A report for:

Soil improvement strategies based on local and high value organic inputs

by Darío Mujica

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Executive Summary

This report examines various strategies to improve soil using organic inputs. It highlights key barriers that limit their adoption, such as a lack of reliable data, insufficient information, and examples of unsuccessful transitions. The report also explores technical aspects and focuses on bio-inputs observed during Nuffield travels and through discussions within the Nuffield network. Key bio-inputs include microorganisms, liquid fertilizers, biochar, and compost, among others.

Compost is identified as a particularly promising solution due to its wide range of benefits. The report also presents innovative practices observed in the trips, which have the potential to become future trends in sustainable agriculture.

Cultural factors are also addressed, as they play a crucial role in encouraging the adoption of these bio-inputs and regenerative techniques. Examples include the importance of education in raising awareness and building skills, collaboration between universities and farmers to share knowledge and support implementation, and the role of institutional investors in validating and promoting sustainable management practices.

Finally, this report concludes that there is a significant opportunity to integrate bio-inputs into agricultural systems, offering both environmental and economic benefits. However, overcoming technical challenges and driving cultural shifts will be essential to scaling these solutions and enabling farmers to fully realize their potential.

Table of Contents

Foreword

I grew up on a dairy farm that belonged to my grandfather and was later managed by my father, which connected me to agriculture from an early age. However, during my school years in the city, I became distanced from the agricultural environment. Years later, I decided to study agronomy, driven by my interest in technical topics and soil science, which marked the beginning of my professional career.

My first job was at a large vegetable company, where I gained experience in large-scale agricultural production. Later, I participated in regenerative agriculture projects in Africa, which broadened my perspective on sustainability and agricultural systems. Upon returning to Chile, I took on the management of fruit farms, specializing in crops like walnuts, almonds, citrus, and avocados. I also led research and development (R&D) projects focused on soil improvement and plant nutrition.

Currently, I am in charge of Research and Development at Abonos San Francisco, a company I founded three years ago dedicated to waste management and the production of organic inputs such as compost, soil amendments, and biological liquid products. With a strong focus on research and development, we drive technical solutions to improve soil fertility, promoting a vision of agricultural sustainability and continuous development. Additionally, we handle waste management for agroindustry companies.

I decided to explore this topic further because I strongly believe in the transformative power of healthy soils and the importance of addressing agricultural challenges from a technical and sustainable perspective. This interest aligns not only with my personal experience but also with my desire to contribute to the development of regenerative practices that benefit both agriculture and the environment.

During my Nuffield program, the Global Focus Program (GFP) offered a rich exploration of global agricultural practices. In **Singapore**, the focus was on urban agriculture and sustainability, with visits to vertical gardens, wholesale markets, and biotechnology companies. **Australia** provided insights into large-scale agricultural systems, tropical fruit production, aquaculture, and horticultural research across Darwin and Kununurra. In **Delaware**, USA, the program focused on advanced crop techniques and grain storage, with a highlight on the University of Delaware's Extension Department, showcasing innovative research and sustainable practices. The **Netherlands** emphasized agricultural policies, innovative trends, including flower auctions and organic vegetable farming. Finally, **Norway** focused on advanced agricultural technologies, research for sustainability, and innovations in fruit production.

Beyond the GFP, individual trips allowed for a deeper dive into specific regions and topics. In **Argentina**, the focus was on large-scale soy production, poultry operations, and agroindustry, with visits to processing plants and crop fields. **California, USA**, centered on soil health and regenerative agriculture, with visits to vineyards, strawberry fields, and biochar production. The **Compost Conference in Florida, USA**, explored global composting practices and innovations in organic waste management. **Spain and Portugal** showcased composting techniques, organic vineyards, vermiculture, and alternative waste management strategies. In **Chile**, visits included fruit orchards, nurseries, phosphate rock extraction sites, and meetings with Nuffield groups, exploring local agriculture and strategies for soil improvement.

Figure 1. Diagram of travel destinations.

Acknowledgements

I want to sincerely thank my sponsor, Nuveen, for making this experience possible. Their support went beyond just funding the scholarship, they helped guide my research, connected me with experts in the field, and gave me the chance to visit their fields in California to see their soil improvement practices up close.

I also want to thank my team at the company, who allowed me to take time off during key moments, even during the busy season of compost deliveries. Their collaboration and support made it possible for everything to run smoothly while I was away.

