021) researched rain-fed cotton in India using black plastic, newspaper mulch and in situ intercrop residues as mulch, compared to conventional cotton practises involving, herbicides, hand weeding and tillage. Among these, **in situ intercrop residues mulch**, particularly sesame, sunnhemp and sorghum, proved the most effective for cotton in India, with sesame preforming best across all parameters.

Green manure, which involves planting legumes along cotton fields and incorporating harvested leaves into the soil while still green during the growing season, provides another alternative approach to cover soil surface (Gabhane et al., 2023). It differs from mulch tilling, which often involves incorporating crop residues after harvest. Central India is struggling with the depletion of potassium (K) in the cotton soils. Gliricidia is a potassium-rich nitrogen-fixing legume that can offer a viable solution. Incorporating green Gliricidia leaves into the soil can efficiently replace 15–20 kg of fertiliser K, helping to meet the potassium needs of cotton plants while reducing the dependence on chemical fertilisers (Gabhane et al., 2023). It is planted along the bunds (raised ridges along the boundary of cotton fields) where the tops of the plants are lopped to be mulched into the cotton soil 30 days after sowing cotton. Bunds itself are often used to aid in retaining soil moisture and reducing soil erosion during heavy rain and are an ancient Indian practise (Aithal & Ramanathan, 2024).

ALWAYS MAINTAIN LIVING ROOTS IN THE SOIL

The third RF principle is to always maintain living roots in the soil, to keep plants growing year-round to enhance soil microbiology, carbon sequestration and prevent soil erosion. This can be done using crop rotations, where crops are alternated based on their opposite growth period to optimise land use. This also benefits temporal diversity, by varying crops over time to break pest cycles and improve soil health. Rainfed cotton is a summer crop in India, sown in June/July with the commencement of the monsoon and harvested early winter (National Food Security Mission, 2017). Cotton is often rotated with wheat or maize, which is sown from October to December and harvested early summer (Parihar et al., 2011). Cotton based cropping systems in India are mostly **cotton-wheat rotations**, which also dominates literature (Choudhary et al., 2016; Das et al., 2024; Matloob et al., 2020; Riar et al., 2020; K. Singh et al., 2023).

Maintaining living roots in the soil year-round can also be achieved by planting catch and cover crops between the growth cycles of the main cash crop. These crops prevent empty fields, which are highly susceptible to weeds and soil erosion. Relay planting involves sequentially planting cover crops into the same garden bed during or after the main crop's cycle. Legumes are particularly effective as cover crops due to their ability to fix atmospheric nitrogen, enhance soil fertility, and outcompete pests and weeds (Matloob et al., 2020). Their rapid growth and short life cycle make them suitable for cover cropping with cotton, while their deep rooting systems access nutrients from different soil layers (Matloob et al., 2020). **Legume cover crops** are typically terminated and left to decompose in the field after their growing season. J. Singh et al. (2023) proved cover crops should be terminated ideally 6 weeks before planting cotton, to prevent cotton yield penalties. It is essential to distinguish between crop rotations and catch or cover crops. Crop rotations involve planting a secondary crop, such as a winter crop, which is harvested for profit. In contrast, catch and cover crops are grown primarily to capture nutrients, suppress weeds, and prevent soil erosion, without being harvested for economic gain.

MAXIMISE DIVERSITY

The fourth RF principle is to maximise diversity. The aim is to enhance biodiversity above and below ground, referring to variety in plant and animal species, to create resilient ecosystems. This can be done using semi-natural landscape elements like alternative vegetation such as hedgerows, wildflower margins and trees. Not much was found on this for cotton in India specifically, however research was found on how semi-natural habitat could benefit diversity in cotton agroecosystems (Esquivel et al., 2021). While cotton is primarily a self-pollinating crop, it can still benefit from cross-pollination, which can enhance yield and quality. Increasing biodiversity through hedgerows or wildflower margins can enhance the population of natural pollinators, which in turn may improve pollination diversity and pest management (Muhammad et al., 2020). However, there was no peer-reviewed research found on this in the context specific to cotton in India. The best paper found on agroforestry as semi-natural landscape elements is from combining cotton with jujube (Chinese dates) trees in China. Even though it is not quite applicable to the Indian cotton conditions, it does prove agroforestry supports a wide range of biophysical interactions between the cotton and the trees (Wang et al., 2016). However it also states how resource competition and shading becomes a problem after one year.

Where crop rotations create temporal diversity, varying crops over time, mixed crops create spatial diversity, growing different crops together in the same space. This can be done by intercropping or strip cropping. Intercropping is growing two or more crops in the same field simultaneously. This can be done in alternating rows or randomly distributed. Strip cropping is easily mechanised intercropping by creating distinct strips of the different crops, wide enough for individual management, but close enough to provide mutual benefits. **Intercropping** is a well-researched practise for cotton in India and easily combined with other measures. Common intercrops for cotton in India are; mung bean, sorghum, sunn hemp, sesame and onion. Mung bean grows in rows alongside cotton, it does not interfere with the cotton's growth because they have different growth habits, leading to minimal competition for resources such as solar radiation, soil water, and nutrients (Choudhary et al., 2016). Intercropping can add additional income and improve soil quality. Blaise et al. (2021) also used crop residues from sorghum, sunn hemp and sesame intercrops after harvesting as in situ mulch for cotton cultivation in India.

LIVESTOCK INTEGRATION

The fifth RF principle is to integrate livestock. The aim is to reintroduce animals into farming systems to recycle nutrients and improve soil health. Research was found on livestock grazing on forage crops in winter in the USA (Crowell et al., 2022). Forage crops are high nutrition cover crops like grasses or legumes, specifically planted for livestock grazing. The results suggest that integrating winter-grazing livestock does not negatively or positively impact selected soil properties of cotton soils in the short-term (Crowell et al., 2022). Not much is found on this for cotton in India, while it is mentioned that including livestock in a cotton farming system can provide additional income (Ghosh et al., 2023). Additionally, farming systems that already have livestock present can use its manure as bio-fertiliser to reduce reliance on chemical inputs as mentioned in Jadhav et al. (2024), which also fits under the umbrella term of regenerative farming.

4.2 **RQ2**: ECOSYSTEM SERVICE ASSESSMENT

An Ecosystem Service Assessment (ESA) was done to identify, analyse and evaluate the benefits these RFMs provide to humans. First, nine Ecosystem Services (ES) were defined in the context of cotton agroecosystems in India and can be found in Figure 9.

