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Master's Thesis

**From Industry 4.0 to Regenerative Practices in the Agri-Food
Sector: Comparing Technological and Nature-Based Models**

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Abstract

In response to the increasing pressure on agri-food systems to reconcile productivity, environmental sustainability, and climate resilience, regenerative agriculture (RA) has emerged as a potential long-term strategy for systemic transformation.

At the same time, the diffusion of Industry 4.0 (I4.0) technologies is reshaping agricultural practices. In fact, digital tools are increasingly being integrated into farming processes to improve efficiency, data management, and supply chain transparency.

Yet, despite the simultaneous expansion of these two parallel trends, the extent to which digital technologies can concretely support regenerative practices remains underexplored.

This thesis addresses this gap by comparing high-tech, technology-intensive configurations with predominantly nature-based approaches.

Adopting a multiple case study design, the research analyzes corporate initiatives, technology providers, hybrid configurations, and regenerative carbon projects. The findings indicate that digital technologies (such as the Internet of Things, remote sensing, Artificial Intelligence, and blockchain) primarily operate as supporting infrastructures for monitoring, traceability, and certification, rather than as direct drivers of ecological restoration. On the other hand, nature-based cases show that regenerative outcomes can emerge through ecological processes implemented at farm level, often with limited reliance on technological mediation.

The examination of comparative data indicates a structural tension: in fact, digital infrastructures also introduce issues related to costs, governance centralization, and accessibility for smallholders, while nature-based configurations often encounter limitations in standardization, verification, and economic recognition.

Overall, the regenerative transition in agriculture does not follow a single, linear path but emerges through different combinations of ecological practices and digital tools. By offering a comparative perspective, the study clarifies both the potential contributions and constraints of digital technologies in regenerative agriculture.

These results also point to the need for further empirical research, including the collection of primary data, to better understand under which conditions digital technologies can meaningfully contribute to regenerative transitions without reinforcing existing structural inequalities.

Keywords: Digital Transformation; Industry 4.0; Regenerative Agriculture; Sustainability Transitions

1. Introduction

The agri-food sector, due to factors such as globalization and the rapid growth of the global population, is facing major sustainability challenges: climate change, biodiversity loss, resource depletion and food insecurity. A sustainability-oriented shift has become an urgent matter and a central focus for policymakers, researchers, and firms (FAO, 2025; Clapp & Moseley, 2020).

By prioritizing short-term productivity over long-term resilience, modern agriculture is critically contributing to the degradation and growing vulnerability of natural systems: nearly 80 percent of global deforestation is driven by farming practices (Zhao et al., 2025).

As a result, Regenerative Agriculture (RA), a holistic farming approach that moves away from industrial agricultural practices, is gaining increasing attention (Gordon et al., 2023; Alexanderson et al., 2023).

Regenerative practices seek to restore and maintain ecosystem health by enhancing soil fertility and biodiversity. However, despite its potential, the implementation of RA in practice remains complex and context-dependent: in fact, this approach often requires large long-term investments and adjustments in farm management that can result in a risk of temporary productivity losses (Gordon et al., 2023; Tittonell et al., 2022).

In this context, Industry 4.0 technologies have increasingly been proposed as potential enablers of the regenerative transition of agri-food systems (Maffezzoli et al., 2022; Cricelli et al., 2024).

Yet, the extent to which these technologies can effectively support this transition, as well as the limitations and trade-offs associated with their use compared to predominantly nature-based approaches, remains insufficiently explored (Giller et al., 2021; Sharma et al., 2024).

This thesis therefore addresses the following research question:

“To what extent can Industry 4.0 technologies support the transition toward regenerative agriculture in the agri-food sector, and what limitations emerge when compared to predominantly nature-based approaches?”

To answer this question, this work combines an initial literature review with a multiple case studies analysis of thirty-eight selected agri-food projects, adopting a Context–Intervention–Mechanism–Outcome (CIMO) analytical framework.

The cases include high-tech, hybrid, and predominantly nature-based models, examined to explore how Industry 4.0 technologies interact with regenerative practices across diverse contexts.

The thesis is structured as follows: after a review of the relevant academic literature on sustainability challenges in the agri-food sector, regenerative agriculture, the role of Industry 4.0 technologies and their intersection (Chapter 2), it outlines the methodology adopted (Chapter 3) with a subsequent presentation and discussion of the case study analysis (Chapter 4).

Finally, it concludes by summarizing the main findings and future research directions (Chapter 5).

2. Agri-Food Systems in Transition: Sustainability, Regeneration and Digital Innovation

2.1 The agri-food sector and the sustainability challenge

With the world population projected to reach 9.7 billion by 2050, pressures on land and natural resources are expected to increase, further intensifying the environmental challenges that already affect the global agri-food sector (FAO, 2025).

Global food systems are in fact characterized by patterns of overconsumption and exploitation and are simultaneously confronted with sustainability challenges such as resource depletion, biodiversity loss, climate change and food insecurity (Clapp and Moseley, 2020).

Land constitutes the foundation of agri-food systems, accounting for over 95% of food production while sustaining biodiversity and providing fundamental ecosystem services (FAO, 2025).

Soil represents the biologically active upper layer of land. According to the European Commission's *Proposal for a Directive on Soil Monitoring and Resilience* (2023), soil health is "the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services".

Findings from the Joint Research Centre (JRC) indicate that about 61% of EU soils are considered unhealthy, reflecting soil erosion rates 1.6 times higher than soil formation rates, critically high levels of compaction and declining biodiversity (Joint Research Centre, 2023).

One of the main issues that emerge is land degradation: the reduction in the capability of land to deliver benefits under a given land use and management system, with impacts that range from slight productivity losses to complete agricultural abandonment. As land represents the basis of food production, land-use practices are essential for ensuring global food security, affecting the stability and availability of food supplies (FAO, 2025).

Under these circumstances of increasing land scarcity and soil degradation, food loss and waste emerge as a major structural inefficiency along the food chain, particularly given the land- and resource-intensive nature of food production (UNEP, 2024).

As reported by the *UNEP Food Waste Index Report 2024*, in 2022 more than 1.05 billion tonnes of food were wasted worldwide.

This phenomenon can occur across different stages of the agri-food chain: households account for the largest share, followed by the food service and retail sectors.

Food loss and waste alone are responsible for approximately 8–10% of global greenhouse gas (GHG) emissions: nearly five times higher than the aviation sector! Beyond emissions, wasted food also implies that land, water, energy, and

agrochemical inputs are used without delivering real benefits, intensifying pressures on ecosystems and compromising long-term agricultural stability.

At the same time, global food demand is expected to increase by about 30%, while 783 million people suffer from hunger and nearly one-third of the global population faces food insecurity (UNEP, 2024; FAO, 2025).

Although adaptation to land degradation may help mitigate productivity losses in the short-term, this approach alone does not represent a sufficient long-term solution, as modern agricultural systems often prioritize immediate output at the expense of resilience over time (FAO, 2025; Tittonell et al., 2022).

This critical situation has led to an active debate on the necessity of new farming practices capable of sustainably increasing food production, while enabling agriculture to limit, reduce and reverse land degradation without compromising productivity. In this context, the concept of “sustainable intensification” emerged to describe the need to boost agricultural output on existing land while improving environmental outcomes (FAO, 2025; OECD, 2021).

More recently, regenerative practices have gained increasing attention. Regenerative Agriculture (RA) describes holistic farming principles and practices that “work with nature instead of against it”: by restoring soil health, they aim to enhance biodiversity and reverse biodiversity losses, improve watersheds and air quality, and mitigate climate change (Gordon et al., 2023; Alexanderson et al., 2023).

To support and facilitate the transition towards RA, emerging strategies range across two different approaches.

On the one hand, high technology-based practices (including precision agriculture and Industry 4.0 applications), rely on advanced inputs and digital tools to optimize real-time monitoring, decision-making and production processes (Maffezzoli et al., 2022; Wolfert et al., 2017). On the other hand, ecology- and nature-based practices focus on natural processes and dynamics to enhance soil health and ecosystem services (Tittonell et al., 2022; Gordon et al., 2023).

Yet, the intersection between these two paradigms remains relatively underexplored, particularly with respect to the potential synergies and benefits that may arise from their integration (Maffezzoli et al., 2022; Cricelli et al., 2024; Sharma et al., 2024).

2.2 From sustainable to regenerative agriculture

Throughout the past century, agricultural practices have constantly evolved to address the persistent issue of land degradation and climate-related pressures (Fig.1). As this phenomenon persists, it is crucial to shift from short-term “coping strategies” to long-term solutions to restore and protect land (FAO, 2025).

Between the 1920s and the 1950s, in response to the Dust Bowl, first efforts were made: organic farming and early soil conservation techniques were developed.

The Dust Bowl was a period of severe dust storms that greatly damaged ecosystems and agriculture in the United States, exacerbating an already existing agricultural recession: 6.5 million hectares of land were affected (Cook et al., 2009).

This phenomenon was caused by a combination of natural factors (intense drought), amplified by unsustainable land-use practices, such as the lack of dryland farming methods to prevent wind erosion and the extensive removal of natural topsoil by settlers.

The Dust Bowl led to a positive increase in government involvement in land management and soil conservation: many federal agencies intervened through different initiatives, for example producing detailed soil maps and aerial photographs by the Soil Conservation Service, in addition to resettlement programs.

Under President Franklin D. Roosevelt's "New Deal", soil conservation became for the first time a key policy objective, supported by legislation linking farm subsidies to conservation measures, and large-scale programs promoting soil conservation practices. These efforts substantially reduced soil erosion by the late 1930s and continued beyond the end of the drought (Cook et al., 2009).

From the 1970s onwards, as a new conceptual framework emerged: agroecology, "the science that studies how different components of the agroecosystem interact" (FAO, 2023).

By integrating ecological principles into farming practices and adopting an ecosystem-based view of farms (shaped by interactions among soils, plants, insects and human activities), it represented a first shift away from purely input-intensive production models (Tittonell et al., 2022).

By the late 1990s, Conservation Agriculture gained more and more attention, translating ecosystem-based principles into practical soil management strategies, and bringing first improvements (FAO, 2025).

Conservation Agriculture is defined by the Food and Agriculture Organization of the United Nations (FAO) as a "farming system that promotes minimum soil disturbance, maintenance of a permanent soil cover, and diversification of plant species".

By supporting biodiversity and natural biological processes above and below the soil surface, this approach contributes to increased water and nutrient use efficiency and to improved and sustained crop production (FAO, 2025; Dang et al., 2020).

By the 2000s, a new threat had emerged: climate change, with agriculture identified as one of the most significant sources of GHG. The need for a solution had become urgent.

In 2010, the FAO introduced the concept of Climate-Smart Agriculture (CSA), an approach designed to reach three main objectives: increasing agricultural productivity

in a sustainable way, building resilience to climate change, and reducing/removing GHG emissions.

CSA sought to transform agri-food systems towards environmentally sustainable and climate-resilient practices (FAO, 2025).

In the 2010s, in response to the growing awareness of soil degradation and climate-related risks, the concept of Regenerative Agriculture (RA) started to gain renewed attention (Gordon et al., 2023; Alexanderson et al., 2023).

Natural systems act as a carbon sink, with soils storing approximately 80% of the organic carbon in the global biosphere, offering potential for the sequestration of emissions from fossil fuels and industrial activities. The progressive loss of this function due to climate change and soil overexploitation highlighted the potential role of RA as a solution (Sharma et al., 2024).

Initially introduced in the early 1980s, RA emerged as an approach to address the limitations of organic farming, particularly its reliance on intensive tillage for weed control and seedbed preparation (Gordon et al., 2023).

This system is based on a set of farming principles and practices: “minimize soil disturbance, maximize crop diversity, keep the soil covered, maintain living roots year-round, and integrate livestock”, aimed at soil health restoration and biodiversity enhancement (Gordon et al., 2023; EU CAP Network, 2024).

Based on these principles, RA employs a combination of diverse farming practices: managed grazing, improved manure management, agroforestry, minimal tillage, permanent soil cover, crop diversification, soil amendment, and biostimulation, tailored to specific contexts (FAO, 2025).

Regenerative agriculture seeks to restore soil health while simultaneously promoting biodiversity, improving water retention, supporting climate adaptation and mitigation, and potentially strengthening farm profitability (Gordon et al., 2023; Cammarata et al., 2025).

Still, regenerative practices face several limitations. These include the absence of a shared definition and standardized indicators, barriers related to knowledge, economic viability, and cultural resistance (that make RA strongly dependent on local contexts), and in general technical and agronomic challenges (Gordon et al., 2023; Shennan-Farpón et al., 2025).

In addition, climate change increasingly constrains the implementation of key regenerative principles, particularly in water-limited regions (FAO, 2025; Shennan-Farpón et al., 2025).

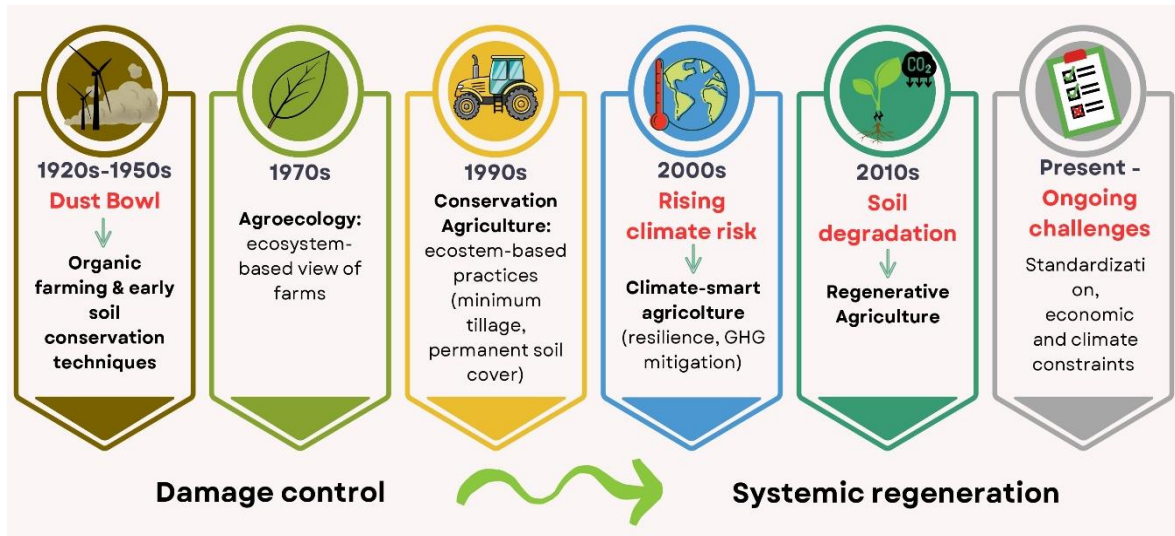


Figure 1: From soil conservation to regenerative agriculture: historical evolution and ongoing challenges. Source: Author's elaboration based on the reviewed literature.

2.3 Regenerative Agriculture: core principles and practices

Regenerative Agriculture is typically described as an outcomes- and principles-based approach to agriculture that prioritizes the restoration of soil health through the implementation of context-specific practices (Gordon et al., 2023; EU CAP Network, 2024).

RA does not confine itself to prescribing a fixed set of techniques, but focuses instead on desired agronomic and ecological results: regeneration as a gradual and dynamic process (Shennan-Farþón et al., 2025). Therefore, farms cannot be classified as fully “regenerative” or “non-regenerative”, but rather as operating at different stages along a continuum of soil and ecosystem restoration (Gordon et al., 2023; Alexanderson et al., 2023).

Across the literature, a common set of five core principles can be identified as the foundation of regenerative farming systems (Fig.2).

These “conceptual pillars” include: minimizing soil disturbance, maintaining continuous soil cover with living plants, preserving living roots year-round, maximizing crop and plant diversity, and integrating livestock into farming systems (Gordon et al., 2023; Alexanderson et al., 2023; EU CAP Network, 2024).

Together, these principles provide a conceptual framework that guides the selection and combination of practices, while allowing flexibility in their application according to specific environmental and socio-economic conditions (Gordon et al., 2023; Shennan-Farþón et al., 2025).



Figure 2: Core principles of Regenerative Agriculture. Source: Author's elaboration based on the reviewed literature.