I also want to thank my GFP group, with whom I had the chance to travel to different countries. Their friendship and the knowledge they shared helped me learn so much and made the journey unforgettable. I also want to mention the Nuffield Chile team for their guidance and support, which helped me prepare for and make the most of this program.

Finally, I want to thank my family for their incredible support throughout this process. Without their love and encouragement, none of this would have been possible.

Figure 2. GFP group in Delaware, 2023: Exploring agricultural practices and sharing global perspectives.

Objectives

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- Evaluate the impact of organic inputs on soil health and agricultural productivity, focusing on their effectiveness in improving fertility and sustainability.

- Identify barriers to adoption of regenerative techniques, exploring technical, economic, social, and cultural challenges that limit the implementation of these practices.

- Identify new trends in regenerative agriculture, including technological innovations and market changes that can facilitate the transition to more sustainable systems.

- Identify practices or organic inputs that could benefit Chilean agriculture and incorporate them into the current portfolio

- Study methods to support the adoption of organic-based systems without compromising crop productivity, while ensuring long-term economic viability and environmental health.

- Provide practical recommendations to guide farmers and industry stakeholders in advancing regenerative agriculture practices based on the findings of this study.

Introduction

“We are the first generation of farmers to leave the soil in a worse condition than we found it.” This phrase, which was also the title of one of the presentations during the Global Focus Program (GFP) in the Netherlands, captures the urgency of rethinking our agricultural practices and their impact on soil health. This report, titled "Soil Improvement Strategies Based on Local and High-Value Organic Inputs", aims to address this critical issue by offering an integrated perspective on how regenerative strategies can reverse this trend and build a more sustainable future for agriculture.

Regenerative agriculture emerges as a transformative approach focused on restoring and enhancing soil health using local, high-value organic inputs. Bio inputs- such as organic amendments, biofertilizers, and herbal extracts are essential for improving soil health, encouraging plant development, and decreasing the negative effects of chemical-intensive agriculture (Banerjee, N, 2024). These practices integrate the biological, physical, and chemical management of soils, not only to repair the damage caused by decades of agricultural intensification but also to boost their ability to produce food sustainably. Healthy soils support life, store water, capture carbon, and efficiently recycle nutrients. Techniques such as advanced composting, bio-input applications, and diversified rotations are essential for achieving these goals.

This report explores concrete strategies to improve soil health using local and high-value inputs. It draws on experiences from farm visits during the GFP, discussions with experts, individual trips and standout cases within the global Nuffield network. Additionally, the study incorporates insights from virtual meetings and collaborations with other scholars, providing a broader perspective on the global and local trends shaping the path toward more regenerative agricultural systems.

Chile, as a major fruit producer, faces increasing demands from international markets for regenerative management practices. This report also addresses techniques aimed at supporting the development of national industry and promoting the use of scientifically backed organic bio-inputs. By offering practical, science-based solutions, this document seeks to contribute to the ongoing debate on how to integrate regenerative strategies into modern agriculture and tackle the pressing challenges of sustainability and agricultural profitability.

Barriers to Transition

The transition to soil improvement strategies based on local, high-value organic inputs, as proposed in this report, faces numerous challenges that block their large-scale adoption. These obstacles, identified through experiences observed during travels and visits to countries such as the Netherlands, the United States, and Australia, highlight how structural, cultural, and technical factors limit progress toward effective and sustainable regenerative practices.

Lack of Concrete Data on the Benefits of Bio-Inputs

In most of the countries visited, from California to Darwin, a widespread lack of reliable and standardized data supporting the benefits of bio-inputs was observed. While there are relevant initiatives, such as the trials visited at Braga Fresh in California, USA, (Braga Fresh, 2024) during one of the individual trips, which demonstrate promising advancements, These studies still need to be shared widely enough to become industry standard.

Moreover, although there is concrete data and studies that support the efficacy of bio-inputs in certain contexts, this information does not always reach farmers effectively. (Revista Cultivar, 2024) Often, the results remain confined to academic or technical circles, making it difficult for those working directly in the field to understand and apply them in practice. This gap between knowledge generation and its transfer limits the adoption of these technologies, perpetuating the perception that bio-inputs may be less effective or riskier than conventional alternatives.