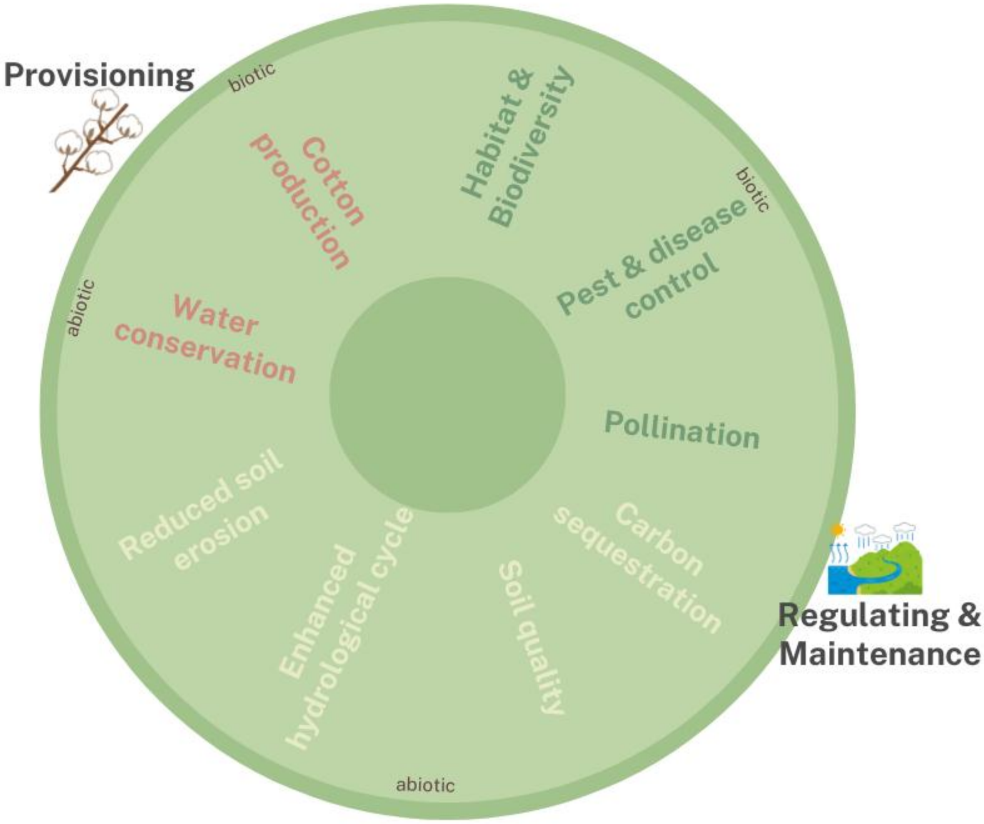

Figure 9 *The Ecosystem Services the agroecosystem of cotton cultivation in India could potentially provide, adapted from previous MSc research (Keresztes, 2024). Orange represents the provisioning ES, yellow the abiotic Regulating & Maintenance ES and green the biotic Regulating & Maintenance ES.*

CLASSIFICATION & INDICATORS

In the context of this research provisioning ES include cotton production (biotic) or water conservation (abiotic). Abiotic regulating & maintenance ES in the context of cotton in India include; reduced soil erosion, enhanced hydrological cycle, soil quality and carbon sequestration. Biotic regulating & maintenance ES in the context of cotton in India include; pollination, pest & disease control and habitat & biodiversity. Various indicators and units are used to quantify ecosystem services (ES) (Table 4). See the appendix for information on the sources the indicators were used in (Table 2A).

Table 4 *Ecosystem Services per category and the indicators and units to quantify them found in literature. Orange represents the provisioning ES, yellow the abiotic Regulating & Maintenance ES and green the biotic Regulating & Maintenance ES.*

Category:	**Ecosystem Services:**	**Possible Indicators**	**Unit**
Provisioning	**Cotton production**	Seed Cotton Yield (SQY) Lint Cotton Yield	Mg ha^{-1} or kg ha^{-1}
	Water conservation	Water Productivity (WP) or Water Use Efficiency (WUE)	kg grain m^{-3} or mm^{-1} water
Regulating & maintenance (abiotic)	**Reduced soil erosion**	Soil loss	Mg ha^{-1}
	Enhanced hydrological cycle	Infiltration Rate (IR) Run off	mm h^{-1} mm
	Soil quality	Organic Matter (OM) content/ TOC Bulk density Porosity	g kg^{-1} or % g cm^{-3} %
	Carbon sequestration	Total organic carbon stock (TOC) Global Warming Potential (GWP)	Mg ha^{-1} (t C ha^{-1}) kg CO2 eq ha^{-1}
Regulating & maintenance (biotic)	**Pollination**	# of beneficial insects	-
	Pest & disease control	# of pests/diseases	- -
	Habitat & Biodiversity	Species richness	# of species

The provisioning ES cotton production is usually indicated by seed cotton yield. Seed cotton yield refers to the total harvested raw cotton weight, including both seeds and fibre, whereas lint cotton yield represents only the weight of the cotton fibre usable for textile production. Cotton seeds are often used for oil production, animal feed or replanting (Aglawe et al., 2022). In some studies, additional indicators such as plant height, boll weight, and the number of bolls per plant were used to measure growth and yield. However, seed cotton yield, expressed in megagrams per hectare (Mg/ha) was most used. The other provisioning ES water conservation refers to the ability of farming systems to use water efficiently, reducing water waste and improving crop hydration and is usually indicated by water productivity or water use efficiency.

The abiotic regulating ES soil erosion refers to the prevention of soil loss due to wind or water, maintaining land fertility and preventing degradation. The ES hydrological cycle refers to the improvement of water movement through the soil, increasing infiltration and reducing runoff. Soil quality refers to the ability of soil to support plant growth and maintain biological activity, including nutrient content and structure. Soil quality was often assessed using a wide range of indicators, including for example microstructure parameters and pH, additionally to organic matter. The regulating ES of carbon sequestration refers to the capture and storage of atmospheric carbon dioxide in soil and plant biomass, helping mitigate climate change. Total Organic Carbon (TOC) is a key indicator of soil health and fertility, as it reflects the amount of organic matter in the soil. It also represents the carbon stored in the soil as part of organic matter, meaning this has been removed from the atmosphere and stored in a stable form in the soil (Das et al., 2024). Runoff and infiltration rate were also sometimes linked to soil quality (Blaise et al., 2021), in this research however these are directly assigned as indicators for an improved hydrological cycle.

The biotic regulating ES pollination refers to the process by which pollinators, like bees, transfer pollen, increasing cotton yield and seed quality and can be measured by the number of beneficial insects present in the agroecosystem. Pest & disease control refers to the natural regulation of pests and diseases, reducing the need for chemical insecticides. In Aglawe et al. (2022) this is measured by reducing the number of insecticide sprays needed to achieve the same or even higher cotton yields and in Ahmad & Hasanuzzaman (2020) and Bhatt et al. (2024) the number of pest or disease occurrences is measured over a longer period of time. Biodiversity & habitat refers to the presence of diverse plant and animal species within cotton agroecosystems, contributing to ecosystem resilience and is usually indicated by the number of species in the ecosystem.

There is recognised that RFMs may lead to several benefits and co-benefits, which is called a synergy, or may increase one ES but decrease another one, which is called a trade-off. For example, soil quality automatically positively influences soil erosion and the soil’s hydrological cycle, while water conservation also serves as a proxy for an improved hydrological cycle. Additionally, healthier soils can support stronger plant growth, which may enhance the plants' resilience to pest pressures and improve yields (K. Singh et al., 2023). Highlighting the interconnected nature of the different ES. Understanding trade-offs and synergies can help choosing a RFM to support or enhance several ES or to prevent unwanted consequences on other ES than the targeted one.

ECOSYSTEM SERVICE ASSESSMENT

The values for the indicators and information from the sources was translated into a +/- matrix for the final results of the ESA. This was done for all eight identified RFMs best suited for cotton cultivation in India from RQ1.