2.3.1 Minimizing soil disturbance

The principle of minimizing soil disturbance is central to regenerative systems, as intensive tillage (frequent/intensive soil disturbance caused by the repeated use of heavy equipment, commonly employed to produce a homogeneous seedbed) is well documented in the literature as a major driver of soil erosion, loss of soil organic matter, and disruption of soil microbial communities (Gordon et al., 2023; EU CAP Network, 2024; Dang et al., 2020).

In regenerative systems, soil disturbance is typically reduced through reduced-till, strip-till or no-till approaches, a variety of practices that avoid ploughing. Strip-till is a reduced-tillage practice in which tillage is confined to narrow strips to a depth of about 15–20 cm, covering less than 30 % of the field area. The rest of the field is typically covered by cover crop residue (FAO, 2025; Dang et al., 2020).

No-till farming can be implemented through three main methods: "sod seeding", which involves planting crops directly into chemically terminated cover crops using specialized seeding equipment; "direct seeding", which places seeds into the soil through the residues of the previous crop while maintaining surface cover; and "surface seeding", that consists of leaving seeds on the soil surface and is mainly applicable in flat landscapes where machinery and labor requirements are minimal (Dang et al., 2020).

Reduced or no-tillage practices help preserve soil structure, protect soil biota, and limit erosion processes, contributing also to improve long-term soil functioning, including aggregate stability and water infiltration capacity (Dang et al., 2020; Whitmore & Schröder, 2007).

However, there are some limitations, including difficulties in pests control, temporary soil compaction during the transition phase (before organisms and roots take over the soil structure), reduced options for perennial weed control often relying on herbicides, slower soil warming and mineralization in spring, and lower productivity under wet conditions (Dang et al., 2020; Maffezzoli et al., 2022).

2.3.2 Maintaining permanent soil cover and living roots

Soil health restoration can also be achieved by maintaining continuous soil cover with living plants (or dead plants residues) and preserving living roots year-round, which represent two additional foundational elements of RA (Gordon et al., 2023; EU CAP Network, 2024).

Common practices include cover cropping, growing plants to cover the soil rather than for the purpose of harvesting; green manures, covering the soil during the time in between two main crops; mulching, applying a temporary or permanent layer of material to the surface of soil; and ground cover in perennial systems (“soil armor”), planting a perennial species that persists for multiple years alongside annual row crops to keep soil covered year-round (FAO, 2025; Dang et al., 2020).

These approaches help to protect the soil surface from wind and water erosion, regulate soil temperature and moisture, and enhance nutrient cycling. The presence of living roots throughout the year sustains soil microbial activity and mycorrhizal networks, are central in soil aggregation, nutrient availability, and carbon stabilization (Dang et al., 2020; Whitmore & Schröder, 2007).

Despite these benefits, these systems often involve increased management complexity and potential competition for water and nutrients, with outcomes strongly dependent on local pedoclimatic conditions (Dang et al., 2020; Shennan-Farpon et al., 2025).

2.3.3 Maximizing crop diversity

In traditional agriculture, crops are usually grown in monoculture, a production system that increases vulnerability to pests and diseases (Tittonell et al., 2022). This implies that a single disease, overcoming a variety's resistance, may destroy an entire harvest, as demonstrated by the historical case of the Great Famine of Ireland, where the widespread cultivation of genetically uniform potato varieties led to catastrophic crop failure following the outbreak of *Phytophthora infestans* (Kinealy, 1994).

Therefore, increasing the variety and variability of crops can contribute to soil health and biodiversity enhancement by increasing system resilience, interrupting pest and disease cycles, and reducing nutrient depletion (Tittonell et al., 2022; Shennan-Farpon et al., 2025).

For this reason, regenerative agriculture promotes crop diversification strategies aimed at increasing functional diversity within agroecosystems (Gordon et al., 2023).

Diverse crop rotations involve using three or more crops in sequence, varying families, root depths, and nutrient needs (Dang et al., 2020).

Intercropping is a field-level strategy for crop diversification in which two or more crop species are grown simultaneously within the same area, constituting a form of spatial multiple cropping (Picard et al., 2010; Whitmore & Schröder, 2007). This

practice may combine two commercial crops, such as oats and peas, or a commercial crop and a service crop, such as oilseed rape and frost-sensitive legumes.

Undersowing is a form of intercropping where the main crop (e.g., pumpkin, soybean, etc.) is established first, followed by the sowing of grasses or legumes (Picard et al., 2010).

Crop diversity can also be enhanced through agroforestry systems, which consist in growing trees alongside crops, efficiently mixing agriculture and forestry, decreasing soil erosion (Tittonell et al., 2022; Jose, 2009).

Agroforestry is a practice that increases ecological diversity within agricultural systems and aims to restore ecosystem health while promoting sustainable food production (EU CAP Network, 2024).

Woody perennials (trees or shrubs) are intentionally integrated with crops and, in some cases, livestock within the same land unit, creating production systems that combine agricultural and forestry components. Their integration into agricultural landscapes has been associated with several environmental benefits and ecosystem services: trees contribute organic matter through litter inputs and participate in nutrient cycling processes, while their root systems can help stabilize soil and reduce erosion (Jose, 2009).

In addition, agroforestry systems contribute to various ecosystem services, including carbon sequestration, biodiversity conservation, increased soil fertility, and improvements in air and water quality (Jose, 2009).

By increasing biological diversity within agricultural landscapes, agroforestry systems may also contribute to maintaining the ecological processes that sustain the functioning of agricultural ecosystems over time (Jose, 2009).

From an agroecological perspective, the use of diversification strategies (which include agroforestry) is considered an important element in the transition from simplified agricultural systems to farming approaches that rely more strongly on ecological processes (Tittonell et al., 2022).

In addition to agroforestry, other farm management practices (e.g., legume-based cropping systems) can help maintain ecosystem function in diversified systems. The inclusion of legumes can contribute to improving SOC, enhancing nitrogen fixation, and, in many cases, to more stable yields over time (Dang et al., 2020; Whitmore & Schröder, 2007).

Increased plant diversity can also support above- and below-ground biodiversity, reinforcing ecosystem services essential for long-term productivity (Tittonell et al., 2022; Gordon et al., 2023).

While these methods can enhance ecosystem function, they may also involve potential competition for resources (water and nutrients) and increased management complexity. They can also pose challenges for mechanization (systems based on intercropping, undersowing, and complex crop rotations are not always compatible with standard agricultural machinery), weed control, and yield stability with highly context-dependent outcomes (Dang et al., 2020; Shennan-Farpón et al., 2025).

2.3.4 Integrating livestock

By “integration of livestock”, we refer to farming systems in which crop and livestock production are intentionally combined within the same farm/landscape, allowing interactions between animals, crops, soil, and nutrients (Gordon et al., 2023; Shennan-Farpón et al., 2025).

Within regenerative systems, livestock integration plays a complementary role in closing nutrient cycles and enhancing soil biological activity (Tittonell et al., 2022; Gordon et al., 2023).

Managed grazing, the intentional movement of livestock between paddocks with alternating grazing and resting periods, and the use of cover crops as forage facilitates the contribution of livestock to nutrient recycling, soil structure improvement, and organic matter inputs through manure (Alexanderson et al., 2023).

Evidence from European and North American contexts (Fig. 3) suggests that long-term livestock integration and rotational grazing can progressively improve soil structure, vegetation cover, and biodiversity over time (Rowntree et al., 2020).

Beyond soil-related benefits, the integration of livestock can also enhance farm resilience by diversifying production and reducing dependence on external inputs (Gordon et al., 2023; Alexanderson et al., 2023).

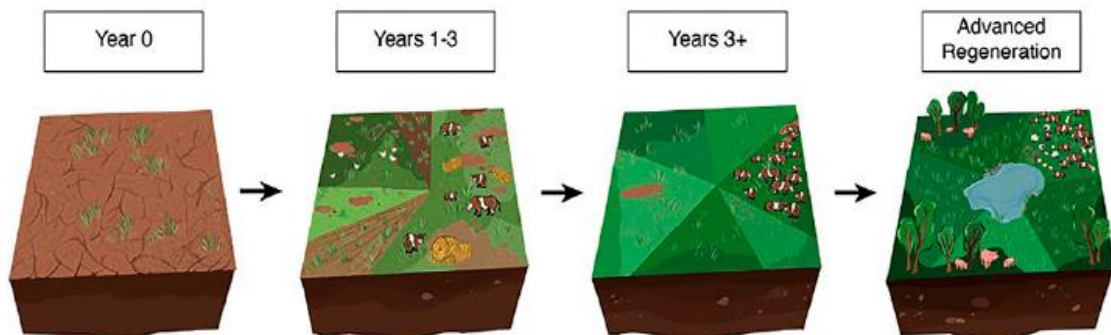


Figure 3: The regeneration process employed by White Oak Pastures, USA, illustrating the effects of rotational grazing on degraded cropland. Source: Rowntree et al., 2020

Additional benefits include improved pasture productivity and reduced labor associated with feed production and distribution, which can contribute to greater overall efficiency in livestock management (Shennan-Farpón et al., 2025).

At the same time, the large amount of emission of greenhouse gases associated with animal production, particularly from ruminants, is one of the main criticisms limiting the complete reintegration of livestock within regenerative systems (FAO, 2025).

Other practical limitations mainly relate to increased labor during the transition phase due to fencing and monitoring requirements (FAO, 2025; Shennan-Farpón et al., 2025).

2.3.5 Systemic integration of regenerative practices

Overall, regenerative agriculture does not rely on the adoption of single practices in isolation: the use of a single technique labelled as “regenerative” (e.g., cover cropping, no-till) is not sufficient to achieve the outcomes sought by RA.

Instead, regenerative outcomes emerge from the combination of different management strategies, selected and adapted according to local environmental conditions, farm characteristics, and socio-economic constraints (EU CAP Network, 2024; Tittonell et al., 2022).

Successful regenerative systems are therefore characterized by adaptive combinations of the different practices described above: reduced tillage, cover crops, diversified rotations, agroforestry elements, and livestock management, rather than standardized solutions (Gordon et al., 2023; Alexanderson et al., 2023).

From this perspective, regenerative agriculture can be viewed as an ecosystem-based approach to farming, agricultural systems as agroecosystems determined by the interactions between soils, plants, insects and human activities (Tittonell et al., 2022). Farmers therefore do not simply manage agricultural production, but they are also active participants, influencing environmental processes through their management choices. This approach is consistent with agroecological thinking, which considers farms as complex ecological systems instead of simplified production units.

Research in agroecology shows that interactions among organisms in agricultural landscapes can play an important role in processes such as nutrient cycling, natural pest control, and the maintenance of soil fertility (Altieri, 1999). Similar mechanisms are also central to regenerative agriculture, which aims to restore soil health while also contributing to biodiversity conservation, the restoration of water cycles, and climate adaptation and mitigation (EU CAP Network, 2024). By enhancing soil health and ecological processes, regenerative agriculture’s objective is to improve ecosystem functioning and support productive agricultural systems over time (EU CAP Network, 2024; Gordon et al., 2023).

As a part of this larger agroecological perspective, biodiversity is a key element in ensuring the functioning of agricultural ecosystems. Many types of organisms, such as pollinators, beneficial insects and soil fauna, contribute to ecological processes that are relevant for pollination, pest regulation and soil functioning (Altieri, 1999; Tittonell et al., 2022). Regenerative farming practices aim to generate conditions favorable to these ecological interactions by increasing plant diversity, maintaining permanent soil cover and reducing soil disturbance. In this sense, biodiversity can be viewed as an integral component of the agroecosystem, contributing to its ecological functioning and resilience (Tittonell et al., 2022; EU CAP Network, 2024).

Beyond environmental considerations, regenerative agriculture may also have important social and economic implications. Recent literature indicates that regenerative systems could reduce dependence on synthetic fertilizers, pesticides and

other external inputs, lowering production costs and improving the economic resilience of farm businesses over time (Gordon et al., 2023; Berthon et al., 2025). Reduced reliance on external inputs may also increase farm autonomy and decrease exposure to fluctuations in input prices.

However, evidence regarding these socio-economic outcomes remains limited: much of the existing research focuses on the adoption of individual practices rather than on whole-farm transitions. Moving toward regenerative agriculture can often involve uncertainty, greater knowledge requirements, and significant changes in management. In some situations, farmers may also face short-term economic risks during the initial phases of the adoption of these practices.

Yield losses may occur during the early stages of transition, while the benefits of regenerative practices may take several years to become fully visible. The transition may also require investments in new knowledge, equipment, or management strategies. For these reasons, the financial feasibility of RA, especially in the initial transition phase, remains an important topic of discussion in the literature.

Some studies suggest that regenerative farming approaches may create new opportunities for farmers, particularly when diversified management practices contribute to improving soil functions that support agricultural production. In some cases, these changes may also allow farmers to access to sustainability-oriented markets or benefit from environmental incentive schemes. At the same time, the literature suggests that these advantages are not guaranteed and may vary widely depending on local farming conditions and environmental contexts (Schreefel et al., 2020).

Overall, current evidence suggests that the socio-economic performance of regenerative systems is highly context-dependent and influenced by factors such as farm type, starting conditions, the combination of practices adopted and local environmental characteristics (Berthon et al., 2025).

2.4 The role of technology: Industry 4.0 and the digitalization of agri-food systems

Alongside regenerative and nature-based approaches, the agri-food sector is undergoing a parallel process of digitalization driven by the diffusion of digital technologies associated with the Industry 4.0 (I4.0) paradigm (Maffezzoli et al., 2022; Cricelli et al., 2024).

Originally introduced in the manufacturing sector, the Fourth Industrial Revolution (also known as 4IR or Industry 4.0), represents a profound transformation of industrial processes, driven by digitalization - mainly through the integration of cyber-physical systems (CPS) - connectivity, and automation (Maffezzoli et al., 2022).

Industry 4.0 is characterized by the adoption of advanced digital production technologies designed to improve workplace conditions, promote innovative business models, and increase productivity and product quality (Cricelli et al., 2024).

The increasing adoption of 4IR technologies is reshaping agri-food systems, contributing to the definition of the Agriculture 4.0 (Agri 4.0 or A4.0) framework, a topic of rising importance in the literature (Maffezzoli et al., 2022; Wolfert et al., 2017). Agriculture 4.0 is a growing topic, and the literature still presents a limited number of contributions aimed at clearly identifying its main characteristics (Escamilla-García et al., 2020; Monteleone et al., 2020).

A4.0 can be described as the evolution of Precision Agriculture (PA), a concept introduced in the 1980s, towards more integrated, data-driven, and automated farming systems.

While PA mainly focuses on site-specific management and the optimization of individual field operations, A4.0 extends this approach by enabling the continuous collection, integration, and analysis of data from multiple sources, including sensors, machinery, remote sensing technologies, and external information systems (Wolfert et al., 2017; Maffezzoli et al., 2022; Zhai et al., 2020).

Agriculture 4.0, often described as the “digital revolution of farming”, includes a new approach to farm management (influencing how food is produced, processed, distributed, and monitored) based on the use of real-time data and precision agriculture methods (Maffezzoli et al., 2022).

These techniques enable farmers to optimize the use of economic, human, and technological resources while promoting traceability and supporting decision-making based on real data and with reduced environmental impacts (Zhai et al., 2020; Cricelli et al., 2024).

Recent policy-oriented literature emphasizes that Agri 4.0 emerges as a response to increasing pressures on food systems by leveraging digital technologies to improve efficiency, resilience, and sustainability across the entire agri-food value chain (OECD, 2021).

As illustrated in Figure 4, the adoption of Agriculture 4.0 technologies is driven by multiple, interrelated factors rather than by a single technological objective.