Balancing Traditional and Regenerative Agricultural Practices

One of the biggest challenges in modern agriculture is the difference in access to information. Large chemical companies, with their global presence, resources, and ability to share information, have played an important role in offering agricultural solutions. These solutions aim to help farmers use modern technologies in the field. These tools, promoted worldwide, have helped increase productivity and address urgent food security problems in many regions. A report from the Food and Agriculture Organization of the United Nations (FAO) says that chemical inputs have helped improve crop yields by more than 50% in recent decades, especially in intensive grain production (FAO, 2022).

On the other hand, many regenerative practices, like using bio-inputs, compost, and agroecological techniques, are developed by small entrepreneurs, independent researchers, or local initiatives. These solutions, often focused on sustainability and resilience, have difficulty becoming well-known because they lack resources and platforms to share their knowledge. A study by IFOAM shows that agroecological and regenerative methods are very effective in improving soil health and making farms more resilient to climate change. However, their use is limited by economic and market barriers (IFOAM, 2021). Even though the benefits of these practices are being studied more and more, as shown in a Nature Sustainability article, the lack of promotional infrastructure similar to that of large companies makes it harder for them to reach a bigger audience (Giller et al., 2021).

Examples of failed transitions

During many conversations with farmers, they shared unsuccessful experiences with organic inputs or regenerative techniques. One common reason for these failures was poor implementation. In some cases, farmers did not follow the right steps or did not have enough technical support, which led to bad results and disappointment.

Another issue was not considering the specific conditions of each location. Farmers often tried solutions without adapting them to the soil, climate, or crop needs in their area. This made the practices less effective. Also, many farmers did not do enough chemical or biological tests to understand the starting condition of their soil. Without this information, it was hard to apply the right solutions.

Many transitions were also made too quickly instead of slowly, as is recommended. Regenerative agriculture needs time for the soil to adjust and improve. When changes happen too fast, the results may not meet expectations, which leaves farmers frustrated.

These problems create doubt and mistrust about regenerative practices. When farmers share these negative experiences, it spreads skepticism and makes others hesitant to try these methods. This can slow down the shift to more sustainable farming systems. To build confidence, it is important to address these challenges and show how regenerative practices can work when done correctly.

Farmers Under Pressure: The Impact of Political and Regulatory Challenges on Agriculture

Farming is already a difficult business, with challenges like unpredictable weather, changing market prices, and high input costs. When farmers try to adopt organic inputs or switch to regenerative methods, these challenges increase. Farmers need to invest time and money in learning new techniques, adapting their farming systems, and waiting for the soil to improve, which can take time. On top of this, if new regulations add extra pressure, such as strict rules or limits on what they can or cannot do, it makes farming even harder. These rules often increase costs and reduce profits, making it less attractive for farmers to stay in business. When natural challenges, economic difficulties, and regulatory pressures all combine, it becomes almost impossible for many farmers to adopt sustainable practices, even if they want to. This makes it harder to move towards more sustainable and environmentally friendly farming systems.

In Europe, particularly in the Netherlands, environmental regulations on the use of ammonium and nitrates have created tensions between conventional agriculture and sustainability policies. These regulations aim to reduce pollution but impose significant challenges on farmers, who often lack the necessary tools to comply without compromising their profitability. Such situations emphasize the importance of incorporating technical and scientific knowledge into the formulation of legislation that impacts agriculture.

In this context, Prime Minister Mark Rutte's government launched an ambitious national plan in 2022 aimed at halving nitrogen emissions by 2030. One of the plan's most controversial measures involves reducing the national livestock population by 30%, directly impacting farmers and livestock producers. To mitigate the economic impact of these measures, the government has allocated a €25 billion fund to compensate affected producers. However, these initiatives have caused strong political and social reactions, as many farmers see the plan as a risk to their operations (Ignacio Urbasos Arbeloa, Real Instituto Elcano, 2022).

These challenges show how hard it is to balance environmental sustainability with economic needs and food security. Policies are important for fighting climate change and protecting ecosystems, but they work best when governments create strategies that include the needs and limits of farmers. Regulations should come with technical support to help farmers make changes without hurting their incomes.