Table 5 *Findings on the effect of different RFMs on the ES in cotton agroecosystems in India, translated to a +/- matrix. '+' indicates a positives effect and '-' represents a negative effect compared to conventional cotton or a control. Double '++' or '--' indicates a strong effect. Bolded symbols represent strong scientific evidence, not bolded symbols represents weaker scientific evidence (i.e. no direct measurements). The +'s marked with * are benefits accounted to only the intercropping part and not the mulching part of this RFM. Orange represents the provisioning ES, yellow the abiotic Regulating & Maintenance ES and green the biotic Regulating & Maintenance ES.*

Ecosystem Services:	**Cotton production**	**Water conservation**	**Reduced soil erosion**	**Enhanced hydrological cycle**	**Soil quality**	**Carbon sequestration**	**Pollination**	**Pest & disease management**	**Biodiversity & Habitat**	**References:**
Permanent Broad Beds (PBB)	**++**	**++**	+	+	**++**	**++**				(Choudhary et al., 2016; Das et al., 2024; K. Singh et al., 2023)
Integrated Pest Management (IPM)	**++**						+	**++**	+	(Aglawe et al., 2022; Muhammad et al., 2020)
Biochar	+				**++**	**++**		++	**+**	(Bhatt et al., 2024; Han et al., 2017; Soni et al., 2023)
Sesame residue mulch	+	**++**	**++**	**++**	**++**		+*	+*	+*	(Blaise et al., 2021)
Legume green manure	**++**			+	**++**	**++**			+	(Gabhane et al., 2023)
Cotton-Wheat rotation	**--**		+					+	+	(Feng et al., 2017; Matloob et al., 2020)
Legume cover	**+/-**	**+/-**	+	+	**++**	**++**			+	(Matloob et al., 2020; J. Singh et al., 2023; Yemadje et al., 2025)
Mung bean intercropping	**+/-**	**+**		**+**	**+**		+	+	+	(Blaise et al., 2021; Jayakumar & Surendran, 2017; Matloob et al., 2020)

PERMANENT BROAD BEDS (PBB)

The scientific literature showed PBB has a strong positive effect on cotton production, water conservation, soil quality, carbon sequestration (**++**) and a positive effect on reduced soil erosion and enhanced hydrological cycle (+). Studies showed cotton planted on PBB produced significantly higher seed cotton yields compared to conventional tillage varying from 13 to 52% higher and saved about 50% of irrigation water (Choudhary et al., 2016). There are no measurements on soil erosion provided in the research that was reviewed, however conservation agricultural practises generally aim to reduce soil disturbance, which can help mitigate soil erosion (Maskell et al., 2023). Das et al.(2024) mentions PBB reduces soil evaporation and conserves a higher soil moisture content than conventional tillage, suggesting positive effects on the hydrological cycle. Studies also found that PBB lowered the bulk density of the soil and had a 27,5% higher total organic carbon (TOC) compared to CT, which is crucial for soil fertility and health and leads to better carbon storage in the soil (Das et al., 2024; K. Singh et al., 2023).

INTEGRATED PEST MANAGEMENT (IPM)

The scientific literature showed IPM has a strong positive effect on cotton production, pest & disease management (**++**) and enhance pollination and biodiversity (+). Aglawe et al. (2022) proves cotton growers using IPM had 25,25% yield increase compared to conventional cotton cultivation. While IPM led to a significant reduction in insecticide sprays of more than 50% less and 60% less expenditure on pesticides. Muhammad et al. (2020) outlines the importance of maintaining natural habitats to support pollinator populations, which are crucial for cotton production. Encouraging biodiversity and maintaining the ecological balance through IPM practices can enhance pollinator activities and support both beneficial insects and plant diversity. Aglawe et al. (2022) also provides data on farmers income and costs benefits ratio, which are positive but not taken into account in this ESA.

BIOCHAR

The scientific literature showed biochar application has a strong positive effect on soil quality, carbon sequestration (**++**), pest & disease management (++) and enhances biodiversity & habitat (**+**) and cotton production (+). Soni et al. (2023) and Han et al. (2017) provide data stating that biochar can improve nutrient availability and absorption rates by plants, increase soil microbial diversity and activity, enhance ion exchange capacity, and alter pH, which collectively contribute to soil quality, biodiversity and improved crop productivity. Analysis revealed that biochar generated from chick pea straw had a higher carbon content (68,30%) compared to the initial chickpea straw 48,10% before pyrolysis (Soni et al., 2023). This indicates a significant potential for carbon sequestration when biochar is used as a soil amendment. Bhatt et al. (2024) showed biochar-treated soils had increased populations of plant-growth-promoting fungi (e.g. *Zygomycota*). The study also indicates biochar supresses pathogens and shows a reduction in plant disease incidence, however this is not a India specific study.

SESAME RESIDUE MULCH

The scientific literature showed in situ sesame intercrop residue mulch has a positive effect on water conservation, reduced soil erosion, enhanced hydrological cycle, soil quality (**++**) and cotton production (+). Blaise et al. (2021) emphasises the benefits of using in situ crop residue mulch, which can significantly improve soil conditions by enhancing porosity, increasing water stable aggregation, and promoting greater infiltration rates of 30% higher. While simultaneously reducing runoff with 55% and soil loss with 35% compared to the conventional cultivation. The study indicates indirect cotton yield improvement through healthier soil and weed control, this is however not put into measurements. The intercropping part of this measure provides habitat for various beneficial organisms, improves pollination and reduces pest pressures through diversification, competition and supporting a richer biodiverse community (Ahmad & Hasanuzzaman, 2020; Maskell et al., 2023; Riar et al., 2020).

LEGUME GREEN MANURE

The scientific literature showed legume green manuring has a strong positive effect on cotton production, soil quality, carbon sequestration (**++**) and enhances hydrological cycle and biodiversity & habitat (+). Gabhane et al. (2023) shows a cotton yield increase through green manuring using the legume *Gliricidia* of about 105-122% compared to the non-fertilised control and 17-27% higher compared to the conventional fertiliser control. This study also indicates that integrating *Gliricidia* improved key soil quality indicators such hydraulic conductivity, organic carbon, and microbial biomass carbon. The improvement in soil organic carbon (SOC) of 11,4-36,6% due to the incorporation of organic matter suggests increased carbon sequestration in the soil. Hydraulic conductivity measures the soil's ability to transmit water through its pores, while not mentioned directly, this can also be an indicator for an improved hydrological cycle. *Gliricidia* is planted along the bunds of cotton fields, where it stays year-round to harvest the tops to be mulched into the cotton soil, while not specifically mentioned this is assumed to enhance the biodiversity of the cotton agroecosystem. There should be noted, Gabhane et al. (2023) states green manuring *Gliricidia* can only replace a significant part of the K demand of cotton, reducing the reliance on chemical fertiliser.

COTTON-WHEAT ROTATION

The scientific literature showed cotton-wheat rotations have a strong negative effect on cotton production (**--**) and a positive effect on reducing soil erosion, pest & disease management and biodiversity & habitat (+). Feng et al., (2017) emphasises the positive effect of cotton-wheat rotation on total productivity and economic viability, through ecological intensification and better nutrient uptake management compared to continuous mono-cropping of cotton. Solely looking at cotton production, however, cotton yield decreases in wheat crop rotations, on similar cotton soils in China. Matloob et al. (2020) accounts this reduced cotton yield to lower N uptake from cotton and advocates the use of nitrogen-fixing legumes or crop residue to overcome the issue. Crop rotation, including cotton-wheat systems, can contribute to reducing soil erosion. Different root structures can help bind the soil, maintaining its integrity and preventing erosion (Matloob et al., 2020). Rotating cotton with wheat can reduce the build-up of pests and diseases that typically occurs when the same crop is grown continuously. This practice can disrupt the life cycles of pests and help reduce reliance on chemical pesticides (Matloob et al., 2020). This temporal (bio)diversity, fosters a more diverse agroecosystem.