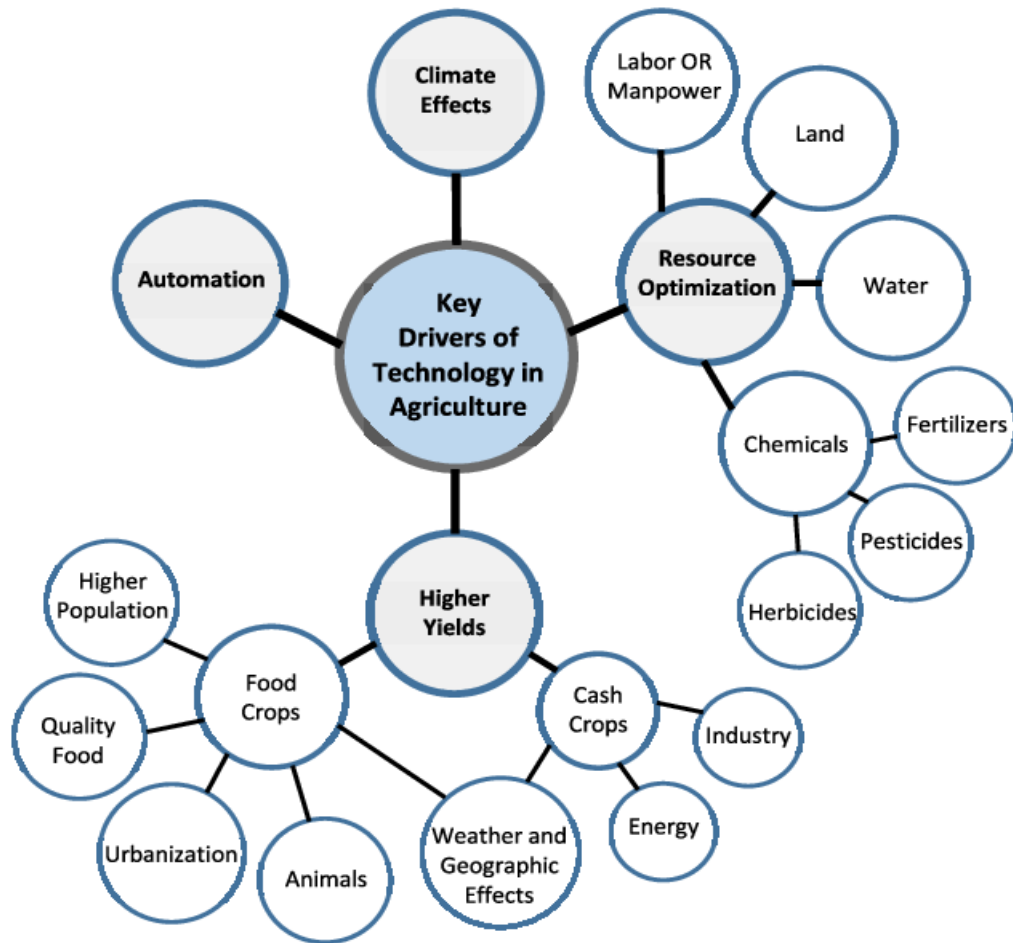


Figure 4: Key drivers of technology adoption in agriculture. Source: Ayaz et al.(2019).

Similarly to what was previously highlighted for regenerative agriculture, digitalization in agri-food systems is not limited to the adoption of individual technologies. Instead, it reflects a systemic shift toward data-centric and interconnected production models, integrating Internet of Things (IoT), Big Data analytics, Artificial Intelligence (AI), remote sensing, robotics, and blockchain-based traceability systems (Wolfert et al., 2017; Maffezzoli et al., 2022; Zhai et al., 2020). In this sector, examples of the application of these technologies include smart greenhouses, drones and robotic systems, sensing technologies and wireless sensor networks (WSNs), soilless farming techniques (hydroponics, aeroponics), and vertical farming (Wolfert et al., 2017; Zhai et al., 2020).

While the possible benefits of Agriculture 4.0 technologies are increasingly recognized, the research on their adoption remains at an early stage, with limited attention to farmers' acceptance, technology transfer processes, and enabling factors (Cricelli et al., 2024).

Most studies predominantly focus on adoption barriers, including limited technical skills, high investment costs, fear of new technologies and market fragmentation, rather than on the drivers and mechanisms that contribute to their successful implementation and diffusion (Cricelli et al., 2024; OECD, 2021).

This research gap can be partly attributed to the novelty of the phenomenon and to the lack of clear guidelines for improving global adoption rates.

In this context, understanding how specific enabling technologies operationalize the Agriculture 4.0 paradigm is essential for assessing both its potential future advantages and its limitations (Wolfert et al., 2017; Zhai et al., 2020).

2.4.1 Internet of Things (IoT) and sensor-based monitoring

The term Internet of Things (IoT) refers to physical objects equipped with sensors, software, and processing capabilities that enable them to collect, transmit, and exchange data with other devices over the Internet or other communication infrastructures, without human intervention (ITU, 2012; IBM, n.d.).

Within the A4.0 framework, IoT constitutes a central element in the digitalization of agri-food systems by enabling the continuous collection of real-time data from on-farm environments through the use of interconnected sensors and devices (Wolfert et al., 2017; Maffezzoli et al., 2022).

In agriculture, such technologies include networks of wireless sensors deployed across fields and farming equipment to collect detailed information on soil conditions, crop status, irrigation needs, and pest or disease presence (Ayaz et al., 2019; Mehedi et al., 2024).

Often integrated with communication networks and cloud-based platforms, these systems facilitate remote data access and analytics, and automated decision support (Zhai et al., 2020; Mehedi et al., 2024).

Acting as a remote “eye in the field,” IoT systems also reduce the need for manual field inspections (Ayaz et al., 2019).

The application areas for IoT technologies in smart agriculture are many, spanning the entire agricultural production cycle, assisting monitoring activities from crop development to post-harvest handling and transportation (Wolfert et al., 2017; Ayaz et al., 2019).

For example, at the field level, IoT sensors are broadly employed for precision irrigation, soil sampling and mapping, and fertilization control (Zhai et al., 2020; Mehedi et al., 2024).

In fact, sensing technologies can measure soil moisture, nutrient levels, temperature and humidity, enabling more precise and efficient input use (Ayaz et al., 2019).

Crop monitoring applications include instead the observation of plant growth and stress conditions, contributing to early interventions and risk mitigation (Yu et al., 2022; Wang et al., 2024).

IoT technologies can also be applied to yield monitoring and estimation by integrating sensor data with GPS-enabled machinery to detect variability across the field and assess crop performance during harvesting (Wolfert et al., 2017; Zhai et al., 2020).

Beyond crop production, IoT can also support greenhouse management, livestock monitoring, and farm machinery tracking, enabling automation, remote supervision, and optimized equipment use (Ayaz et al., 2019).

At the supply-chain level, they can be employed to track storage, handling, and transportation conditions, helping preserve product quality, improve traceability, and reduce post-harvest losses (Wolfert et al., 2017; Cricelli et al., 2024).

Numerous sensing technologies are applied in smart agriculture, including soil moisture and nutrient sensors, climate and meteorological sensors, crop growth and stress sensors, and vision-based systems integrated with unmanned aerial vehicles (UAVs) (Yu et al., 2022; Wang et al., 2024).

The literature emphasizes that sensor-based monitoring helps farmers and supply chain actors to move from the traditional, experience-based decision-making towards a data-driven and site-specific farm management (Wolfert et al., 2017; Zhai et al., 2020; Ayaz et al., 2019).

In conclusion, IoT can be seen as a core technology within Agriculture 4.0, enabling data-based decision-making, operational efficiency, and sustainability across the agri-food system.

2.4.2 Big Data analytics and Decision-Support Systems (DSS)

The growing availability of data generated by IoT sensors, remote sensing technologies (satellites), and digital platforms has increased the relevance of Big Data analytics in agri-food systems (Zhai et al., 2020; Liakos et al., 2018).

In precision and smart agriculture, large volumes of data are continuously produced across different locations over time, ranging from field-level sensor measurements to satellite- and UAV-based observations, creating new opportunities but also new challenges for data management and analysis (Wolfert et al., 2017; Yu et al., 2022).

Big data analytics involve the collection and analysis of large and complex datasets using advanced tools and techniques (e.g. Machine Learning, Artificial Intelligence) to detect patterns and correlations that facilitate data-driven decision-making (OECD, 2016; Liakos et al., 2018).

Integrating and analyzing heterogeneous information, raw data can be transformed into practical insights that can guide agricultural practices. In this context, Decision-Support Systems (DSS) are fundamental in turning analytical results into practical recommendations for farmers (FAO, 2022; Zhai et al., 2020).

DSS are designed to combine data acquisition and analytical models; they can support decisions related to optimizing production planning and input management (Zhai et al., 2020; Mehedi et al., 2024).

For example, DSS are increasingly being used for irrigation scheduling, nutrient management, crop protection, and yield optimization (FAO, 2022).

Recent studies emphasize how modern Decision-Support Systems are relying more and more on big data analytics to manage large-scale datasets and to deliver time- and site-specific recommendations under variable environmental conditions (Zhai et al., 2020; Maffezzoli et al., 2022).

In fact, by identifying patterns and correlations that are not easily observable through traditional methods, big data analytics can improve the outcomes of DSS systems, particularly in field-level management decisions (Zhai et al., 2020; Liakos et al., 2018).

Particularly relevant in A4.0 is also the integration of remote sensing data into DSS: satellite and UAV-based observations can provide spatially explicit information on crop growth, stress conditions, and field variability, which can be combined with ground-based sensor data to enhance the accuracy and robustness of decision-making processes (Yu et al., 2022; Wang et al., 2024).

However, the practical implementation of Big Data-driven DSS in agriculture continues to face several challenges. These include the need to integrate heterogeneous data sources, issues related to data quality and spatial/temporal resolution, the uncertainty associated with the models, and the development of user-friendly systems that can be effectively adopted by farmers (Wolfert et al., 2017; Zhai et al., 2020; Verdouw et al., 2016).

2.4.3 Artificial Intelligence (AI) and Machine Learning (ML)

Artificial intelligence (AI) and Machine Learning (ML) are very important techniques within the Industry 4.0 paradigm, enabling data-driven and automated decision-making in complex production systems. In the agricultural context, their increasing relevance is closely linked to their capacity to process high volumes of data generated by IoT sensors, remote sensing technologies, and digital farming platforms (Maffezzoli et al., 2022).

Artificial Intelligence is the capability of machines to carry out tasks that typically require human intelligence, including reasoning and problem-solving.

By recognizing patterns in data, AI systems can learn from experience and improve their performance over time, assisting or automating decision-making processes (IBM, n.d.).

Machine learning is a subset of AI that focuses on the development of algorithms that make it possible for systems to learn directly from data; rather than being explicitly programmed for each task, these models recognize patterns to generate predictions or decisions (OECD, 2021).

As more observations become available, ML-based systems continue to refine their predictions, improving their performance. This characteristic makes them particularly appropriate for a dynamic and data-intensive environment like agriculture (Liakos et al., 2018).

Within agri-food systems, AI and ML are frequently applied to precision farming and crop management.

The AI-driven image recognition techniques are often used for crop and pest monitoring, while predictive models are fundamental for yield estimation, and optimization algorithms for logistics and distribution (Yu et al., 2022).

In this way, it is possible to take specific interventions, reducing crop losses and improving resource efficiency (Wolfert et al., 2017; Zhai et al., 2020).

Predictive analytics constitutes another key application of AI in agriculture: machine learning models are employed to forecast crop yields, soil moisture dynamics, and weather-related risks by integrating historical data (including remote sensing observations) and real-time sensor measurements (Liakos et al., 2018; Wang et al., 2024).

AI- and ML-based systems are also increasingly employed to optimize the application of agricultural inputs (water, fertilizers, and agrochemicals), reducing their use while maintaining or improving crop productivity (Zhai et al., 2020).

AI algorithms can also contribute to supply-chain optimization helping with harvest planning, storage management, and distribution decisions (Cricelli et al., 2024).

These trends are illustrated in Figure 5, which summarizes the potential impacts of AI adoption on yield prediction accuracy, resource-use efficiency, and farm productivity (Basa, 2024).

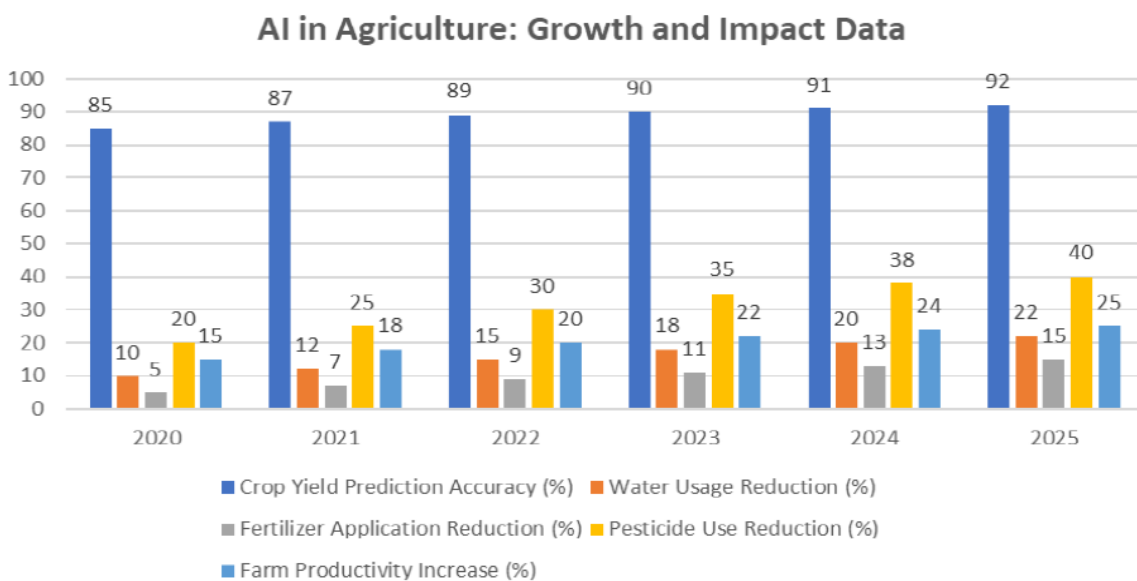


Figure 5: Trends in AI-driven performance improvements in agriculture. Source: Basa (2024)

Despite their potential, the effective deployment of AI and ML in agriculture, as previously said for IoT and big data analytics, depends on the availability of high-quality data, adequate digital infrastructures, and user-friendly systems.

Challenges such as implementation costs, lack of technical expertise, and data management remain critical factors influencing the large-scale adoption of AI-driven solutions (Rose et al., 2016; Liakos et al., 2018).

2.4.4 Remote sensing

Remote sensing is the collection of information about objects from a distance, without being in direct contact with them, using satellite imagery, drones, and other aerial platforms (European Space Agency, 2021).

In precision agriculture, the integration of these technologies with geospatial analysis and DSS, permits the continuous monitoring of crops and field conditions across extensive areas (Zhai et al., 2020).

Data collected from satellite and UAV platforms can support site-specific agricultural practices by providing detailed information on crop conditions. In particular, multispectral, hyperspectral, and thermal sensors mounted on UAVs are commonly used to derive vegetation indices and other indicators related to crop health and biomass (Yu et al., 2022).

Compared with traditional satellite systems, UAV-based remote sensing offers higher spatial resolution and greater operational flexibility, making it possible to have a more detailed monitoring of crop growth, stress conditions, and field variability. Access to timely and reliable information on crop development and environmental conditions is essential for effective crop management (Wang et al., 2024).

Remote sensing data are often combined with other precision agriculture technologies for applications in irrigation management, nutrient monitoring, and yield estimation (Zhai et al., 2020; Wolfert et al., 2017).

For example, machine learning and deep learning (DL) have significantly improved the capabilities of Unmanned Aircraft Systems (UAS), by improving near real-time data processing and interpretation. In fact, integrating remotely sensed data with ground-based measurements improves the accuracy of crop assessment and strengthens the effectiveness of site-specific management strategies under heterogeneous field conditions (Yu et al., 2024; Wang et al., 2024).

This integration supports timely decision-making and reduces the need for frequent manual field inspections, contributing to more efficient and sustainable agricultural practices (Zhai et al., 2020).

Several issues are associated with the adoption of remote sensing technologies in precision agriculture; these include data processing complexity, variability in sensor performance, and the need for technical expertise.

Even though precision agriculture technologies can reduce input waste, lower environmental impacts, and increase productivity (particularly when integrated with IoT and AI), adoption barriers related to costs, skills, and infrastructure remain significant, especially for small-scale farmers (Rose et al., 2016).

2.4.5 Blockchain and digital traceability systems

Blockchain technology can be used as a tool to improve traceability, transparency, and trust along the supply chain (Beck et al., 2018).

In digitalized agricultural and food systems, blockchain-based solutions are usually applied to record, store, and share information related to product origin, production stages, and transactions in a secure and immutable way (Cordero-Gutiérrez et al., 2025; Beck et al., 2018).

The use of a distributed ledger (a system where digital data are stored and synchronized across different locations) allows information sharing among supply-chain actors without the need of a centralized authority (IBM, n.d).

In the context of agri-food traceability, these systems are used to track products from primary production to final consumption: stakeholders can verify information on production practices and handling conditions at each stage of the supply chain (Cordero-Gutiérrez et al., 2025).