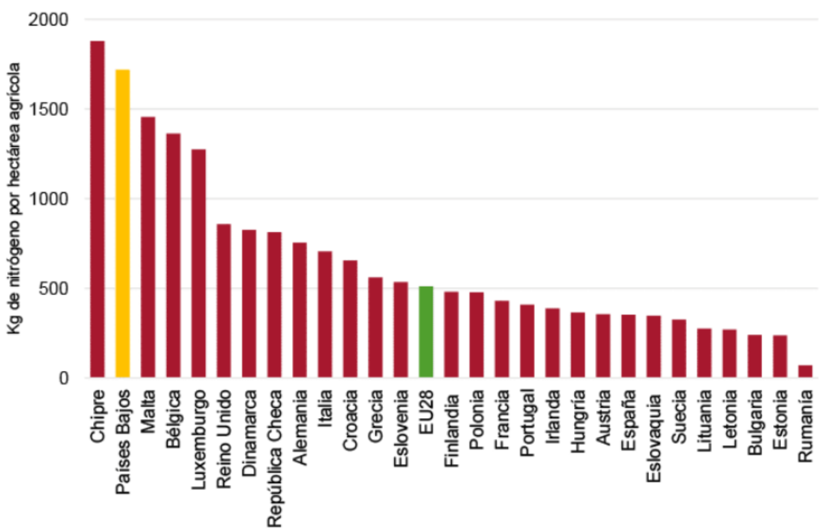

Figure 3. Graph of kilograms of nitrogen per hectare of agricultural land (Ignacio Urbasos Arbeloa, Real Instituto Elcano, 2022).

The Role of Measurement and Data

A recurring issue observed during the trips is the lack of strong measurement systems to help with agricultural decisions. In California, for instance, companies like Braga Fresh have made progress in using technologies to measure parameters such as microbial biodiversity, soil respiration, and sap analyses. However, these efforts remain an exception rather than the norm. Collecting reliable data is essential to demonstrate the benefits of regenerative practices and to build trust among farmers and decision-makers.

Agriculture, like many other sectors, operates in an increasingly uncertain environment, characterized by fluctuations in production levels, highly competitive markets, and growing pressure for immediate results. In this context, data emerges as a critical asset—not only to support strategic decision-making but also to anticipate risks and opportunities in a constantly changing landscape (Toro, M. 2021).

However, many agricultural organizations still fail to recognize the importance of having a strong data management strategy. Advanced tools and well-defined analytical systems not only allow for the measurement of the effectiveness of regenerative practices but also integrate these metrics into more sustainable and competitive business models. In a sector where trust and scientific evidence are key, data facilitates the communication of results and strengthens credibility with demanding markets and critical decision-makers. A solid data strategy is, therefore, not just desirable but indispensable for the sustainability and success of agriculture.

Technical Aspects

Healthy soil is defined as soil that enables plants to grow to their maximum productivity without diseases or pests and without the need for external supplements. Healthy soil is teeming with bacteria, fungi, algae, protozoa, nematodes, and other tiny organisms. These organisms play a vital role in plant health. Soil bacteria produce natural antibiotics that help plants resist diseases, while fungi assist plants in absorbing water and nutrients. Together, these bacteria and fungi are referred to as "organic matter." The more organic matter a soil sample contains, the healthier the soil will be (Rodale Institute).

Understanding how soil functions is fundamental for implementing effective agricultural management strategies. In this context, bio-inputs are defined as substances, biological agents, or mixtures of these, derived from natural origins, that are applied to plants, seeds, soil, or substrates to enhance the productivity, quality, and health of plants, soils, and/or substrates. These bio-inputs may include microorganisms, macroorganisms, biological extracts, or natural biomolecules and their equivalents (Red Chilena de Bioinsumos, 2017). Bio-inputs have emerged as a key tool for improving soil health by optimizing its biological, physical, and chemical components. This chapter focuses on the various technical strategies based on bio-inputs and regenerative agriculture, observed and analyzed during visits to Spain, Argentina, Chile, Norway, the Netherlands, the United States, and Australia as part of the Nuffield program.

A key idea behind strategies is the crucial role of roots in soil dynamics. Estimates suggest that 30% to 50% of total photosynthates are allocated to roots in pasture plants and 20% to 30% in cereals such as wheat and barley (Kuzyakov & Domanski, 2000). For cereals, about half of this carbon remains in the roots, one-third is released from the rhizosphere through root or microbial respiration within a few days, and the remainder is incorporated into rhizosphere microbial biomass and soil organic matter (Kuzyakov & Domanski, 2000). This process, intrinsic to the plant-soil interaction, underscores the importance of promoting practices that integrate bio-inputs as catalysts to enhance soil functionality.