LEGUME COVER

The scientific literature showed legume cover crops have no effect on cotton production or water conservation (**+/-**), have a positive effect on soil quality, carbon sequestration (**++**) and reduces soil erosion, enhances hydrological cycle and improves biodiversity & habitat (+). J. Singh et al. (2023) simulated the effects of different legume cover crops on similar rainfed cotton soils that are assumed to be able to be extrapolated to Indian conditions. The study showed there was no significant difference in cotton yield and water use in the treatments with and without cover crops. The cover crop treatments did show higher soil organic carbon and total nitrogen, suggesting a strong positive effect on soil quality and carbon sequestration. While not providing direct measurements, Maskell et al. (2023) mentions the planting of cover crops, including legumes, during winter reduces soil erosion by avoiding periods of bare soil, limiting surface run off and suppressing weeds. The planting of legume cover crops in between the growth season of cotton, provides temporal (bio)diversity (Maskell et al., 2023; Riar et al., 2020).

MUNG BEAN INTERCROPPING

The scientific literature showed intercropping with the green gram legume; mung bean has no effect on cotton production (**+/-**), but has a positive effect on water conservation, enhanced hydrological cycle, soil quality (**+**), pollination, pest & disease management and biodiversity & habitat (+). Choudhary et al. (2016) proves intercropping with mung bean did not adversely affect cotton yield compared to other treatments. The study noted that intercropping seemed to minimise competition for resources because cotton and mung bean have different growth habits, suggesting that intercropping can be beneficial without reducing cotton yields. Mungbean intercropping saved 10% irrigation water compared to its control (Choudhary et al., 2016). This study also illustrates that intercropping can enhance soil moisture retention, reduce run off and improve soil quality through nitrogen fixation. Intercropping also provides habitat for various beneficial organisms, improves pollination and reduces pest pressures through diversification, competition and supporting a richer biodiverse community (Ahmad & Hasanuzzaman, 2020; Maskell et al., 2023; Riar et al., 2020). Choudhary et al. (2016) even states mung bean can act as a break crop, reducing pest pressure by diversifying the cropping system.

4.3 **RQ3**: MUTLI-CRITERIA ANALYSIS

Regenerative farming practices are often implemented as a combination of measures rather than as isolated techniques (Alexanderson et al., 2023; Maskell et al., 2023; Venugopalan et al., 2021) Two regenerative cotton scenarios were created in the methodology in the context of India based on common RFM combinations in literature and expert insights.

The first regenerative cotton scenario is based on the combination of Blaise et al. (2021) and J. Singh et al. (2023). In this cotton based farming system, cotton is intercropped with sesame, of which its residue is used as in situ mulch, and legume as cover crop during the winter season.

The second regenerative cotton scenario is based on Choudhary et al. (2016) and Matloob et al. (2020). In this cotton based farming system, cotton is intercropped with mung bean and rotated with wheat on Permanent Broad Beds (PBB).

These scenarios were evaluated using an MCA, with criteria derived from the identified ES and its indicators.

CRITERIA WEIGHTING

Table 6 presents the weighting assigned to each criterion by the experts in the interviews. The variability in their responses reflects differing perspectives on what ES are most important.

Table 6 *Weighting of the criteria by the experts, along with the calculated average weight and its standard deviation (σ). Orange represents the provisioning ES, yellow the abiotic Regulating & Maintenance ES and green the biotic Regulating & Maintenance ES.*

Criteria:	**Expert 1:**	**Expert 2:**	**Expert 3:**	**Expert 4:**	**Average weight:**	***σ***
Cotton production	11	11	5	28,5	**13,92**	8,81
Water conservation	11	13	5	14	**10,85**	3,56
Reduced soil erosion	11	11	10	0	**8,03**	4,65
Enhanced hydrological cycle	11	13	5	0	**7,28**	5,14
Soil quality	11	13	30	28,5	**20,67**	8,66
Carbon sequestration	11	0	10	0	**5,28**	5,29
Pollination	11	13	10	0	**8,53**	5,04
Pest & disease control	11	11	15	28,5	**16,42**	7,20
Habitat & Biodiversity	11	15	10	0	**9,03**	5,53

The weighting is very variable across the experts. Expert 1 argued weighting to be unnecessary as all criteria are equally important, where yield might be most important to the farmer, carbon sequestration is important for everyone. Other comments included that the weighting is very dependent on the scale and required a lot of background information on the specific struggles of the study area. Expert 4 took a less scientific angle and weighted the criteria from the perspective of cotton farmers in India. This resulted in high scores for all criteria that could directly decrease costs, so cotton production, water conservation, soil quality by decreasing fertiliser demand and pest & disease control by decreasing PPP expenditure. Then made the argument that 65% of India's cotton fields are rainfed by monsoons and the farmers are less concerned about water conservation because of this.

Soil quality has the highest average weight, meaning it is most valued by the experts on average. Pest & disease control, cotton production and water conservation also had high average weights. On average the lowest weights were assigned to carbon sequestration.

Water conservation has the lowest standard deviation, meaning the weighting of the each experts was closest together. Soil quality and cotton production have the highest standard deviation as there was a big difference in the weights assigned. This difference was mainly caused by the high weights given to cotton production and soil quality by Expert 4.

SCORING

Before the weighting is applied, the output from the ESA from RQ2 was used as input for the MCA and translated to a point system. The effects the individual RFMs have on the ES are assumed to be accumulated in the combined scenarios. Figure 10 shows the scores for the scenarios without weighting.

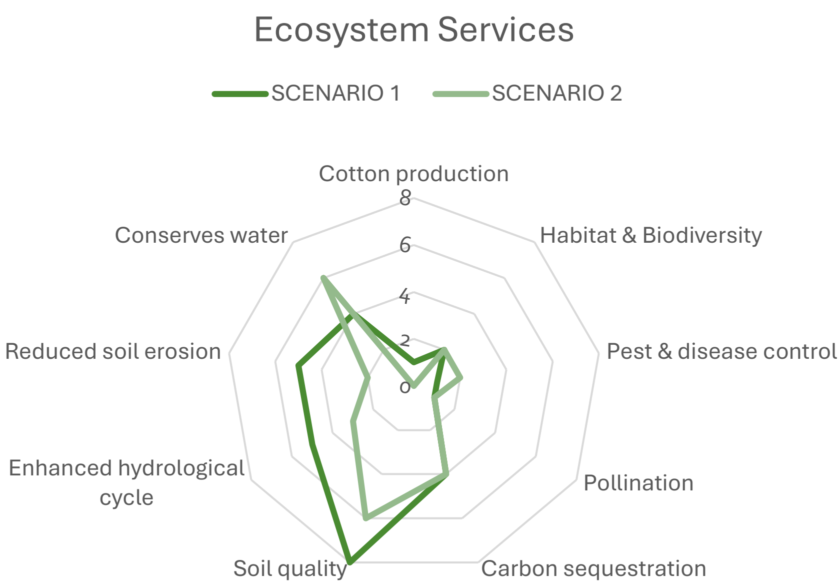

Figure 10 *Visualisation of the combined ecosystem services of the scenarios. These are the unweighted values for the MCA criteria per scenario.*

The ESA and thus the scoring of the scenarios is compared to conventional cotton cultivation, meaning the Business-as-Usual scenario would score 0 on all criteria. Both regenerative cotton scenarios only have positive scores on all criteria, except for the cotton production of scenario 2 which would be similar to the cotton production of conventional cotton. Scenario 2 scores better than scenario 1 on water conservation and pest & disease control. The scenarios score similar on pollination, carbon sequestration and habitat & biodiversity. Scenario 1 scores better than scenario 2 on soil quality, enhanced hydrological cycle and reduced soil erosion.

Table 7 shows the final MCA scoring table with the input from the +/- matrix, the scores from Figure 10 and the weighted scores.