This is particularly important for food safety and quality assurance, since it makes it easier to identify contamination sources and respond promptly when and if problems occur. By providing transparent and verifiable information on product origin and production processes, consumer trust and value creation are improved too, particularly in high-value agri-food chains (Beck et al., 2018).

Blockchain-based traceability systems are often combined with other digital technologies, such as IoT sensors and digital platforms, to automate data collection and improve data reliability (Cricelli et al., 2024; Wolfert et al., 2017).

Sensor-generated data related to environmental conditions, storage parameters, and transportation can be directly recorded on the blockchain, reducing manual data entry and limiting the risk of data manipulation (IBM, n.d.).

This integration strengthens the credibility of traceability information and supports a more effective monitoring of supply chains (Cordero-Gutiérrez et al., 2025).

High implementation costs, technical complexity, interoperability issues, and the need for adequate digital skills among supply-chain actors are the major challenges associated with the adoption of blockchain technologies in agri-food systems.

In addition, governance aspects related to data ownership, data privacy, and responsibility for data validation represent critical issues that influence the effectiveness of blockchain-based traceability systems (Beck et al., 2018).

These barriers are particularly relevant for small-scale producers, who may face difficulties in accessing the required infrastructure and technical expertise.

2.5 The intersection between regenerative agriculture and Industry 4.0

In recent years, the intersection between Industry 4.0 and regenerative agriculture has become an increasingly relevant area of discussion, as the agri-food sector is facing growing pressures to reconcile productivity, environmental restoration, and long-term resilience (Gordon et al., 2023; Maffezzoli et al., 2022; Sharma et al., 2024).

Regenerative agriculture has gained attention as an approach aimed at restoring soil health, biodiversity and ecosystem services, and strengthening the resilience of farming systems, while maintaining an economically viable production (Gordon et al., 2023; Alexanderson et al., 2023).

At the same time, the diffusion of Industry 4.0 technologies is reshaping agricultural practices by enabling data-driven, connected, and automated farming systems (Maffezzoli et al., 2022).

Within this context, digital technologies associated with Industry 4.0 (Internet of Things, remote sensing, big data analytics, Artificial Intelligence, blockchain and digital platforms) can offer new opportunities to support the implementation and monitoring of regenerative practices (Gordon et al., 2023; Shennan-Farpón et al., 2025).

Precision data collected at field level can help better understand soil conditions, crop performance, and ecosystem dynamics, thereby contributing to management strategies that are aligned with regenerative principles, such as reduced input use, diversified cropping systems, and improved soil management (Wolfert et al., 2017; Shennan-Farpón et al., 2025).

The intersection between Industry 4.0 and regenerative agriculture is therefore not limited to technological adoption, but reflects a broader transformation in how agricultural systems are managed and evaluated (Maffezzoli et al., 2022; Gordon et al., 2023).

Digital technologies can contribute to making regenerative practices more measurable, traceable, and scalable, addressing some of the challenges related to their adoption, including uncertainty about outcomes, monitoring complexity, and economic performance (Gordon et al., 2023; Shennan-Farpón et al., 2025).

At the same time, the integration of advanced technologies into regenerative systems raises important questions regarding costs, accessibility, data governance, and the risk of excluding smaller or resource-constrained farmers (Cricelli et al., 2024).

The different ways in which Industry 4.0 technologies can support regenerative functions are summarized in Table 1.

Table 1: Intersections between Industry 4.0 technologies and regenerative practices. Source: Author's elaboration based on the reviewed literature.

I4.0 Technology	Soil & Ecosystem Monitoring	Input Reduction	Soil & Cropping Management	Traceability	Scalability
<i>IoT</i>	Real-time field-level data collection	Targeted irrigation/fertilization based on field conditions	Supports real-time management decisions	/	Can contribute to data standardization (when integrated)

					into digital platforms)
<i>Big Data Analytics</i>	Data integration and pattern analysis (of heterogeneous agronomic datasets)	Identification of optimization strategies aligned with regenerative principles	Can support management choices (including crop planning/rotation decisions) when such data are available	Supports performance reporting and sustainability metrics	Enhances comparability and large-scale data processing
<i>AI</i>	Predictive modeling	Enables precision input management and use	AI-powered DSS for regenerative management	/	Enables automated and scalable decision processes
<i>Remote Sensing</i>	Vegetation and soil indices monitoring	Detection of crop stress to optimize interventions	Monitors vegetation patterns over time	/	Facilitates large-scale spatial monitoring
<i>Blockchain</i>	/	/	/	Enables transparency and traceability in the certification of regenerative claims (N.B. conditional on data integrity)	Can support market-oriented claims (e.g. provenance, verified practices) and standardized reporting

Despite the growing interest in both regenerative agriculture and digital innovation, empirical evidence on how these two dimensions interact in real-world farming systems remains very limited. In particular, there is a need to better understand how companies and agricultural enterprises are combining Industry 4.0 technologies with regenerative practices in practice, and what outcomes emerge from these hybrid approaches (Giller et al., 2021; Sharma et al., 2024).

For this reason, this study presents and analyzes a set of case studies of agri-food companies that are starting to integrate Industry 4.0 technologies into regenerative agricultural models, in contrast to predominantly nature-based cases.

The analysis also includes cases in which digital tools associated with Industry 4.0 are used to quantify, monitor, and support the generation and commercialization of carbon credits derived from regenerative practices.

Through the evaluation of heterogeneous case studies, the research aims to explore how digital tools can be used to support regenerative objectives, identifying enabling factors and barriers.

3. Methodology

3.1 Research design

This study adopts a multiple case study approach to understand how, based on observed patterns, Industry 4.0 technologies can support the shift toward regenerative agriculture and what limitations emerge compared to nature-based approaches.

First of all, the existing literature was examined to establish the conceptual and analytical framework presented in the previous chapter, while the study is primarily based on the analysis of selected cases.

The main objective of this research was to capture the diversity of technological applications and regenerative practices across different agri-food contexts, to better understand how digital tools operate within regenerative models in real-world contexts.

A qualitative multiple case study design can be considered appropriate given the exploratory nature of the research question. Case study research is “an empirical method that investigates a contemporary phenomenon in depth and within its real-world context” (Yin, 2018, p. 45).

Multiple cases allow for cross-case comparison and theory building in emerging research domains (Eisenhardt & Graebner, 2007); while the heterogeneity of cases further enables richer analytical insights into process dynamics and contextual variation (Langley & Abdallah, 2011).

Thirty-eight different cases were selected through a progressive and iterative process. Rather than relying on a single database, multiple sources of secondary data were consulted, including corporate sustainability reports, institutional platforms, blogs and innovation databases related to digital agriculture and regenerative initiatives (e.g. CORDIS, for EU-funded innovation projects; Crunchbase, a database for startups, funding, tech ventures).

The identification of initiatives began with well-known agri-food corporations publicly communicating the adoption of Industry 4.0 technologies in support of regenerative-oriented objectives. This first screening phase made it possible to focus

on large-scale actors playing a visible role in shaping the digital-regenerative transition.

These high-profile “corporate” examples were established by analyzing firms’ annual reports and publicly available technical documentation.

Additional cases were identified through the mapping of these companies’ partnerships and technology providers mentioned in corporate documentation. This process also allowed the identification of hybrid actors (e.g., agri-tech startups and other digital enablers collaborating with larger corporations) which integrate digital technologies into their practices.

A further subset of observations was identified through reviewing certification and carbon market platforms, including registries such as Verra (methodology VM0042) and Gold Standard (GS). The databases reviewed were used to identify projects that utilize digital MRV systems to measure carbon credits generated from regenerative land management practices.

In parallel, nature-based cases with no or very limited technological integration were identified through institutional and policy-oriented platforms, such as the EU CAP Network and FAO, focusing on projects explicitly based on agroecological and regenerative principles.

The details regarding each example are described in detail in Appendices A-E.

3.2 Criteria for case selection

Case selection followed different criteria depending on the configuration analyzed.

The sampling process developed gradually, beginning with a set of relevant cases and progressively expanding the sample over time. Every new case was evaluated using the same inclusion criteria to ensure coherence and comparability.

For the high-tech cases, three main criteria were applied: (1) the organizations had to explicitly integrate at least one Industry 4.0 technology within their agricultural or agri-food operations, (2) an explicit or demonstrable regenerative orientation (for example through documented practices aimed at soil restoration, biodiversity enhancement, climate mitigation, or ecosystem resilience), and (3) only cases with sufficient publicly available documentation were included, in order to ensure consistency and allow for data triangulation.

Even though the high-tech organizations included vary in scale and geographical location, they share a common attempt to link digital innovation with regenerative objectives: in some cases, I4.0 technologies mainly support monitoring and traceability; in others, they are embedded in farm-level decision-making. In carbon projects, they serve as MRV tools.

At the same time, the strong presence of SMEs and technology startups suggests that the convergence between RA and Industry 4.0 technologies is still in an exploratory phase.

For the nature-based cases, selection focused primarily on the implementation of regenerative agronomic practices at farm level, such as no-till, cover cropping, livestock integration, and agroforestry. In these cases, digital technologies were not considered central drivers of change.

As with the high-tech sample, sufficient documentation was required to allow comparative analysis.

The final resulting sample includes organizations that differ in size, technological intensity (from very high to none), and position within the agri-food system (from primary agricultural production to technology providers and carbon certification projects), facilitating a comparison across diverse contexts.

4. Case studies and results

Data collection took place between October 2025 and December 2025 and was based on a structured review of secondary sources.

The analysis relied primarily on corporate sustainability and annual reports, project documentation, and publicly available technical materials. Additional information was retrieved, where relevant, from institutional platforms and innovation-oriented databases.

Only cases supported by sufficiently detailed and transparent documentation, particularly regarding the use of digital technologies and regenerative objectives, were retained. The empirical material was analyzed through a qualitative comparative approach: each case was examined individually with attention to the technologies adopted, the stated sustainability and regenerative objectives, and the documented outcomes.

Following the individual case analysis, organizations were grouped into broader analytical categories in order to facilitate structured comparison. The categories used were developed by the author as part of the research design: they do not represent predefined typologies in the literature, but analytical groupings reflecting different ways in which technology is integrated into regenerative models.

Cases were organized as follows: first, a macro-category of high-tech configurations was identified, including (1) high-tech corporate cases, (2) digital enablers providing I4.0 solutions to other actors, (3) hybrid models integrating digital technologies directly at field level, and (4) carbon-credit-based initiatives combining regenerative practices with digital MRV and verification systems.

Second, a distinct category of predominantly nature-based approaches was defined, including cases in which regenerative practices were implemented with no reliance on advanced digital infrastructures.

This categorization aimed at organizing empirical complexity rather than establishing a rigid classification.

4.1 Summary statistics

The final dataset consists of thirty-eight heterogeneous cases spanning different geographic regions, organizational scales, and technological configurations (Table 2). The sample includes multinational corporations, small and medium-sized enterprises, startups, and project-based initiatives, reflecting different degrees of integration between Industry 4.0 technologies and regenerative practices.

Table 2: Overview of the organizations included in the dataset

Configuration	Organization	Sector (main business/ activity)	Operational Location	Size
High-Tech (Corporate)	Mars	Agri-food value chain	Global; HQ: Virginia, USA	Large
High-Tech (Corporate)	Carrefour	Agri-food value chain	France, Italy, Spain	Large
High-Tech (Corporate)	Cargill	Agri-food value chain	Global; HQ: Minnesota, USA	Large
High-Tech (Corporate)	Barilla Group	Agri-food value chain	Italy, Europe	Large
High-Tech (Corporate)	Andriani S.p.A	Agri-food value chain	Italy	Medium
High-Tech (Corporate)	BF bonifiche ferraresi	Agri-food value chain; Livestock farming	Italy	Large
High-Tech (Provider)	xFarm Technologies	Multi-value-chain technology enabler	Global; HQ: Italy, Switzerland	Medium
High-Tech (Provider)	Soil Capital	Multi-value-chain technology enabler	Belgium, France, UK	Medium
High-Tech (Provider)	Regrow Ag	Multi-value-chain technology enabler	USA	Large
High-Tech (Provider)	Horta Srl	Multi-value-chain technology enabler	Italy	Medium
High-Tech (Provider)	Landprint	Multi-value-chain technology enabler	Brazil	SME

High-Tech (Provider)	RoboCare	Multi-value-chain technology enabler	Tunisia	SME
High-Tech (Provider)	Nature Robots	Multi-value-chain technology enabler	Germany	SME
High-Tech (Hybrid)	SOSTVAN Project	Extensive livestock farming	Spain	SME
High-Tech (Hybrid)	EZ Lab	Technology enabler; wine sector	Italy	Medium / SME
High-Tech (Hybrid)	Fasal	Technology enabler; horticultural production	India	SME
High-Tech (Hybrid)	DroneDeploy x Bowles Farming Company	Multi-value-chain technology enabler; agri-food value chain	USA	Medium
Carbon Project	Agreena	Multi-value-chain technology enabler for diversified agricultural systems	Europa, UK	Medium
Carbon Project	Involtor Consult SRL	Environmental technical consultancy for diversified agricultural systems	Romania	SME
Carbon Project	Trees for the Future Inc.	Multi-value-chain technology enabler for diversified agricultural systems	Kenya	Medium
Carbon Project	Carbon Friendly Pty Ltd.	Technical-operational enabler for diversified agricultural systems	Australia	SME
Carbon Project	Boomitra Inc.	Technical-operational enabler for	Kenya, Rwanda, Tanzania, Uganda	SME

		diversified agricultural systems		
Carbon Project	NaturAll Carbon Limited	Technical–operational enabler for diversified agricultural systems	Brazil	SME
Carbon Project	Agoro Carbon Alliance US Inc.	Technical–operational enabler for regenerative livestock systems	USA	Medium
Carbon Project	Orizon Agriculture (Pty) Ltd.	Technical–operational enabler for diversified agricultural systems	South Africa	SME
Carbon Project	Anthesis B.V.	Technical–operational enabler for diversified agricultural systems	South Africa	Large
Carbon Project	Dimitra Incorporated	Multi–value-chain technology enabler for diversified agricultural systems	Global platform; Local project (Messico, Nayarit)	Medium
Nature-based	Tynnelä Farm	Cereal production	Finland	SME
Nature-based	Southern Lights Farm	Fruit and vegetable production and olive growing	Greece	SME
	Fröhlich Farm	Fruit and vegetable production	Switzerland	SME
Nature-based	Eichhof Farm	Dairy sector	Germany	SME
Nature-based	First Milk Ltd	Dairy sector	UK	Medium

Nature-based	Agricultural Cooperative Krakovany-Stráže	Agricultural sector	Slovakia	SME
Nature-based	Cortijo Maestre Farm	Agricultural sector	Spain	SME
Nature-based	Wild Ken Hill	Agricultural sector, livestock sector	UK	Medium
Nature-based	Cooperativa Agricola Nuovo Cilento	Organic agriculture, olive growing, agri-food supply chain	Italy	SME
Nature-based	Società Agricola Terzeria	Agricultural sector	Italy	Medium
Nature-based	Società Cooperativa Amico Bio	Agricultural sector, livestock sector	Italy	SME

Six cases involve large corporate actors that are adopting digital technologies as part of their regenerative strategies. Seven additional cases represent high-tech providers, such as agri-tech startups and specialized technology companies that develop digital tools to support regenerative practices. Four projects were classified as hybrid, field-level implementations, in which digital technologies are directly integrated into on-farm regenerative practices.

Ten additional initiatives consist of carbon-oriented regenerative projects, that combine the implementation of regenerative agricultural practices with digital MRV systems.

Finally, eleven cases were categorized as nature-based, which are characterized by limited or entirely absent reliance on advanced digital technologies (Figure 6).

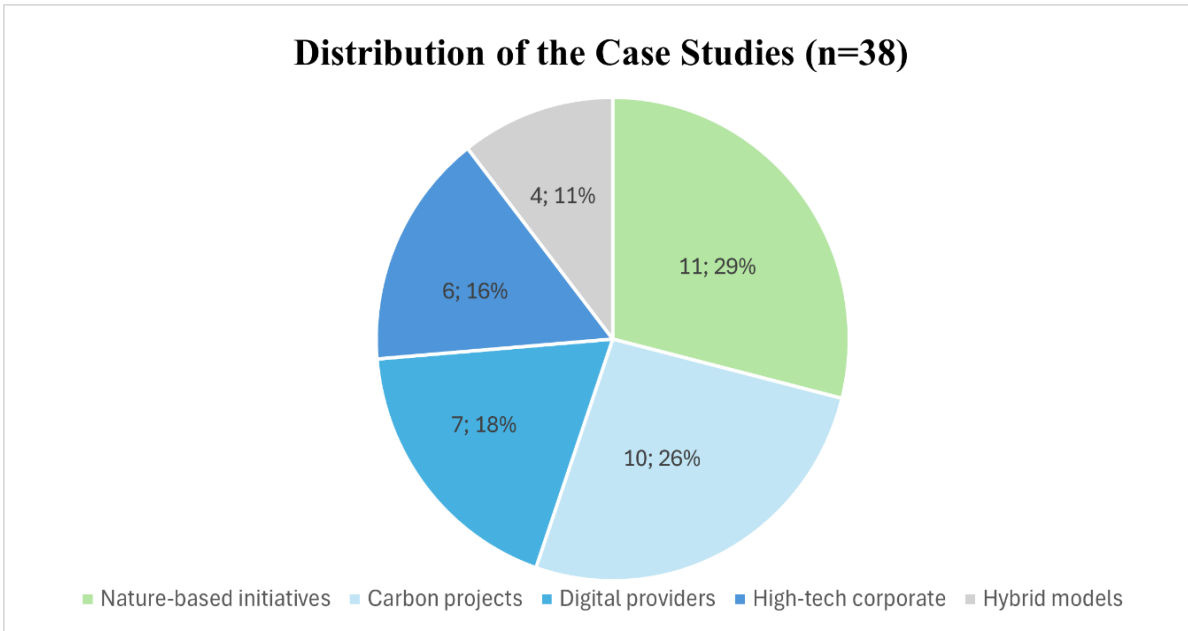


Figure 6: Distribution of the analyzed cases by technological configuration (n = 38). Source: Author's elaboration based on Appendices A–E.

This distribution makes it possible to compare different levels of technological intensity and strategic approaches, helping to detect recurring patterns, complementarities, and the types of outcomes achieved in the different configurations.

The initiatives included in the dataset operate in different organizational contexts and vary significantly in terms of organizational size. As illustrated in Figure 7, the distribution of cases differs across configurations: high-tech corporate initiatives are predominantly associated with large organizations, whereas high-tech providers, hybrid initiatives, and carbon projects show a more heterogeneous distribution across organizational sizes. Nature-based initiatives, instead, are more frequently implemented by small and medium-sized enterprises (SMEs).

Most high-tech initiatives are linked to large agri-food corporations, digital technology providers, or carbon certification projects operating across extended supply chains. Nature-based cases are more commonly implemented by farms or cooperatives operating at a more local level.

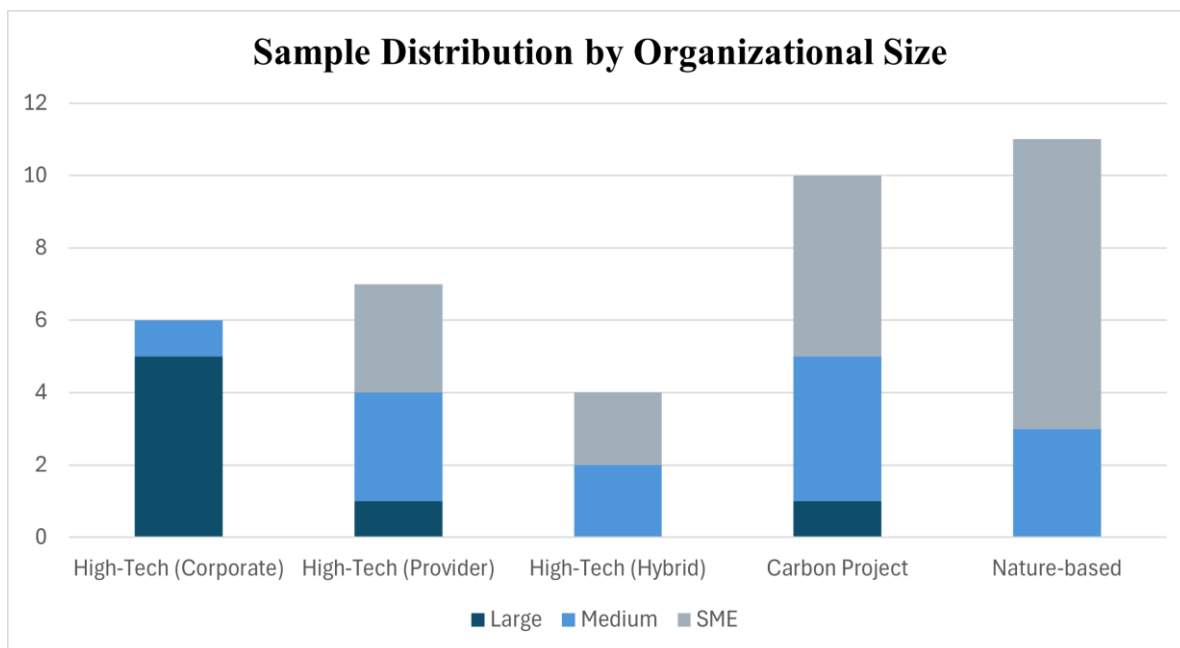


Figure 7: Distribution of the analyzed cases by organizational size. Source: Author's elaboration based on Appendices A–E.

The role of digital technologies varies across the different configurations considered in the analysis. In technology-intensive initiatives, digital tools are mainly used to collect, process, and verify environmental data related to regenerative practices. These technologies enable MRV activities, the verification of environmental indicators associated with regenerative management practices and, in some cases, they can also facilitate the aggregation and analysis of data across multiple farms.

Finally, similar types of environmental outcomes are reported across the sample. However, the way these outcomes are reported across both configurations varies, with high-tech initiatives generally relying on more formalized measurement and reporting systems.

These observations provide an initial overview of the main trends emerging from the dataset and serve as a starting point for the more detailed analysis presented in the following sections, while also helping to highlight some of the key differences among the configurations analyzed.

4.2 High-tech cases

The identification of high-tech corporate cases began with large agri-food companies that publicly disclose the integration of Industry 4.0 technologies within their regenerative-oriented strategies. Six significant and well-documented cases were selected, as detailed in Appendix A.

These companies operate across different segments of the agri-food value chain and geographical contexts. Despite differences in scale and governance structures, all

cases demonstrate the structured adoption of advanced digital technologies to monitor, verify, and in some cases directly implement regenerative practices.

Even if these examples are extensively documented and provide detailed information about technological deployment and sustainability strategies, it should also be understood that the majority of the evidence comes from corporate sustainability reports and official communications of the corporations. Although those sources can help explain how firms conceptualize and execute their regenerative-oriented projects, they remain internally produced documents and therefore reflect the companies' own narratives.

Therefore, there is a need for caution when interpreting the results.

Across this category, a recurring tendency emerges: digital technologies mainly function as enabling infrastructures for data collection, reporting and verification. Tools such as remote sensing, blockchain, IoT sensors, AI-based models, and decision-support systems are used to standardize and measure regenerative practices, rather than to replace agronomic processes. Their main contribution is in making agroecological activities more traceable and comparable across different contexts and supply chains.

At the same time, a difference in the way digital solutions are implemented can be observed. In some cases, they primarily reinforce supply-chain governance through compliance monitoring and traceability mechanisms. In others, they are directly embedded into farm-level management through precision agriculture tools, predictive algorithms, and input optimization systems.

This distinction suggests that, while Industry 4.0 technologies play a very important role in structuring regenerative transitions, agronomic and ecological practices remain central at the operational level (ecological practices implemented in the field).

Beyond corporate adopters, additional high-tech configurations include digital enablers, hybrid models, and carbon-credit-based initiatives, whose detailed descriptions are provided in Appendix B, Appendix C and Appendix D. In most cases, digital platforms permit the measurement of soil health indicators, biodiversity metrics, carbon emissions and input optimization, thereby making regenerative practices monitorable and, in some instances, certifiable.

Technology providers differ in their technological approaches (see Appendix B). In fact, some of them operate primarily through carbon farming and digital MRV models, focusing on emissions quantification and certification, while others emphasize operational optimization at field level through precision agriculture tools, robotics, and real-time DSS.

Overall, these actors play an important “mediating” role: they can transform regenerative practices into more structured and scalable processes, supporting both farm-level implementation and supply-chain integration.

Appendix C presents hybrid configurations in which high-tech actors are directly involved in field-level activities alongside farmers, research institutions, or agricultural companies. In these cases, digital systems are directly connected to the regenerative practices implemented in the field. Blockchain, IoT sensors, AI-based decision-support tools, and drone mapping technologies are applied within specific production contexts (extensive livestock farming, viticulture, horticulture) to improve transparency, input optimization, and monitor environmental conditions.

Large-scale carbon projects in which RA practices are linked to certified carbon credit generation (Appendix D) represent the most extensively documented examples, providing precise data regarding the tonnes of CO₂ removed and related environmental co-benefits.

Digital MRV systems, combining remote sensing, soil carbon modeling, GIS analyses, and structured agronomic data collection, constitute the basis of verification processes under internationally recognized standards such as the Verified Carbon Standard (VCS). Regenerative practices become part of a formal certification system that converts environmental improvements into quantifiable and tradable carbon credits.

These cases illustrate the growing financial dimension of regenerative agriculture, in which I4.0 technologies make an important contribution in transforming ecological practices into standardized and market-compatible outcomes.

Taken together, the high-tech cases show how different digital technologies can work in combination to sustain regenerative practices. Industry 4.0 solutions function as enabling tools (improving traceability, measurement and transparency) and they help scale regenerative initiatives by translating farming practices into outcomes that can be monitored and certified.

At the same time, their contribution remains primarily supportive rather than transformative in ecological terms (technology does not replace agronomic knowledge but interacts with it, providing feedbacks, data-driven recommendations, and market-oriented reporting mechanisms).

Regeneration itself ultimately depends on ecological processes and on-farm practices.

This pattern is consistent with the emerging literature on digital agriculture and smart farming, which generally describes Industry 4.0 technologies less as direct drivers of ecological regeneration than as tools for data collection, monitoring and decision support (Klerkx et al., 2019; Wolfert et al., 2017). In the empirical configurations analyzed in this thesis, these data infrastructures are used more specifically to collect information on regenerative practices, thereby supporting their documentation and verification.

In this sense, the cases analyzed provide empirical support to the argument that digital technologies mainly contribute to making regenerative practices more measurable and governable (Rose & Chilvers, 2018; Rotz et al., 2019).

These projects also reveal a number of structural constraints, including high implementation costs, the need for technical expertise, and a tendency toward centralized governance models.

These limitations suggest that advanced digital structures may not be equally accessible to all actors, raising important concerns about accessibility and inclusiveness.

4.3 Nature-based cases

To provide a more balanced perspective, the analysis now considers predominantly nature-based configurations (see Appendix E), examining cases in which regenerative transformation is mainly driven by ecological processes implemented at farm level, rather than by digital infrastructures.

For these organizations, regeneration relies on restoring soil biological activity, enhancing biodiversity, and strengthening ecosystem resilience without relying on I4.0 technologies.

Practices such as no-till, cover cropping, diversified rotations, agroforestry, regenerative grazing, and livestock integration contribute to measurable environmental improvements, including increased soil organic carbon (SOC), reduced erosion, and improved habitat diversity.

Unlike the high-tech projects discussed earlier, these cases do not necessarily translate ecological outcomes into market-standardized metrics. While several organizations report reductions in synthetic inputs and fuel use, and in some instances carbon sequestration levels, the depth and methodological rigor of the documentation vary significantly: some of them only rely on internal monitoring, whereas others are supported by institutional reports or cooperative-level data collection.

Environmental improvements therefore remain embedded within the farming system itself, reflecting a bottom-up regenerative approach based on ecological processes rather than digital verification frameworks.

Most of these initiatives are led by small and medium-sized farms or cooperatives, often operating with limited financial resources and reduced access to technological infrastructures. Limited funding capacity, technical expertise, and also awareness of available digital providers may further constrain the scalability and external visibility of these initiatives.

As a result, although ecological outcomes may be substantial, their economic valorization and formal recognition can be more difficult to achieve compared to high-tech configurations.

These findings also contribute to the existing literature by showing that meaningful regenerative outcomes can emerge even in the absence of advanced digital infrastructures. While recent studies emphasize the potential of digital technologies to improve agricultural management through data-driven approaches (Klerkx et al.,

2019; Ayaz et al., 2019; Chlingaryan et al., 2018), the nature-based cases examined here suggest that regenerative outcomes may also arise from agronomic practices that do not rely on advanced digital systems. These outcomes often occur even when they are not formally standardized or verified through digital monitoring systems, highlighting the practice-based character of regenerative farming processes (Alexanderson et al., 2023).

4.4 Emerging patterns across the CIMO framework

The cases included in the dataset are structured according to the Context–Intervention–Mechanism–Outcome (CIMO) framework.

The CIMO logic is commonly used in management research to analyze how specific interventions operate within particular contexts, through underlying mechanisms, and with which outcomes (Denyer, Tranfield & Van Aken, 2008).

This section highlights the main tendencies emerging across its dimensions and helps clarify how the different initiatives included in the sample are structured and how regenerative practices are implemented across different contexts.

Examining the cases through these four dimensions makes it possible to observe how specific types of organizations involved are associated with particular technological interventions, which mechanisms these interventions support, and which types of outcomes are reported in the available documentation.

The detailed CIMO framework applied to the cases is presented in Appendices A–E.

4.4.1 Context

The configurations included in the dataset involve different types of actors across the agri-food system: for the high-tech cases, some initiatives are led by large agri-food corporations (which incorporate regenerative practices within broader sustainability programs), while others are developed by technology providers that offer digital tools or monitoring infrastructures designed to support farmers and supply-chain actors.

In contrast, the predominantly nature-based cases are implemented directly at farm level; these initiatives are often promoted by cooperatives or small and medium-sized agricultural organizations that apply regenerative practices within their own production systems.

Technology-intensive configurations are more often associated with large corporations and agri-tech companies that operate across extended supply chains.

By comparison, nature-based initiatives tend to be implemented by farms or cooperatives working at a smaller scale and within more localized agricultural contexts.

This difference also reflects the resources required to adopt the different configurations. As already discussed, high-tech initiatives frequently involve

significant financial investment, technical expertise, and access to digital infrastructures: these conditions are typically easier to meet for large corporations or specialized technology providers. Nature-based initiatives, on the other hand, are more often adopted by smaller producers that rely primarily on agronomic knowledge and field-level ecological management.

The main types of actors involved across the two configurations identified in the dataset are summarized in Table 3.

Table 3: Types of actors across the analyzed configurations. Source: Author's elaboration based on Appendices A–E.

Actor type	High-tech configurations	Nature-based configurations
<i>Large agri-food corporations</i>	Frequent	Absent
<i>Technology providers / agri-tech startups</i>	Frequent	Absent
<i>Carbon-markets initiatives</i>	Present	Absent
<i>Farms / family farms</i>	Limited (participating actors)	Frequent
<i>Cooperatives / local organizations</i>	Absent	Frequent

Table 3 suggests that the type of actors involved is closely related to the resources required by each configuration, with high-tech initiatives more common among large organizations and nature-based approaches more often developed by farms and cooperatives.

In high-tech configurations, farmers typically participate in the implementation of regenerative practices, but initiatives are generally coordinated by corporations, technology providers, or carbon-market platforms.

These contextual differences are not neutral. The organizational settings in which initiatives operate influence not only who implements regenerative practices, but also which forms of regenerative value become visible and formally recognized. As a result, the context partly shapes how regenerative outcomes are assessed and integrated into governance frameworks.

4.4.2 Intervention

The nature of the intervention considered differs across the two configurations.

In the high-tech cases, the intervention dimension mainly refers to the digital technologies deployed to support regenerative initiatives, including tools such as remote sensing systems, IoT sensors, artificial intelligence models, decision-support systems, and blockchain-based traceability platforms.

In the nature-based initiatives, the term “intervention” relates instead to the regenerative agricultural practices implemented; these practices typically include principles such as crop diversification, cover cropping, reduced or no-tillage, agroforestry, or integrated livestock management.

Across the technology-intensive examples, a variety of digital tools is used to support monitoring activities and farm management practices. The cases analyzed show how different technological tools contribute to the collection, analysis, and verification of environmental data related to regenerative practices.