Table 7 *Scoring table of the MCA. Orange represents the provisioning ES, yellow the abiotic Regulating & Maintenance ES and green the biotic Regulating & Maintenance ES.*

	Scenario 1				Scenario 2				
Criteria:	***Sesame intercropping/ sesame residue mulch***	***Legume cover crops***	***Score***	***Score * weight***	***PBB***	***Cotton-wheat rotation***	***Mung bean intercropping***	***Score***	***Score* weight***
Cotton production	+	+/-	1	13,9	++	--	+/-	0	0,00
Water conservation	++	+/-	4	43,4	++		+	6	65,1
Reduced soil erosion	++	+	5	40,1	+	+		2	16,1
Enhanced hydrological cycle	++	+	5	36,4	+		+	3	21,8
Soil quality	++	++	8	165,4	++		+	6	124
Carbon sequestration		++	4	21,1	++			4	21,1
Pollination	+		1	8,5			+	1	8,5
Pest & disease control	+		1	16,4		+	+	2	32,8
Habitat & Biodiversity	+	+	2	18,1		+	+	2	18,1
		TOTAL:	31	363,4			**TOTAL:**	26	307,5

Table 7 shows the total score before and after weighting to show the effect of the weighting. Scenario 1 scores a 31 before weighting and a 363,4 after weighting, while scenario 2 scores a 26 before weighting and a 307,5 after weighting, compared to a score of 0 from the conventional BAU scenario. A more accurate sensitivity analysis can be seen in Table 3A in the appendix, which indicates the weighting does not cause a significant difference between the scenarios. With only the weights from Expert 4 applied, the difference between the scenarios becomes smaller.

4.4 **RQ4**: BARRIERS AND BENEFITS

Regenerative farming practices offer a promising approach to enhancing soil health, increasing biodiversity, and improving the sustainability of cotton cultivation in India (see section 4.2 and 4.3). The interviewed experts gave insights into how their implementation can bring sociopolitical benefits to Indian farmers and faces significant sociopolitical challenges.

BENEFITS OF IMPLEMENTATION

The three main sociopolitical benefits of implementation include higher income and lower input costs, a more diversified income and government support.

A key motivation for Indian farmers to adopt new practices is the potential for higher income. Higher income, not only through higher cotton yields, but also through lower input costs. Regenerative farming, when properly implemented, can also lead to long-term cost savings by reducing water use and dependency on expensive synthetic fertilisers and pesticides (Expert 4).

Crop rotations or intercropping provide not only additional income, but also a more diversified income, strengthening farmers financial resilience against failed harvests. Incorporating soybean or other legumes can be particularly beneficial in central Indian states, where vegetarian diets are prevalent (Expert 4). This enhances food security while complementing a cotton-based farming system with additional income sources.

Additionally, the Indian government has recently shown support for sustainable and natural farming practices, which share principles with regenerative farming. Initiatives like this, if expanded, could provide financial and policy support for regenerative cotton farming. Such support could accelerate adoption and help farmers transition from conventional practices.

BARRIERS OF IMPLEMENTATION

The four main sociopolitical barriers of implementation include the long time it takes to see results, the difficulty of breaking a pesticide dependency cycle, lack of financial business models or incentives and scepticism.

One of the biggest hurdles in adopting regenerative farming is the time it takes to see tangible results. Soil health improvements can take six months to a year (Expert 4), economic benefit however can take up to three years, depending on the measure according to literature. Additionally, initial cotton yield penalties are common. Unlike conventional farming, where chemical inputs provide immediate effects, regenerative measures focus on rebuilding soil health over multiple growing seasons. This delay can discourage farmers who need short-term economic gains to sustain their livelihoods.

Decades of conventional farming have trapped many Indian farmers in a pesticide dependency cycle, making it difficult to transition to regenerative practices (Expert 2). The Green Revolution, which aimed to meet the demands of a rapidly growing population in Asia, encouraged excessive use of synthetic fertilisers and pesticides. Today, many farmers fear production losses if they abandon these inputs.

Transitioning to regenerative farming is further complicated by a lack of financial business models or incentives (Expert 3). Most Indian cotton farmers are smallholders with limited resources, making them hesitant to take economic risks without guaranteed rewards. Without viable financial models or incentives, such as premium pricing for regenerative cotton or subsidies for transition, the shift remains economically unfeasible for many smallholders.

In addition to economic barriers, scepticism present a major challenge. Tilling is deeply ingrained in Indian farming practices, and many farmers are sceptical of zero-tillage methods, as ploughing is associated with better yields and weed control. Furthermore, there is a misconception that regenerative farming is synonymous with organic farming, leading to concerns about complete pesticide and GMO prohibition. While 97% of Indian cotton is a transgenic hybrid resistant to bollworms, a pest that once devastated cotton crops before the genetically modified Bt cotton was introduced in 2002. Overcoming this cultural resistance will require extensive education and demonstration of successful regenerative farming systems. Some initiatives, such as RegenCottonIndia by ACRE, are working to bring smallholders together to strengthen their market position, but significant investment and policy support are needed to make large-scale adoption possible.

DISCUSSION

This thesis explored the effect of regenerative cotton cultivation on ecosystems services in India as a possible solution for the environmental challenges associated with conventional cotton cultivation, such as its synthetic input dependency and declining soil health.

INTERPRETATION OF MAIN RESULTS

RQ1: This study identified eight RFMs most suitable for cotton cultivation in India; Permanent Broad Beds (PBB), Integrated Pest Management, biochar, intercrop residue mulch, legume green manuring, cotton-wheat rotations, legume cover crops and mung bean intercropping. While, available reports generally centre their general agreement around the 5 principles used in this research (Ahmad & Hasanuzzaman, 2020; Giller, 2022; Newton et al., 2020; Ritz, 2021), there remain inconsistencies in the principles of regenerative farming, as well as in definition and classification of the measures. For instance, cover cropping, crop rotations, and intercropping are frequently used interchangeably, particularly in the context of legumes, due to the versatility of the plant family (Ahmad & Hasanuzzaman, 2020; Maskell et al., 2023).

This research also found discrepancies between academic literature and actual field practices. For example, no studies were found documenting the implementation of semi-natural landscape elements or livestock grazing in cotton systems in India, yet expert interviews noted that agroforestry is commonly practiced. This suggests a gap between documented research and on-the-ground realities. Moreover, even where agroforestry is studied, its effectiveness appears highly context-dependent. Wang et al. (2016) reported unfavourable outcomes in Chinese cotton systems due to shading and resource competition, raising concerns about its applicability in different agronomic settings.

RQ2: The ES are divided into Provisioning ES: cotton production, water conservation and Regulating & Maintenance ES: reduced soil erosion, enhanced hydrological cycle, soil quality, carbon sequestration (abiotic) and pollination, pest & disease control and habitat & biodiversity (biotic). However, these services do not operate independently, and their interactions create synergies and overlap, complicating their assessment. Regulating & Maintenance ES have an effect on the Provisioning ES and also, for instance, soil erosion is directly linked to soil quality and the hydrological cycle, making it difficult to separate their effects and potentially leading to double counting. This overlap is also seen in the possible indicators from literature used for the ES in Table 4. An indicator can be used as a proxy for one ES and in another article used for a different ES.

Among the RFMs analysed, cotton-wheat rotations were the most extensively studied (Choudhary et al., 2016; Das et al., 2024; Matloob et al., 2020; K. Singh et al., 2023) and widely adopted in India (Riar et al., 2020). This is likely due to its role in enhancing overall farm productivity and economic viability, particularly through additional wheat yield. However, the ESA indicated a strong negative effect on cotton yield, which is expected to be due to nitrogen depletion and can be mitigated using legumes (Matloob et al., 2020). This was applied in scenario 2.