Remote sensing technologies and satellite data are commonly used to monitor vegetation dynamics, land-use changes, and soil conditions over time; IoT sensors support the collection of field-level data related to soil moisture, nutrient availability, and other environmental variables.

Artificial intelligence models and decision-support systems can process these datasets and provide information that may assist farmers in planning irrigation schedules, fertilization strategies, or crop management practices.

In some cases, blockchain infrastructures are used to improve transparency and traceability within the supply chain, allowing regenerative practices to be recorded and verified across multiple actors.

Table 4 provides an overview of the main categories of digital tools identified in the case studies.

Table 4: Digital technologies implemented across the analyzed cases. Source: Author’s elaboration based on Appendices A–E.

Technology category	Typical application in regenerative initiatives	Main actors
<i>IoT sensors</i>	Measuring soil moisture, nutrients and environmental variables	Technology providers; hybrid initiatives; high-tech corporate initiatives
<i>Artificial Intelligence and DSS</i>	Data analysis, predictive modelling and decision-support tools	Technology providers; hybrid initiatives; selected high-tech corporate initiatives
<i>Remote sensing</i>	Monitoring land-use changes and soil conditions	High-tech corporate initiatives; technology providers; carbon farming projects

<i>Blockchain</i>	Supply-chain traceability and documentation of regenerative practices	High-tech corporate initiatives; hybrid initiatives
<i>Digital MRV systems (remote sensing + modelling + agronomic data)</i>	Monitoring, reporting and verification of carbon and environmental indicators	Carbon farming programs / carbon-credit platforms; technology providers

As the table shows, these technologies perform different functions within regenerative initiatives, ranging from environmental data collection and assessment to decision-support and supply-chain traceability mechanisms.

4.4.3 Mechanism

In the technology-intensive configurations, the mechanisms identified mainly concern how regenerative practices are translated into measurable environmental outcomes. In several initiatives, digital systems make it possible to connect farming practices with environmental indicators and to provide evidence of their implementation over time.

Through these infrastructures, data related to soil conditions, change in vegetation over time, and agricultural practices can be collected and aggregated. This information allows organizations to document regenerative activities and, in some cases, to evaluate their environmental effects. In addition, the availability of structured environmental data can facilitate comparisons across farms or projects and support the long-term monitoring of regenerative initiatives.

Another recurring mechanism concerns the traceability and standardization of environmental information. When agricultural practices and environmental indicators are recorded through digital platforms, regenerative activities can be communicated along supply chains and connected to certification schemes, sustainability reporting systems, or carbon credit programs. In this way, environmental improvements that occur at farm level can become visible to a broader range of actors within the agri-food system.

In the predominantly nature-based cases, the mechanisms operate in a different way. Environmental improvements tend to result directly from agronomic practices and ecological processes implemented at farm level, while documentation and verification are usually based on internal monitoring or project-level reporting rather than on structured digital infrastructures.

The main mechanisms observed across the technology-intensive cases are summarized in Table 5.

Table 5: Main mechanisms identified across the analyzed cases. Source: Author's elaboration based on Appendices A–E.

Mechanism	Example initiatives	Approx. frequency
<i>Monitoring of environmental indicators</i>	Mars, Cargill, Barilla, Regrow	Frequent
<i>Measurement and verification of carbon outcomes</i>	Agreena, Boomitra, Involtor	Several cases
<i>Supply-chain transparency and traceability</i>	Carrefour, SOSTVAN project	Limited
<i>Data-driven farm management support</i>	Horta, xFarm, Fasal	Moderate

Monitoring and verification mechanisms appear most frequently, followed by traceability systems and digital MRV platforms.

Through these mechanisms, regenerative practices implemented at farm level become more visible, measurable, and consistent across different contexts.

4.4.4 Outcome

The outcomes reported across the analyzed cases relate to several environmental dimensions commonly associated with regenerative agriculture. Many initiatives report improvements in soil health indicators, reductions in the use of chemical inputs, increases in SOC, reductions in greenhouse gas emissions, and positive impacts on biodiversity. These results reflect the main ecological objectives typically associated with RA practices.

In some cases, the available documentation also refers to improvements in soil structure, water retention capacity, or habitat diversity within agricultural landscapes. Certain initiatives also report additional benefits such as reductions in fuel consumption and more efficient use of agricultural inputs.

The level of detail in which these outcomes are documented varies across the cases. Some initiatives (especially the technology-intensive ones) report quantified environmental indicators supported by digital monitoring systems or certification frameworks, while others describe environmental improvements in a more qualitative way, based on project documentation or internal monitoring activities. As a result, the availability and comparability of environmental data differ across the initiatives included in the dataset.

Table 6 summarizes the main results observed across the four CIMO dimensions.

Table 6: Summary of results across the CIMO framework. Source: Author's elaboration based on Appendices A–E.

Technology category	Results
<i>Context</i>	Corporations, agri-tech providers, carbon projects, farms and cooperatives
<i>Intervention</i>	<p>High-tech: Remote sensing, IoT sensors; AI and ML models; DSS; Blockchain; Digital MRV systems</p> <p>Nature-based: Crop diversification; Cover cropping; Reduced or no-tillage; Regenerative grazing / rotational grazing; Livestock integration within cropping systems; Permanent soil cover</p>
<i>Mechanism</i>	Measurement and verification of environmental indicators; Documentation and communication of regenerative practices; Traceability and standardization of environmental information
<i>Outcome</i>	SOC increase, reduced GHG and synthetic inputs, biodiversity improvements

Taken together, the CIMO analysis suggests that the main differences between the initiatives do not concern their ecological objectives, but rather the systems through which regenerative outcomes are measured, documented, and incorporated into broader governance frameworks.

4.5 Comparative analysis

Comparing all thirty-eight cases reveals shared objectives but also clear structural differences between high-tech and nature-based configurations. While all initiatives aim to promote regenerative agriculture, they operate through very different mechanisms.

These observations emerge from the cross-case analysis of the thirty-eight initiatives included in the dataset and summarized in Appendices A–E.

At the environmental level, improvements are observable across both groups. However, the way these outcomes are evaluated, formalized, and integrated into broader governance and market structures varies considerably.

To clarify this first dimension, Table 7 summarizes the main environmental outcomes identified across the sample.

Table 7: Comparison of environmental outcomes across configurations. High-tech configurations include corporate adopters (n=6), providers (n=7), hybrid cases (n=4), and carbon projects (n=10); nature-based initiatives (n=11).

Environmental Dimension	High-tech Configurations	Nature-based Configurations
<i>Soil Organic Carbon (SOC)</i>	Digitally monitored or modeled	Reported improvements; standardization varies
<i>GHG reductions</i>	Reported; sometimes certified (carbon projects)	Occasionally reported
<i>Biodiversity</i>	Often reported as co-benefit; sometimes monitored	Embedded in agroecological practices
<i>Input Reduction</i>	Supported by precision tools	Core agronomic objective
<i>Soil erosion control</i>	Monitored	Directly addressed through practices

Table 7 shows that environmental improvements are present across both groups. The main difference, therefore, concerns the degree of formalization and monitoring: high-tech models rely on digital infrastructures to standardize and document results, while nature-based initiatives embed environmental improvements within farm-level practices, often without systematic verification mechanisms.

This comparison based solely on environmental outcomes does not fully capture the deeper structural differences between the two configurations. For this reason, the analysis also considers how regeneration is organized, assessed, and translated into economic value. To make these differences clearer, Table 8 provides a comparative overview of the main structural features identified across the sample.

Table 8: Structural comparison of regenerative configurations. High-tech configurations include corporate adopters (n=6), providers (n=7), hybrid cases (n=4), and carbon projects (n=10); nature-based initiatives (n=11).

Dimension	High-tech Configurations	Nature-based Configurations
<i>Primary driver of regeneration</i>	Digital infrastructures supporting monitoring and certification	Ecological processes implemented at farm level
<i>Degree of formalization</i>	High; standardized digital MRV and reporting systems	Variable; often internal or locally documented
<i>Monitoring and verification</i>	Digital MRV, third-party certification (carbon projects), blockchain traceability in some cases	Primarily internal monitoring; limited external validation

<i>Value creation</i>	Market-integrated (carbon credits, certification, traceability)	Embedded within farming systems; limited market translation
<i>Governance structure</i>	Often centralized; technology providers and platforms coordinate activities	Decentralized; farmer- or cooperative- led
<i>Scalability mechanism</i>	Enabled through digital platforms and standardized metrics	Context-dependent; constrained by local resources
<i>Access to finance</i>	Facilitated through measurable and certifiable outcomes	Often limited; dependent on local markets/support schemes

To provide a synthetic representation of the configurations identified across the sample, Figure 8 visually maps the cases according to their level of digital intensity and degree of formalization and market integration.

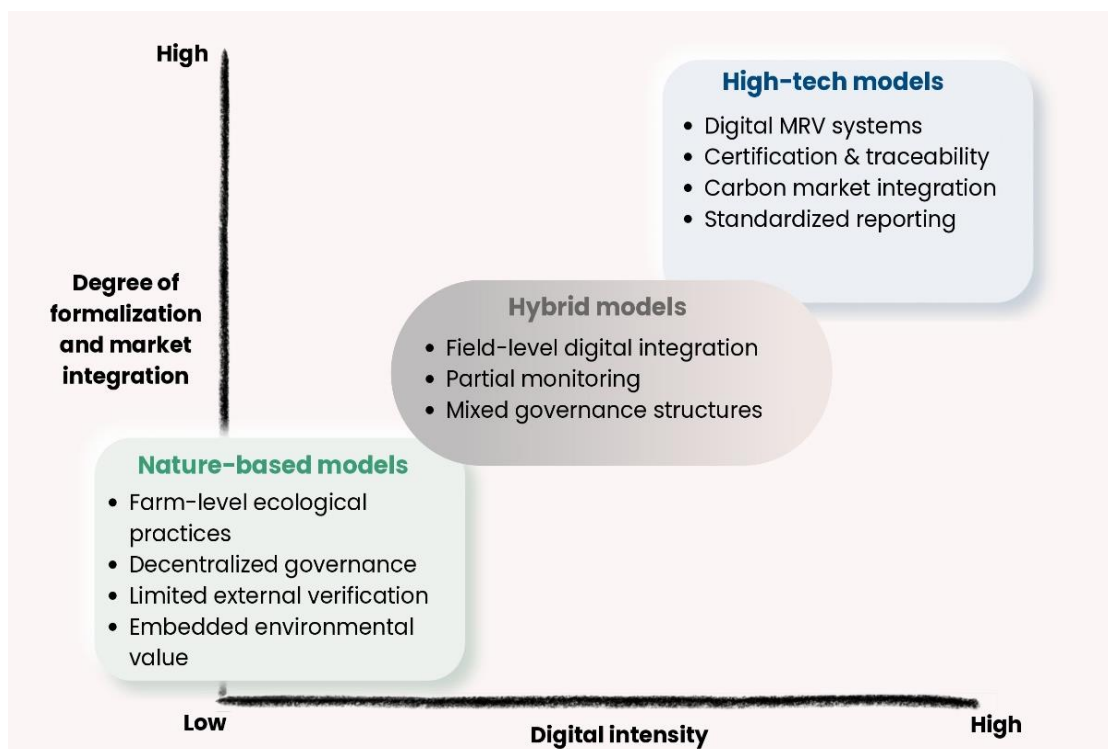


Figure 8: Configurations of regenerative transitions in agri-food systems. Source: Author's elaboration based on Appendices A–E.

What becomes evident is not a hierarchy of environmental performance, but a differentiation in how regenerative value is organized and externalized. As digital intensity increases, regenerative practices tend to be associated with higher levels of formalization and more closely connected to certification frameworks and market mechanisms.

In contexts characterized by lower levels of digital integration, ecological value remains primarily embedded within farm-level processes and local governance arrangements.

Rather than depicting two opposing models, the figure illustrates a gradual transition, with hybrid models occupying an intermediate space between ecology-centered approach and digital formalization.

Overall, the comparison highlights a difference in how regenerative value is produced and recognized. High-tech configurations integrate regenerative practices into digital monitoring and certification systems aligned with market standards (from an economic point of view, this facilitates the external recognition of regenerative outcomes), but they also rely on substantial technological infrastructure, specialized expertise, and often more centralized coordination.

Nature-based configurations, by contrast, rely on ecological processes and farm-level knowledge, and therefore they remain localized and specific to their own environment.

The ecological benefits are a direct result of the agronomic practices and ecosystem management. However, in the absence of standardized monitoring frameworks, these outcomes may remain less visible within market and policy contexts, thereby limiting opportunities for formal recognition and financial support.

Taken together, these findings confirm that regenerative agriculture does not follow a single, fixed path. Instead, it develops through a range of approaches depending on how digital infrastructures and ecological processes interact. These differences have important implications for both policy and governance. Regulatory and support frameworks should facilitate the regenerative transition by providing equal access to technological and financial resources, particularly for small and medium-sized farms, while avoiding over-centralization of decision-making or technological dependency. Ultimately, the ways in which these configurations are developed and integrated will determine the future trajectory of regenerative agriculture within the agri-food system.

5. Conclusion

5.1 Technology and regenerative transitions: contributions and challenges

This thesis analyzes how Industry 4.0 technologies interact with regenerative agriculture and the extent to which digital infrastructures might assist regenerative transitions in the agri-food sector.

The findings suggest that digital technologies do not directly drive ecological regeneration. Instead, they influence how regenerative practices are organized,

monitored and economically recognized within existing governance and market frameworks.

The analysis of thirty-eight case studies shows that technology has both a structuring and enabling role: across high-tech configurations, digital tools (such as sensors, remote sensing systems, artificial intelligence, blockchain-based traceability, and digital MRV platforms) are used to monitor, document, and verify regenerative practices. Their main contribution is to improve the transparency and comparability of regenerative initiatives, particularly when they operate within supply chains or certification frameworks.

Importantly, environmental improvements are not limited to digitally intensive models. Both high-tech and predominantly nature-based configurations report impacts such as increased SOC, reduced input use, improved biodiversity and ecosystem resilience. The difference does not concern ecological ambition, but the way outcomes are formalized and communicated: while high-tech models tend to translate ecological results into standardized and certifiable outputs, nature-based initiatives embed regeneration directly within farm systems, often without systematic digital monitoring or formal certification.

Digital systems therefore improve the visibility and scalability of regenerative practices, but they do not replace their ecological foundations. Soil restoration, biodiversity enhancement, and ecosystem resilience remain grounded in agronomic decisions and biological processes.

Technology can strengthen coordination and accountability, yet regeneration ultimately depends on ecological dynamics at field level.

More specifically, the findings contribute to the existing literature on regenerative agriculture and Industry 4.0 by showing that digital technologies tend to have a stronger role where regenerative practices need to be documented, verified and translated into forms compatible with market or certification requirements. In this respect, the examples analyzed suggest that technology is particularly relevant for governance, reporting, and scaling, rather than in the ecological processes through which regeneration actually occurs.

By comparing digitally intensive and predominantly nature-based configurations, this research also contributes to the literature on sustainability transitions by showing that digitalization does not directly produce ecological transformation. Instead, it reorganizes the mechanisms through which regenerative value is measured, validated, and integrated into market systems.

The regenerative transition therefore cannot be reduced to a purely technological shift, but it represents a broader transformation in which ecological processes and digital infrastructures interact under specific governance and economic contexts.

At the same time, several structural constraints emerge. Advanced digital systems require financial resources, technical knowledge, and organizational capacity that are not evenly distributed across actors: small and medium-sized farms may face difficulties in adopting complex monitoring frameworks or participating in carbon certification schemes.

Moreover, the incorporation of regenerative practices into standardized reporting and verification frameworks can contribute to a greater centralization of governance, as these systems tend to favor models that are more easily compatible with existing certification requirements.

Another critical issue concerns the availability and reliability of documentation. A significant share of the available evidence derives from corporate reports or project documentation, sources that may differ in terms of methodological rigor and external validation. In many cases, especially outside certified carbon projects, independent verification is not always present.

In contrast, nature-based initiatives may achieve substantial ecological improvements, yet their limited formalization can restrict economic valorization and broader policy recognition.

Taken together, these results indicate that regenerative agriculture evolves through diverse configurations in which digital infrastructures and ecological practices interact in different ways. While technology can strengthen regenerative transitions by improving measurability and verification, its contribution remains conditional on accessibility, governance structures, and the extent to which ecological knowledge remains at the core of agricultural transformation.

5.2 Limitations and future directions

This study is based exclusively on secondary data, including corporate reports, institutional documents, certification platforms and publicly available project materials. While this approach permits broad cross-case comparison and the identification of recurring structural patterns, it does not capture direct field-level dynamics or farmer perspectives. Integrating primary data collection, including for example interviews, would provide a more comprehensive understanding of regenerative transitions in practice.

The reliance on publicly disclosed documentation may also result in asymmetries in data quality. Some cases provide highly detailed environmental metrics, while others offer more general descriptions of regenerative practices. Moreover, the analysis focuses on initiatives that explicitly communicate a regenerative orientation, which may lead to a selection bias toward actors that are already engaged in public

sustainability narratives, potentially overlooking less visible or informal regenerative transitions occurring outside formal reporting systems.

Another limitation concerns the measurement of environmental performance. Indicators, baselines, and time horizons vary substantially across the configurations considered, which makes systematic comparison difficult. For this reason, the study does not aim to establish strict quantitative equivalence between cases, but rather to identify structural tendencies emerging from the material examined.

A further limitation relates to the temporal dimension. In most cases, the data provided covers relatively short or medium timeframes, while regenerative processes tend to unfold over much longer ecological cycles. Longitudinal assessments tracking soil health, biodiversity, and farm resilience over extended periods would be necessary to assess the durability and long-term ecological impacts of both digitally supported and predominantly nature-based models.

Geographic, climatic, or socio-economic differences also deserve closer examination. Regenerative agriculture is strongly influenced by local conditions, and the way digital technologies interact with ecological practices may look very different across regions. Elements such as access to infrastructure, land ownership structures, and policy support can shape what is possible in practice.

Future studies could benefit from the use of more harmonized environmental metrics or standardized datasets, which would make cross-case comparison more reliable and explore how different contextual factors can influence the success and evolution of different regenerative models.

At a conceptual level, the analytical categories developed by the author in this thesis were designed to help organize the diversity that emerged from the empirical cases analyzed, rather than reproduce typologies already established in the literature. They were therefore useful in highlighting structural differences; however, further refinement and testing across larger datasets or in different geographic contexts would strengthen their analytical validity and applicability across diverse regenerative contexts.

Future research could also investigate farmers' decision-making processes more closely. In particular, it could address farmers' perceptions of risk and their motivations for adopting (or rejecting) digital tools within the regenerative transition. Integrating qualitative interviews, participatory observation, or mixed-method research designs would facilitate a deeper understanding of how technological and ecological knowledge intersect in practice.

At the same time, it is important to consider both the opportunities associated with digitalization and the constraints that may emerge. Taking these aspects into account is essential for the development of inclusive policies and governance frameworks that aim to support regenerative transitions across different agricultural contexts.

More generally, expanding the empirical evidence and continuing to refine the conceptual tools used will be critical for better understanding under which conditions digital infrastructures can effectively contribute to ecological regeneration, without reducing the diversity of regenerative pathways identified in this study.

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Appendix A: Overview of high-tech corporate organizations (CIMO framework)

Company or Project	Operational location	Size and Ownership	Context (C)	Intervention (I) – Technologies	Mechanism (M)	Outcomes (O)	Partnerships and Collaborations
Mars, Incorporated - "Climate-Smart Agriculture" projects	Global	Large; Private Multinational	Agri-food value chain	Big Data & Data Analytics; Remote Sensing (GIS)	Satellite monitoring and geospatial analyses for the verification of deforestation and land use. Collaboration with technical partners to support the adoption of regenerative practices.	Mars Sustainability Report (2024): <ul style="list-style-type: none"> ➤ 41.833 tCO_{2e} removed from soil in 2024 (CSA projects) ➤ Reduced water consumption, improved soil health 	Technical partners: Agreena, Soil Capital, Horta
Carrefour	France, Italy, Spain	Large; Publicly listed S.A.	Agri-food value chain	Big Data & Data Analytics; Blockchain	Regenerative standards set for suppliers and tiered progress system based on progress toward regenerative practices. End-to-end traceability “from farm to fork”. QR codes to access to information about product origin and certifications.	Carrefour- Sustainability Report (2024): <ul style="list-style-type: none"> ➤ Target 2030: Transform 100% of their supply chain to comply with RA principles (France) ➤ +600 products tracked via blockchain 	IBM Food Trust (end-to-end traceability)
Cargill	Global	Large; Private Multinational	Agri-food value chain	Big Data & Data Analytics;	Near-real-time satellite monitoring and geospatial/GIS analyses to monitor land-use change	Cargill Impact Report (2024): <ul style="list-style-type: none"> ➤ 1,1 millions acres under RA in North 	WRI, Conservation Science Partners

				Remote Sensing	and deforestation. Digital MRV systems to verify outcomes of regenerative practices (RegenConnect®, ReSolu); biodiversity modeling using ecosystem connectivity maps.	America, 74.000 hectares in South America ➤ 2,2 millions hectares monitored for environmental compliance ➤ 41.000 hectares of deforestation avoided	(ecosystem connectivity maps) Satelligence (satellite monitoring), Heifer International and Nestlé (digital tracking, MRV, ESG standard), Universities and agricultural institutes in Brazil
Barilla Group	Europe, Italy	Large; Privately held joint-stock company	Agri-food value chain (wheat, basil, rye)	IoT; Big Data & Data Analytics; AI; Remote Sensing; DSS	“SOCRATE”: uses AI and satellite imagery to monitor soil organic matter; digital platforms (GRANODURO.NET®, Barilla Farming) integrate sensors, predictive models, CO ₂ footprint tracking, and input management. The “Basilicum algorithm” combines data from sensors and satellites to predict downy mildew, reducing pesticide use.	Barilla Sustainability Report (2024): ➤ Target 2030: 250,000 tonnes of raw materials sourced from certified regenerative production ➤ Mandatory use of the digital platform for CO ₂ calculation: reduced emissions and chemical input use	CNR-IBE (development of “SOCRATE”), xFarm (traceability, data collection, and monitoring of sustainable agricultural practices)

Andriani S.p.A	Italy	Medium-sized; private joint-stock company	Agri-food value chain (legumes)	IoT; Big Data & Data analytics; Automation	Introduction of RA in experimental fields combined with supply-chain digitalization through the “Andriani Farm” platform (field monitoring, treatment recording, agronomic datasets). Use of algorithms to assess environmental impacts.	Andriani – Relazione sulla Gestione di Sostenibilità (2023): <ul style="list-style-type: none"> ➤ Official objectives 2024-28: 100 hectares under RA ➤ 150 hectares under automation: +15% yield, improved soil health 	xFarm (traceability, data collection, and monitoring)
BF S.p.A Bonifiche Ferraresi	Italy	Large; publicly listed company	Agri-food value chain (cereals, legumes, vegetables); livestock farming	IoT; AI; Robotics & Automation; Remote Sensing	Precision agriculture: satellite imagery, drones, and geoelectrical sensors to optimize and support the effectiveness of regenerative practices.	B.F. S.p.A Annual Report (2024): <ul style="list-style-type: none"> ➤ Improved soil health and structure (increased earthworm presence in soils) ➤ Improved biodiversity (pollinators) and habitat restoration (planting of shrubs and melliferous species) 	Agriconsulting Europe (technical consultancy, sustainability assessment, precision agriculture implementation)

Appendix B: Overview of high-tech providers (CIMO framework)

Company or Project	Operational location	Size and Ownership	Context (C)	Intervention (I) – Technologies	Mechanism (M)	Outcomes (O)	Partnerships and Collaborations
xFarm Technologies	Global (HQ: Italy, Switzerland)	Medium-sized; Private	Multi-value chain technology enabler	IoT; AI; Big Data & Data Analytics; Remote Sensing; DSS	Collection of data from IoT sensors, satellites, and connected machinery, processed through algorithms and predictive models to optimize irrigation and fertilization. Environmental tracking and supply-chain integration with partners such as Barilla through certified data sharing. Digital protocols aimed at improving soil health and biodiversity.	xFarm Technologies Impact Report (2024): <ul style="list-style-type: none"> ➤ Total emissions avoided: 27,939 tCO₂eq (9,081.666 from fertilization; 1,493.847 from crop protection; 17,028.844 from machinery; 334.882 from irrigation) ➤ Improved water-use efficiency (optimized irrigation) ➤ 1,384,764 hectares optimized 	Collaborations and regenerative programs: Barilla, Andriani, Melinda. Andriani, ongoing legume programs involving 130 farms with a target of 7,000 hectares digitized by 2026 (p. 29). Development of regenerative agriculture protocols in the apple sector (p. 30).
Soil Capital	Belgium, France, UK	Medium-sized; Private	Multi-value chain	Remote Sensing; Digital MRV	Digital platform “mySoilCapital” enables practice tracking through certified MRV.	Soil Capital program: <ul style="list-style-type: none"> ➤ Target 2026: 1 million hectares 	RoyalCanin (Mars Petcare)

			technology enabler		Certified carbon farming and RA program supporting farmers in reducing emissions and increasing soil organic carbon through regenerative practices.	<p>under regenerative management</p> <p>Royal Canin - Soil Capital Case Study:</p> <ul style="list-style-type: none"> ➤ 30,000 tCO₂e reduced/removed in the Royal Canin pilot (Year 1) ➤ 49,809 tCO₂e reduced/removed in the first year of the five-year program ➤ Environmental outcomes: improved soil health, increased biodiversity, improved water-use efficiency, reduced soil erosion 	
Regrow Ag	USA (global operations)	Large; Private	Multi-value-chain technology enabler	AI; Remote Sensing; Digital MRV; Machine Learning	Satellite- and model-based monitoring across 1.4 billion acres, supporting RA programs through an AI-powered platform. The platform enables emissions certification and provides direct financial incentives to farmers for	<p>Regrow Ag Report (2024):</p> <ul style="list-style-type: none"> ➤ 1.3 million tCO₂e of projected abatement from regenerative programs ➤ Unilever case: -40% yield loss avoided through 	PepsiCo, Cargill, General Mills, Oatly, Kellanova, Unilever

					the adoption of regenerative practices.	regenerative practices; improved water-use efficiency	
Horta Srl	Italy	Medium; Private	Multi-value-chain technology enabler	IoT; AI; DSS	Identification of Best Practices, due diligence activities, and feasibility studies for the evaluation and implementation of regenerative practices. DSS designed to guide agri-food value chains through the transition toward sustainable agriculture, providing real-time data and insights.	Horta Srl (website): <ul style="list-style-type: none"> ➤ Reduced synthetic input use ➤ Reduced GHG emissions ➤ Improved soil health (increased organic matter, reduced erosion) ➤ Increased biodiversity 	Spin-off of Università Cattolica del Sacro Cuore (Piacenza); Digital partnership with RINA as “Certification Digital Partner” (integration of certification services)
Landprint	Brazil	SME; Private startup	Multi-value-chain technology enabler	AI; Remote Sensing; Digital MRV	Use of 32 indicators derived from remote sensing, AI, and geospatial analytics, combined with field data and open data, to measure the presence and adoption of regenerative practices and to assess changes in carbon, water, biodiversity, and soil health. The platform enables monitorable and verifiable improvements over time.	LandPrint (website): <ul style="list-style-type: none"> ➤ Increased transparency and decision-support capacity ➤ Supported transition toward regenerative practices 	Collaborations: Cargill and Biofore (regenerative practices in the Cerrado); B4A for soil sampling and analysis.

RoboCare	Tunisia	SME; Private startup	Multi-value-chain technology enabler	IoT; AI; Robotics & Automation; Remote Sensing	Drone scouting, in-field IoT sensors (soil, microclimate), and AI-powered analytics (stress detection, disease risk assessment) to support the application of regenerative practices.	Revolutionizing sustainable agriculture with AI: RoboCare case study: <ul style="list-style-type: none"> ➤ Reduced synthetic input use ➤ Improved soil health (early disease detection, water stress monitoring) ➤ Increased water-use efficiency 	
Nature Robots	Germany	SME; Private startup	Multi-value-chain technology enabler	AI; Robotics & Automation	Development of autonomous agricultural robots (Lero.03), combined with 3D plant mapping and a navigation software platform designed to operate in complex agroecological and regenerative systems. Support to regenerative practices by reducing input use, manual labor, and soil disturbance.	Nature Robots (website): <ul style="list-style-type: none"> ➤ Reduced soil disturbance and input dependency 	Spinoff German Research Center for Artificial Intelligence (DFKI)

Appendix C: Overview of hybrid cases (CIMO framework)

Company or Project	Operational location	Size and Ownership	Context (C)	Intervention (I) – Technologies	Mechanism (M)	Outcomes (O)	Partnerships and Collaborations
SOSTVAN Project	Spain	SME; Research-based local initiative	Blockchain-enabled traceability in extensive livestock farming	Blockchain	Regenerative practices in extensive livestock farming, combined with blockchain technology integrated via QR codes, making these functions verifiable and transparent for consumers.	Report SOSTVAN Project: <ul style="list-style-type: none"> ➤ Increased transparency and carbon monitoring ➤ Increased biodiversity and animal welfare ➤ Consumers willing to pay a +10-15 % price premium 	Research groups from the Universidad de Salamanca and Universidad Pontificia Comillas . “Proyecto Sostenibilidad de Vacas Nodrizas”, financed by the National Rural Development Program of the Spanish Ministry of Agriculture, Fisheries and Food and the European Agricultural Fund for Rural Development
EZ Lab-project "LIFE VitiCaSe"	Italy	Medium / SME; Private company	Technology enabler; wine sector	IoT; Big Data & Data Analytics; Digital Twin	Digital technologies to measure, estimate, and share data on carbon sequestration and soil	Project LifeVitiCaSe-Annual Report (2025): <ul style="list-style-type: none"> ➤ Reduced total emissions 	/

					health, providing feedback and decision-support to optimize regenerative practices in four pilot vineyards belonging to three farms. Data sharing enhances transparency and replicability of the model.	<ul style="list-style-type: none"> ➤ Increased soil organic carbon stocks 	
Fasal (platform) x Chili pepper plantation in Chhattisgarh	India	SME; Private startup	Technology enabler for horticultural production	IoT; AI; Big Data & Data Analytics; DSS	Digital platform based on in-field IoT sensors (soil moisture, temperature, microclimate); cloud-based data collection and analytics; predictive models and AI providing agronomic recommendations (irrigation, fertilization, etc.). The platform transforms raw data into actionable recommendations (e.g. “when to irrigate”).	Paper "Artificial Intelligence in farming", NASSCOM (2023): <ul style="list-style-type: none"> ➤ 30-50% reduction in water consumption ➤ 40%, reduction in chemical inputs (targeted climate and agronomic alerts) ➤ Improved yields (+11.25 t/ha), improved production quality 	Partnership between a high-tech company and local farmers
DroneDeploy x Bowles Farming Company	USA	Medium-sized; Private farming company	Multi-value-chain technology enabler; agri-food value	Robotics & Automation	Use of drones combined with vegetative indices (VARI) and integrated prescription maps. Drone-acquired imagery is analyzed to identify field areas where defoliation is unnecessary or incomplete,	Case-study “Adding Drones to a Precision Agriculture Program”, DroneDeploy’s blog: <ul style="list-style-type: none"> ➤ Reduced chemical input use ➤ Improved soil health and structure 	/

			chain (row crops)		allowing the avoidance of unnecessary chemical applications	➤ Increased operational efficiency	
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Appendix D: Overview of regenerative carbon projects (CIMO framework)