Additionally, studies on intercropping show mixed results, showcasing intercropping to be very dependent on the choice of intercrop. Studies suggest that mung bean does not reduce cotton yields (Blaise et al., 2021; Choudhary et al., 2016), while studies on different intercrops do report cotton yield reductions (Jayakumar & Surendran, 2017; Matloob et al., 2020). This variability underscores the need for crop-specific assessments of RFMs. Riar et al. (2020) however recommends the green gram legume; mung bean as well as sesame as intercrop for Indian cotton crop diversification after elaborate context-specific research and stakeholder panel. This was applied in the scenarios.

There should also be noted that the most reliable ESA values for water conservation come from studies conducted in northwestern India such as Choudhary et al. (2016), Das et al. (2024), K. Singh et al. (2023), where cotton is primarily irrigated rather than rainfed. This is because water measurements and calculations are more straightforward when irrigation is the main water source, with minimal influence from rainfall. However, the specific study area in this research was southern and central India, where cotton is predominantly rainfed. This region was chosen under the assumption that regenerative farming measures would have the greatest impact here, due to their dependency of the monsoons. Despite the difference in water sources, the effects of RFMs on their ecosystem services are still considered applicable.

While most of the reviewed literature focused on combined measures, reflecting real-world practises, this study aimed to include only findings on isolated effects of individual measures in the ESA. This proved more challenging for cotton-wheat rotations compared to the other selected RFMs. As a result, limited strong ESA results were found for this RFM, as many conclusions in literature could not be attributed solely to this practice. Literature from other contexts were sometimes used to strengthen a claim. The only exception is the ESA results for in situ intercrop residue mulching, which combines two separate RFMs, and was therefore analysed as such.

RQ3: The MCA scenarios in this study were not inclusive due to the absence of key RFMs selected in RQ1, such as IPM, green manuring, and biochar. IPM can be a good addition to any cotton-based farming system, however one of the practises of IPM includes tillage against weeds, which highly contradicts the conservation tillage practises of both scenarios. IPM can however be tailored to the exact scenario and the complementary crops, but more research is needed on this. Biochar can always be used as an additional RFM to aid in replacing synthetic fertiliser. Similarly, green manuring was not used in the scenarios due to its redundancy in the crop residue mulching and legume cover cropping Scenario 1 and its incompatibility with PBB no-tillage practises in Scenario 2.

Four different experts assigned varying levels of importance to the various criteria. Expert 4, representative of local farmers initiative in India highly prioritised the indicators with the highest direct economic impact such as cotton production, water conservation, soil quality and pest & disease control as they would result in reduction of synthetic fertiliser and PPP expenditure. In contrast, the researcher experts placed greater emphasis on biodiversity and pollination as well, given their broader environmental significance. The sensitivity analysis (Appendix Table 3A) explored the effects of equal weighting or weighting based solely on Expert 4's input, representing a local farmers' initiative. Equal weights didn't significantly change the scores and only Expert 4's weights equalled the scores. However, conclusions cannot be drawn from a single individual's perspective, as it does not accurately represent the broader farming community. The divergence in the weighting underscores the need for a more diverse and representative stakeholder panel to improve its accuracy. It is expected that the standard deviation will become smaller as the research group becomes larger.

A more accurate weighting approach for the MCA would have been an elaborate stakeholder panel. There was decided against this due to time and resource restrictions. The main stakeholders of this research can be placed in 4 main categories; policymakers, citizens, business & industry and scientists, varying in their interest and their influence. The policymakers exist of government of India, the Ministry of Agriculture & Farmer's Welfare and state Agricultural departments on national level (Riar et al., 2020). On international level there is for example the EU, who influences the market by pushing to more sustainable cotton (Jena, 2013). Their interest, as well as their influence is generally very high. The citizens exist of the general public, consumers of cotton and local residents of central/southern India, whose interest is usually low to medium and influence is very low. The business and industry exists of Indian farmers and the agricultural sector, large cotton buyers such as Arvind and IKEA or other textile and fashion brands, environmental NGO's, such as WWF and Solidaridad and government initiatives, such as Better Cotton

Initiative (BCI) (Jena, 2013). Both their interest and influence is generally medium to high, with a lot of variation. While cotton or cotton items are predominantly supplied to the western countries, these welfare states often avoid the direct environmental effects of its production. Lastly, the scientists who mostly exist of academic and research institutions such as the Indian Council of Agricultural Research (ICAR) (Riar et al., 2020). Whose influence is lower and interest higher than the industry stakeholders. A visualisation of this is placed in the appendix (Figure 1A).

RQ4: While regenerative farming presents numerous benefits for cotton cultivation in India, its adoption is hindered by economic, knowledge-based, infrastructural, and cultural barriers. Addressing these challenges will require a combination of policy support, financial incentives, education, and collaborative efforts among farmers, organisations and governments. By overcoming these barriers, India can move towards a more sustainable and resilient cotton production system that benefits both farmers and the environment.

As mentioned by the experts in the interviews, knowledge-based barriers are particularly significant. Prajapati & Kulkarni (2024) also mentions this as one of the main constraints of establishing effective pest management approaches for cotton in India. Furthermore, experts stated that regenerative farming can enhance income, primarily by improving cotton yields, conserving water, and reducing expenditure on fertilisers and pesticides. Additionally, incorporating complementary crops, such as crop rotations or intercrops, into a cotton-based farming system can diversify income, thereby reducing vulnerability to market price fluctuations as stated in Riar et al. (2020). However, in addition to high input costs, Mohanasundaram (2015) also identifies labour shortages and high wage rates as socioeconomic challenges in India, and cotton cultivation is labour intensive, which is not overcome but perhaps even exacerbated by regenerative farming.

Additionally, strong scientific evidence on the economic viability of regenerative cotton cultivation in India, to support the experts claims on regenerative farming's ability to enhance income, remains limited. While most research suggest economic benefit (Aglawe et al., 2022; Choudhary et al., 2016; Das et al., 2024; K. Singh et al., 2023), most strong analyses prove economic feasibility to be highly specific to the RFM. For example, Dewi et al. (2025) examined the economic feasibility of a no-tillage soybean cropping system in Japan, incorporating cover crops and biochar application. While biochar and cover crops increased material costs, rendering some scenarios unfeasible, the introduction of an additional rice rotation improved the benefit-cost ratio significantly due to the additional income that compensated production costs. This highlights the need for further research, particularly long-term economic analyses of regenerative practices when improvements on soil quality have had time to be able to see tangible results.

STRENGHTS AND LIMITATIONS

One of the primary limitations comes from the fact that regenerative farming measures (RFMs) are often **ambiguous and open to interpretation.** Various RFMs lack a standardised definition, 'reduced tillage' is a good example of this. It leaves space for what depth and frequency qualifies as reduced tillage. Similar ambiguity exists across all RFMs, including Integrated Pest Management (IPM), where the degree of intervention and specific methods can vary significantly. Given this variability observed, RFMs must be defined with a high degree of specificity. Their effectiveness is highly dependent on precise implementation, including factors such as timing, intensity, duration and choice of crop. Ahmad & Hasanuzzaman (2020 and J. Singh et al. (2023) state the timing of sowing of cover crops or intercrops for example is critical, as early or late sowing can adversely affect germination and growth phases, ultimately impacting yield of both cotton and the intercrop. Without clear definitions, results can be inconsistent, leading to misleading conclusions about the success or failure of a given practice. This underscored the importance of this research to rely on context-specific literature that accounts for local environmental conditions, soil types and cropping systems. However, this also limits the external validity of this research, as findings can't easily be generalised to other contexts.

The complexity of interactions between ecosystem services poses another challenge and limitation. Many ES have synergies and overlap, making it difficult to separate their individual effects. For instance, soil quality is directly linked to soil erosion and the hydrological cycle, potentially leading to **double counting** in the ESA. Similarly, certain indicators serve as proxies for multiple ES, which can introduce inconsistencies in how they are measured and compared across studies. Additionally, maintenance ES inherently influence provisioning ES, further complicating impact assessments. These interlinked effects were carefully considered through the selection of ecosystem services (ES) and their indicators. Additionally, the weighting of criteria in the MCA helped account for these complexities, ensuring a more balanced assessment.

Another limitation of this research is the +/- system in the ESA and the point system used to translate these inputs into scores for the MCA. Rather than solely reflecting the strength of an effect, this approach also prioritised effects with the strongest evidence. While it is important to distinguish between certainty of findings, this also creates an bias. Some ES and their indicators, such as cotton production, soil quality and water conservation, are **more easily quantified by direct measurements than others**, such as soil erosion, pest & disease control and pollination, which are harder to measure.

One of the limitations of this research lies in distinguishing the effects from individual RFMs, despite their frequent implementation in combination. Most literature reviewed combined measures, reflecting real-world practise, this complicated data analysis. To ensure accuracy, there was aimed to exclusively include findings from literature in the ESA if they explicitly revealed to effects of an individual measure, unless otherwise stated. Sometimes articles were found where no conclusions could be drawn on RFMs individually due to its research design. These were used to strengthen the claim but not used as main evidence for an effect. However, this output from the ESA was later used as input for the MCA, which assessed combined scenarios. This required the assumption that the **individual effects** observed in the ESA would accumulate in the MCA scenarios, representing a key limitation.

Another limitation is the **exclusion of cultural ES** from the ESA**.** The ES are divided into Provisioning ES and Regulating & Maintenance ES, however the CICES framework usually also distinguishes cultural ES. These could include the cultural heritage of indigenous practices, educational value, or aesthetic appeal. Indian cotton farmers often rely on and value indigenous knowledge, and with tourism contributing significantly to India's GDP, the aesthetic impact of agricultural techniques is not an insignificant factor. For the aim of this research there was decided to exclude these, based on their difficulty to quantify. However, when using this research as a policy decision-making tool, cultural ES are essential for providing a more comprehensive perspective.

Additionally, the ESA does not account for yield trade-offs in land allocation. Logically, there should be more '-' symbols in the ESA for cotton production as many RFMs involve less intensive cotton planting such as wider spacing or intercropping, which can lead to **lower absolute cotton yields**. While in literature the effect on cotton yield is often normalised to planted area, a control group or boll size. These less intensive cotton RFMs do not necessarily indicate lower overall productivity, as complementary crops would also contribute to this. Similarly, in IPM, while reduced pesticide use can be effective, the long-term risk of pest outbreaks and the catastrophic impact on cotton yield must also be considered.

The limitations of the MCA stem primarily from its **incomplete consideration of criteria**. Many studies also highlight factors such as energy inputs (e.g., labour, machinery) and economic benefit-to-cost ratios, which are often positive (Choudhary et al., 2016; Das et al., 2024; K. Singh et al., 2023). Yields of the complementary crop in crop rotations or intercropping is not taken into account in this research, while enhancing overall farm productivity and economic viability. Additionally, RFMs, such as conservation tillage often enhances the yield of complementary crops in cotton-based farming systems as well as the cotton yield (Choudhary et al., 2016; Das et al., 2024; K. Singh et al., 2023). While this could contribute to further economic benefits, it is not adequately reflected within the ESA framework or in the combined scenarios in the MCA.

The use of studies conducted in **northwestern India** such as Choudhary et al. (2016), Das et al. (2024), K. Singh et al. (2023), where cotton is primarily irrigated rather than rainfed, impacts the robustness of this research. The specific study area of southern and central India was chosen under the assumption that regenerative farming would have the greatest impact here, due to their dependency on the monsoons. Despite the difference in water sources and slight variations in soil type, the general effects of RFMs on its ecosystem services are still considered applicable, as they are derived from studies on cotton cultivation within the Indian context.

Another limitation of the MCA is the weighting of its criteria, which remains highly subjective and lacks robustness due to the small research group. In this study, three researchers contributed to the weighting process, while only one local farmer representative was included, limiting the practical relevance of the results. Additionally, the weighting process is highly dependent on the scale of the research and the context provided, making the assignment inherently ambiguous.

RECOMMENDATIONS AND IMPLICATIONS

Further research should include long-term economic analyses to assess the financial viability of regenerative farming in the context of Indian cotton cultivation. While existing studies indicate promising economic outcomes, they also highlight that profitability is highly dependent on the specific farming system. This underscores the need for more context-specific economic evaluations. For this same reason, further research should include the effect of more tailored IPM practises on cotton-based farming systems. Additionally, establishing standardised definitions for RFMs would enhance research consistency and improve practical implementation.

Future studies should also adopt a stakeholder-driven MCA approach, incorporating a broader panel of farmers, researchers, and policymakers to ensure a more balanced weighting of criteria and better implementation. Another important avenue for research is promoting crop diversification strategies beyond the yearly cotton-wheat rotation. For instance, the Organic Cotton Accelerator (OCA) recommends growing cotton only once every two years, breaking the cycle of monocropping and reducing pest pressures even more. Their proposed crop rotation models include a variety of crops such as legumes, oilseeds, and cereals instead of relying solely on a cotton-wheat sequence. This diversification not only enhances system resilience but also mitigates risks associated with price volatility and agronomic failures (Riar et al., 2020). While numerous possible rotation scenarios exist, further research is needed to determine which combinations are most effective in different agroecological contexts.

To support the transition to regenerative cotton cultivation, these findings can serve as a foundation for policymakers and stakeholders to establish financial incentives or invest in initiatives that assist farmers in adopting regenerative practices. By addressing the identified economic, definitional, and agronomic challenges, future research can contribute to a more sustainable and resilient cotton production system in India.

CONCLUSION

Conventional cotton cultivation is facing various environmental challenges due to its high water demand, vulnerability to pests and diseases and soil fertility depletion. This thesis explored the potential of Regenerative Farming Measures (RFMs) as a sustainable alternative to conventional cotton cultivation in India. This was done by identification of the best suited RFMs, an Ecosystem Service Assessment (ESA) of these selected measures, a Multi-Criteria Analysis (MCA) of these measures combined in viable scenarios and identification of the benefits and barriers of implementation, using mainly literature and interviews with relevant experts.

The 8 selected RFMs best suited for cotton cultivation in India were Permanent Broad Beds (PBB), Integrated Pest Management, biochar, intercrop residue mulch, legume green manuring, cotton-wheat rotations, legume cover crops and mung bean intercropping. Where cotton-wheat rotations, while being the most implemented and researched RFM, showed a strong negative effect on cotton yield in the ESA, which is expected to be due to nitrogen depletion and can be mitigated using legumes. Both the regenerative cotton scenarios, cotton with in situ sesame intercrop mulch and legume cover crops (Scenario 1) and cotton intercropped with mung bean and rotated with wheat on PBBs (Scenario 2), showed a positive result compared to the Business-As-Usual scenario of conventional cotton cultivation in the MCA. The main benefits and barriers of implementation were diversified income, lower demand of inputs and government support, and long time to see results, pesticide dependency cycle, lack of financial incentives and scepticism.