Company or Project	Operational location	Size and Ownership	Context (C)	Intervention (I) – Technologies	Mechanism (M)	Outcomes (O)	Partnerships and Collaborations
Agreena – “Agreena Carbon Project”	Europa, UK	Medium-sized; private company	Multi-value-chain technology enabler for diversified agricultural systems	AI; Remote Sensing; Digital MRV	Certification of carbon credits generated through RA practices, integrating satellite remote sensing tools with structured agronomic data collection, consolidated within digital MRV monitoring platforms (to monitor soil carbon, soil fertility, and input use).	<p>Agreena Carbon Project-Report (2024):</p> <ul style="list-style-type: none"> ➤ Carbon removals: 269,616 tCO₂e (2024) ➤ Total emissions reduced: 542,106.78 tCO₂e (2024) ➤ Estimated reductions 2025–2030: ~1,600,000 tCO₂e per year ➤ Estimated VCUs for issuance: 485,487.4125 VCUs (2024) ➤ Environmental co-benefits: improved soil health, increased biodiversity (indirect: improved water-use) 	<p>Validation & Verification Body: Earthood Services Private Limited, (validation phase under VCS standard). Agricarbon provides soil carbon measurement data supporting project verification. Project certified by Verra. Market actors: Radisson Hotel Group (buyer that pre-ordered a significant share of VCUs, based on press releases); Mars.</p>

						efficiency, reduced synthetic inputs)	
Involtor Consult SRL – “Involtor Future Agriculture, East-Europe project”	Romania	SME; Private company	Environmental technical consultancy for diversified agricultural systems	Remote Sensing; Digital MRV	Certification of carbon credits generated through RA practices, integrating satellite remote sensing tools with structured agronomic data collection, consolidated within digital MRV monitoring platforms (to monitor soil carbon, soil fertility, and input use).	Involtor Future Agriculture, East-Europe Report (2023): <ul style="list-style-type: none"> ➤ Verified GHG reductions: 83,617 tCO₂e (2019–2022) ➤ Estimated total GHG reductions/removals: ≈ 836,166.40 tCO₂e (2019–2049) ➤ Environmental co-benefits: increased soil organic carbon, improved soil fertility, increased biodiversity (indirect: improved water-use efficiency, reduced synthetic fertilizer use, reduced soil disturbance) 	Validation & Verification Body: Earthood Services Ltd. Project certified by Verra .
Trees for the Future Inc. – “Lake Victoria	Kenya	Medium; NGO	Multi-value-chain technology	Remote Sensing; Digital MRV	Certification of carbon credits generated through regenerative agroforestry practices (conversion of	Lake Victoria Watershed Agroforestry Carbon Project Reports (2024–2025):	Validation & Verification Body: Earthood Services

Watershed Agroforestry Carbon Project”			Key enabler for diversified agricultural systems		degraded monoculture land into agroforestry systems). The project integrates satellite remote sensing, field data collection, and modeling within a digital MRV system.	<ul style="list-style-type: none"> ➤ Estimated total GHG reductions/removals: ≈ 20,646,527 tCO₂e (entire crediting period, 2020–2060) ➤ Average annual GHG reductions/removals: ≈ 516,163 tCO₂e per year ➤ Environmental co-benefits: increased biodiversity, improved soil fertility and soil carbon, enhanced climate resilience 	Ltd. Project certified by Verra .
Carbon Friendly Pty Ltd. - "Ground-Truth Australian Orchards" project	Australia	SME; Private	Technical – operational enabler for diversified agricultural systems	Remote Sensing; Digital MRV	Certification of carbon credits from regenerative Improved Cropland Management practices, supported by direct soil carbon measurements and GIS/remote sensing within a Verra VM0042–compliant MRV framework.	Ground-Truth Australian Orchards project – Validation Report (2025): <ul style="list-style-type: none"> ➤ Estimated total GHG reductions/removals: 9,039,267 tCO₂e (2020–2040) ➤ Average annual GHG reductions/removal 	Ground-Truth (technical–scientific partner for direct soil sampling); Carbon Check (India) Pvt. Ltd – Validation & Verification Body, Verra-accredited.

						<p>s: 451,963 tCO₂e per year</p> <ul style="list-style-type: none"> ➤ First Project Activity Instance (PAI – Macadamia Farm Holdings): ≈ 1,164 tCO₂e total, ≈ 58 tCO₂e per year ➤ Expected environmental co-benefits: increased soil organic carbon, improved soil fertility, increased water-use efficiency, enhanced cropping-system resilience, increased biodiversity 	Macadamia Farm Holdings – first validated PAI and on-field implementer.
Boomitra Inc. - "Boomitra Carbon Farming in East Africa through Soil Enrichment" project	Kenya, Rwanda, Tanzania, Uganda	SME; Private	Technical – operational enabler for diversified agricultural systems	Remote Sensing; Digital MRV; Digital Twin (RothC)	Certification of carbon credits from Improved Agricultural Land Management practices, supported by satellite remote sensing, RothC soil carbon modeling, and field data within a digital MRV system.	Boomitra Carbon Project – Validation Report (VCS): <ul style="list-style-type: none"> ➤ Estimated total GHG reductions/removals: 1,765,880 tCO₂e (2019–2039) ➤ Average annual GHG 	Earthood Services Ltd – Validation & Verification Body (VVB). Project certified by Verra . Participating smallholder

						<p>reductions/removals: $\approx 88,294$ tCO_{2e} per year (calculated average)</p> <ul style="list-style-type: none"> ➤ Expected environmental co-benefits: increased soil organic carbon, improved soil fertility, enhanced cropping-system resilience 	farmers act as on-field implementers (grouped project structure).
<p>NaturAll Carbon Limited - "NaturAll Carbon Program: Conservation Agriculture and Land Management in Brazil " project</p>	Brazil	SME; Private	Technical – operational enabler for diversified agricultural systems	Remote Sensing; Digital MRV	Certification of carbon credits generated through Conservation Agriculture and Improved Agricultural/Grassland Management practices. The project combines direct soil sampling with soil organic carbon modeling (DayCent), GIS analyses, and satellite remote sensing within a digital MRV framework.	<p>NaturAll Carbon Program – Joint Validation & Verification Report (2025):</p> <ul style="list-style-type: none"> ➤ Estimated total GHG reductions/removals: 29,181,021 tCO_{2e} (2019–2039) ➤ Ex-post verified GHG reductions (first monitoring phase, 2019–2023): 5,623 tCO_{2e} ➤ Expected environmental co-benefits: increased soil organic 	<p>Earthood Services Ltd – Validation & Verification Body (Verra-accredited); Neo Green Consultoria Ambiental (technical consultancy); Apagri Consultoria Agronômica and IBRA – Instituto Brasileiro de Análises (soil sampling); Landowners as on-field implementers.</p>

						carbon, improved soil fertility and productivity, enhanced climate resilience, reduced soil degradation	
Agoro Carbon Alliance US Inc – “Agoro Carbon USA Pastureland” Program	USA	Medium; Private, corporate-backed (Yara International)	Technical – operational enabler for regenerative livestock systems	Remote Sensing; Digital MRV	Large-scale carbon project certifying credits from Improved Grassland Management, supported by satellite remote sensing, DayCentEVI modeling, and farm-level data within a Verra VM0042–compliant digital MRV system.	<p>Agoro Carbon USA Pastureland – Project Description (2025):</p> <ul style="list-style-type: none"> ➤ Estimated total ex-ante GHG reductions/removals: 8,827,057 tCO_{2e} (2021–2041) ➤ Estimated average annual GHG reductions/removals: ≈ 441,353 tCO_{2e}/year ➤ Expected environmental co-benefits: increased soil organic carbon, improved pasture fertility and productivity, enhanced climate resilience of livestock systems 	Yara International (founding partner and industrial support); TÜV SÜD America Inc. (Verra-accredited Validation & Verification Body); Use of USDA models (COMET-Farm / DayCentEVI) for quantification; Participating farms and ranchers act as Project Activity Instances (on-field implementers).
Orizon Agriculture	South Africa	SME; Private	Technical –	Remote Sensing;	Certification of carbon credits generated through	Orizon CarbonCrop Rewards Programme -	SCS Global Services – Verra-

(Pty) Ltd – “Orizon CarbonCrop Rewards Programme”			operational enabler for diversified agricultural systems	Digital MRV; Digital Twin (RothC)	Improved Agricultural Land Management practices, integrating direct soil organic carbon sampling, biogeochemical modeling (RothC), GIS data, and satellite remote sensing within a digital MRV framework.	<p>Joint Validation & Verification Report (2025):</p> <ul style="list-style-type: none"> ➤ Ex-post verified GHG reductions/removals: ≈ 160,159 tCO_{2e} (2018–2022) ➤ Verified average annual GHG reductions/removals: ≈ 32,000 tCO_{2e}/year ➤ Expected environmental co-benefits: increased soil organic carbon, improved soil fertility and agricultural productivity, enhanced cropping-system resilience, reduced soil erosion and degradation 	accredited Validation & Verification Body; Participating farms (22 farms, 905 fields) act as Project Activity Instances and on-field implementers.
Anthesis B.V. – “CNG AgriCarbon Rewards Programme”	South Africa	Large; Private	Technical – operational enabler for	Remote Sensing; Digital MRV; Digital Twin (RothC)	Certification of carbon credits generated through Improved Agricultural Land Management practices, using	CNG AgriCarbon Rewards Programme – Joint Validation & Verification Report (2025):	SCS Global Services – Verra-accredited Validation & Verification Body;

			diversified agricultural systems		biogeochemical soil organic carbon modeling (RothC, process-based), geospatial data (GIS and satellite remote sensing), and digital Monitoring, Reporting and Verification (MRV) systems.	<ul style="list-style-type: none"> ➤ Ex-post verified GHG reductions/removals: ≈ 43,226 t CO₂e (2018–2021) ➤ Declared environmental co-benefits: increased soil organic carbon, improved soil fertility and agricultural yields, enhanced resilience of agricultural systems 	Climate Neutral Group B.V. (project proponent); Trace & Save and Intelact as agricultural extension service providers. Participating farms (35 commercial dairy farms) as on-field implementers;
Dimitra Incorporated - “Mexico Carbon Project”	Local project (Messico, Nayarit); Global platform	Medium-sized; Private	Multi-value-chain technology enabler for diversified agricultural systems	AI; IoT; Remote Sensing; Blockchain	Ten-year RWA (Real World Asset) project combining forest preservation, reforestation, and regenerative agricultural methods to generate certifiable carbon credits. AI, blockchain, and satellite-based MRV to ensure transparency, monitoring, and reporting.	Dimitra RWA Whitepaper – Mexico Carbon Project (2025): <ul style="list-style-type: none"> ➤ 23,000 ha of forest under regenerative practices ➤ 1.1 million carbon units expected over 10+ years ➤ Environmental co-benefits: reduced deforestation, increased carbon sequestration capacity 	/

Appendix E: Overview of nature-based cases (CIMO framework)

Company or Project	Operational location	Size and Ownership	Context (C)	Intervention (I)	Mechanism (M)	Outcomes (O)
Tynnelä Farm	Finland	SME; Independent farm	Cereal production	Reduced tillage; Cover Crops & Crop Rotation	Adoption of regenerative soil practices (minimum tillage, multi-species cover crops, recycling of organic residues and elimination of synthetic inputs) to improve soil biology, nutrient cycling, and carbon sequestration.	Report EARA (2025) (% compared to the “average farm”): <ul style="list-style-type: none"> ➤ 100% reduction in synthetic inputs (N, P, K, pesticides), 38% reduction in fuel use ➤ 100% increase plant biomass, 16% reduction of oat yield ➤ 17% increase in photosynthetic activity, 14% increase in soil cover ➤ Increased microbial biodiversity
Southern Lights Farm	Greece	SME; Farm & non-profit organization	Fruit and vegetable production and olive growing	No-till; Cover Crops & Crop Rotation	Soil and water management according to regenerative principles (permanent vegetation cover), restoration of soil structure and moisture through continuous ground cover and reduced compaction. Closed nutrient cycles: organic residues reintroduced as natural	Report EARA (2025): <ul style="list-style-type: none"> ➤ 100% reduction in synthetic inputs (fertilizers, agrochemicals), 82% reduction in fuel use ➤ 8% increase in photosynthetic activity, 1% increase in soil cover

					fertilizer; elimination of synthetic inputs.	➤ Increased soil health and microbial biodiversity
Fröhlich Farm	Switzerland	SME; Private farm	Fruit and vegetable production (sugar beet)	No-till; Strip tillage; Cover Crops & Crop Rotation	Conservation agriculture and agroforestry. Reduction of mechanical disturbance, preservation of soil carbon and structure. Increase in roots and plant residues. Plant diversity, improved phytosanitary resilience.	Report EARA (2025): ➤ reduction in synthetic inputs (–67% N, –88% pesticides), 52% reduction in fuel use ➤ 13% increase in photosynthetic activity, 12% increase in soil cover ➤ Reduced environmental impact
Eichhof Farm	Germany	SME; Private farm	Dairy sector	Livestock Integration (100% Grass-Fed) + Soil Reinforcement	Regenerative agriculture and controlled grazing. Transition to 100% grass-fed grazing – improved nutrient use through closed biological cycles. Increased photosynthesis and carbon sequestration through permanent cover and deep roots, reduced chemical inputs/fuel consumption.	Report EARA (2025): ➤ 100% reduction in synthetic inputs, 41% reduction in fuel use ➤ 38% increase in photosynthetic activity, 16% increase in soil cover ➤ Reduced environmental impact
First Milk Ltd	UK	Medium; Cooperative	Dairy sector	Livestock Integration; Soil Reinforcement	Focus on livestock and soil integration, input reduction and animal welfare. Rotation and pasture management with increased vegetation cover.	First Milk – “Annual Report and Financial Statements 2025”: ➤ 89,977 ha under regenerative plans

					Organic fertilization and reduced chemical inputs.	<ul style="list-style-type: none"> ➤ Reduced total emissions: 203,000 tCO₂e sequestered ➤ Increase in soil health, soil organic matter, local biodiversity
Agricultural Cooperative Krakovany-Stráže	Slovakia	SME; Cooperative	Agricultural sector	No-till; Cover Crops & Crop Rotation; Permanent Soil Cover	Restoration of soil biological processes through no-till and permanent soil cover, improving organic matter accumulation, water retention, and nutrient cycling while reducing synthetic input dependency.	<p>EU CAP Network (2024); Agriland (2024):</p> <ul style="list-style-type: none"> ➤ 100% reduction in synthetic inputs (artificial fertilizers, insecticides and fungicides) ➤ Increase in soil organic matter: from 1.7% (2013) to 2.6% (2021) ➤ Increase in carbon sequestration: 30–45 t CO₂/ha cumulative, ~4 t CO₂/ha/year ➤ 100 liters/m²/year water retention capacity ➤ Increase in biodiversity, reduced input costs
Cortijo Maestre Farm	Spain	SME; Private	Agricultural sector (cereals, legumes, oilseeds)	No-till; Cover Crops & Crop Rotation; Permanent Soil Cover	Rainfed arable systems with cereal–legume–oilseed rotations and structural adoption of no-till, permanent cover crops and vegetated field margins to regenerate soil. Biostimulants for microbial activity and	<p>EU CAP Network Report (pp. 127–131):</p> <ul style="list-style-type: none"> ➤ Increase in biodiversity (pollinators and insects), soil structure, water efficiency

					fertilizer reduction; vegetated margins against erosion and for biodiversity.	➤ Soil erosion almost eliminated
Wild Ken Hill	UK	Medium; Family farm	Agricultural sector, livestock sector	Permanent Soil Cover; Regenerative/Low-Intensity Grazing; Rewilding	Low-density grazing, integration of livestock, wildlife and soil.	“Resurvey of the vegetation and structure of the open areas of Wild Ken Hill rewilding area” (2023): ➤ Increase in floristic richness: from 16.8 to 33.2 species/plot; ➤ Increase in diversity index and habitat structure: from 3.6 to 4.8 layers/plot ➤ Improvement in natural regeneration
Cooperativa Agricola Nuovo Cilento	Italy	SME; Cooperative	Organic agriculture, olive growing, agri-food supply chain	No-till; Permanent Soil Cover	Organic farming with a regenerative approach (no tillage, compost from prunings, regenerative pruning, reduced inputs). Circular model covering all stages of the supply chain: production, processing (olive mill), restaurant (“Al Frantoio”).	Case study report “Cilento” (2024) – Table 9: ➤ Increase in soil fertility and agricultural biodiversity (olive grove recovery) ➤ Reduced soil erosion
Società Agricola Terzeria	Italy	Medium; “Benefit Corporation”	Agricultural sector	Cover Crops & Crop Rotation	Application of crop rotations, organic compost, efficient irrigation, and recovery of previously degraded land due to salinity/low organic matter.	Re Soil Foundation (2024): ➤ Reduction in synthetic input use ➤ Increase in water efficiency, soil fertility,

						biodiversity and environmental resilience
Società Cooperativa Amico Bio	Italy	SME; Cooperative	Agricultural sector (cereals, legumes), livestock sector	No-till; Permanent Soil Cover; Cover Crops & Crop Rotation	Improvement of soil health through biodynamic compost; biodiversity protection, reduced chemical inputs and climate resilience through crop diversification and permanent soil cover with grassing and green manure.	Re Soil Foundation (2025): <ul style="list-style-type: none"> ➤ Reduction in synthetic input use ➤ Increase in organic matter and microbial activity ➤ Improved soil quality and plant and wildlife biodiversity