In conclusion, the findings of this research indicate RFMs can significantly enhance ecosystems services in the context of cotton cultivation in India, however its implementation is hindered by sociopolitical barriers. Further research is necessary to fill existing knowledge gaps such as economic analysis and to develop support systems that facilitate the transition for farmers.

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APPENDIX

***Table 1A** List of experts, their organisations and expertise.*

	Organisation	Name	Expertise
1.	Wageningen University & Research	Loekie Schreefel	PhD on Regenerative Farming and its Implementation and Measurability
2.	Wageningen University & Research	Kees Hendriks	Senior Researcher on Ecosystem Services, Soil-plant relations and Biodiversity
3.	Wageningen University & Research	Sinead O'Keeffe	Researcher on Regenerative Agriculture and Circular textiles
4.	ACRE (Alliance of Cotton stakeholders on Regenerative Agriculture)	Ranjeeb Sarma	Regen Cotton India - Stakeholder Platform to embrace Regenerative Cotton

Table 2A Ecosystem Services per category and the indicators and units to quantify them found in literature.

Category:	**Ecosystem Services:**	**Indicator**	**Unit**	**References**
Provisioning	**Cotton production**	Seed Cotton Yield (SQY) Lint Cotton Yield	Mg ha^{-1} or kg ha^{-1}	(Aglawe et al., 2022; Ahmad & Hasanuzzaman, 2020; Choudhary et al., 2016; Das et al., 2024; Gabhane et al., 2023; K. Singh et al., 2023)
	Water conservation	Water Productivity (WP) or Water Use Efficiency (WUE)	kg grain m^{-3} or mm^{-1} water	(Ahmad & Hasanuzzaman, 2020; Blaise et al., 2021; Choudhary et al., 2016; Das et al., 2024; K. Singh et al., 2023; Yemadje et al., 2025)
Regulating & maintenance	**Reduced soil erosion**	Soil loss	Mg ha^{-1}	(Blaise et al., 2021)
	Enhanced hydrological cycle	Infiltration Rate (IR) Run off	mm h^{-1} mm	(Blaise et al., 2021; K. Singh et al., 2023)
	Soil quality	Organic Matter (OM) content/ TOC Bulk density Porosity	g kg^{-1} or % g cm^{-3} %	(Ahmad & Hasanuzzaman, 2020; Blaise et al., 2021; Das et al., 2024; Gabhane et al., 2023; Yemadje et al., 2025)
	Carbon sequestration	Total organic carbon stock (TOC) Global Warming Potential (GWP)	Mg ha^{-1} (t C ha^{-1}) kg CO2 eq ha^{-1}	(Ahmad & Hasanuzzaman, 2020; Das et al., 2024)
	Pollination	# of beneficial insects	-	(Ahmad & Hasanuzzaman, 2020)
	Pest & disease control	# of insecticide sprays # of pests/diseases	- -	(Aglawe et al., 2022; Ahmad & Hasanuzzaman, 2020; Bhatt et al., 2024)
	Habitat & Biodiversity	Species richness	# of species per area	(Ahmad & Hasanuzzaman, 2020)

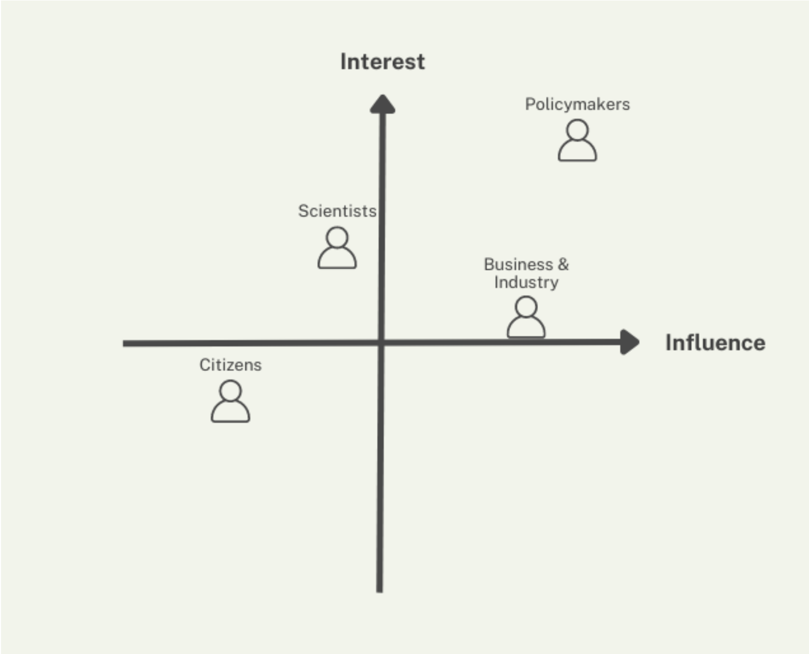

Figure 1A *Visualisation of the interest versus the influence of the different stakeholders.*

***Table 3A** Sensitivity Analysis, scores per scenario using equal weights and using only the weights assigned by expert 4.*

				Scenario 1				Scenario 2			
Ecosystem services:	**Average weight**	**Equal weights**	**Expert 4 weights**	**Score:**	**Score* average weight**	**Score* equal weights**	**Score* Expert 4 weights**	**Score:**	**Score*weight**	**Score* equal weights**	**Score* Expert 4 weights**
Cotton production	13,92	11,11	28,57	1	13,92	11,11	28,57	0	0,00	0,00	0,00
Conserves water	10,85	11,11	14,29	4	43,40	44,44	57,14	6	65,10	66,67	85,71
Reduced soil erosion	8,03	11,11	0,00	5	40,14	55,56	0,00	2	16,06	22,22	0,00
Enhanced hydrological cycle	7,28	11,11	0,00	5	36,39	55,56	0,00	3	21,83	33,33	0,00
Soil quality	20,67	11,11	28,57	8	165,37	88,89	228,57	6	124,02	66,67	171,43
Carbon sequestration	5,28	11,11	0,00	4	21,11	44,44	0,00	4	21,11	44,44	0,00
Pollination	8,53	11,11	0,00	1	8,53	11,11	0,00	1	8,53	11,11	0,00
Pest & disease control	16,42	11,11	28,57	1	16,42	11,11	28,57	2	32,84	22,22	57,14
Habitat & biodiversity	9,03	11,11	0,00	2	18,06	22,22	0,00	2	18,06	22,22	0,00
			TOTAL:	**31**	**363,33**	**344,44**	**342,86**	**26**	**307,54**	**288,89**	**314,29**

STATEMENT ON THE USE OF AI

For the completion of this research, AI was used in different ways. Firstly, for suggestions on how to improve scientific writing, use of synonyms, and improving flow and clarity of a sentence or paragraph. These pieces of AI output were not copied into the document, but taken as suggestions and typed over where in agreement of improvement of the original. Pieces of writing were put in for the purpose of spelling or grammar checking. It was used for suggestions on structure, headings and removal of redundancy. There is recognised AI can be incorrect, so there was made sure to always double check every single output.

There was made use of CoralAI, which aids in reading and understanding scientific articles. After uploading the PDF of a peer-reviewed scientific article, there was sometimes asked to summarise, conclude, translate or explain certain parts (often exact methods or treatments) more. It's output was always thoroughly checked. It is also used as a tool to quickly assess the utility of an article for the purpose that was searched for.