During the program, it was observed how bio-input-based strategies adapt to different contexts and agricultural systems. These practices include the use of beneficial microorganisms, advanced composting, applications of liquid and solid organic matter, cover crops techniques, and measurement tools such as soil respiration, microbial diversity, and sap analysis.

Moreover, it is essential to contextualize these strategies within the framework of sustainable soil management, as discussed in the CSC soil panel in Canada 2023, led by Odette Menard. Her presentation illustrated how the interaction between soil structure, organic matter, and biological activity is essential for soil functionality. These same interactions are enhanced by the use of bio-inputs, reinforcing their role as a tool for sustainable improvement.

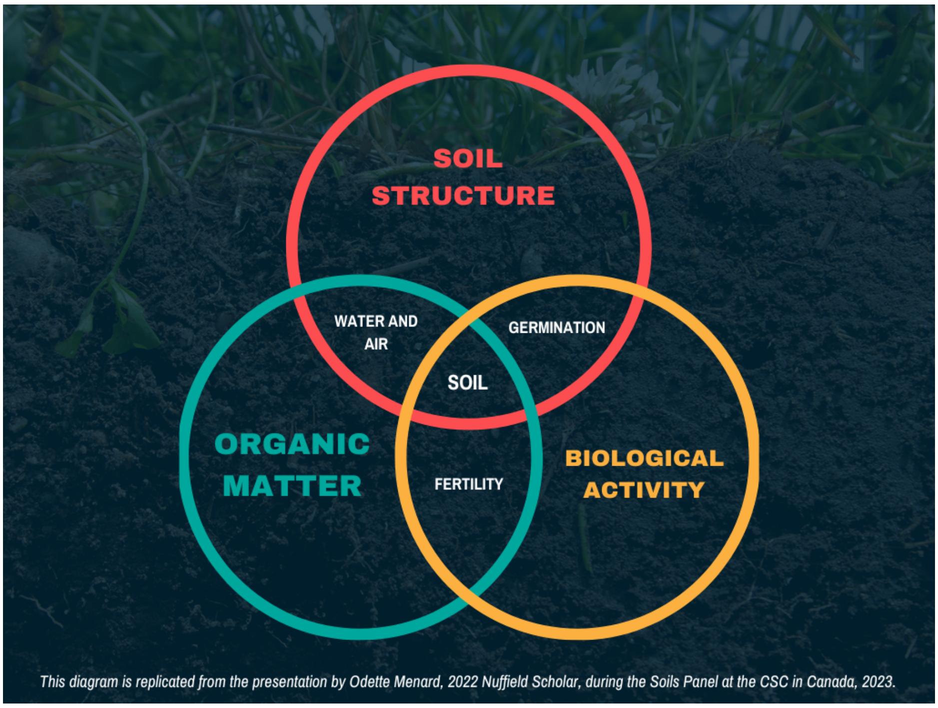

Figure 4. Diagram illustrating the interaction between soil structure, organic matter, and biological activity, highlighting their essential role in soil functionality (Menard. O., 2023)

Main Bio-Inputs Used for Soil Improvement and Their Characteristics:

Bio-inputs are biologically based products applied in agriculture to improve the productivity, quality, and health of plants, soils, and substrates. These include substances, biological agents, or mixtures such as microorganisms, macroorganisms, biological extracts, or natural biomolecules. (Red Chilena de Bioinsumos, 2017)

Cover crops

Cover crops are plants grown primarily to protect and enhance soil quality between cycles of commercial crops. Unlike crops intended for production, cover crops are not harvested for consumption but are used to provide benefits such as preventing erosion, increasing soil fertility, suppressing weeds, and improving soil structure and biodiversity. (Calvo. A., 2021)

During our visit to the University of Delaware's Research Center, we explored various cover crop alternatives. We observed how the implementation of different species can positively influence soil health and enhance the sustainability of agricultural systems.

Figure 5. Discussing cover crop trials with experts from the University of Delaware, 2023

Biological imputs

Biological inputs are products derived from living organisms or their metabolic processes, used in agriculture to improve soil fertility, promote plant growth, and sustainably control pests and diseases. These include biofertilizers, biopesticides, biostimulants, and bioinoculants, among others. (En tu finca, 2024)

During our visit to Delaware, we observed the evaluation of more than 20 nitrogen-fixing microorganisms. These microorganisms are essential for converting atmospheric nitrogen into plant-available forms, reducing dependence on chemical fertilizers and promoting more sustainable agricultural practices. These alternative Nitrogen sources are important for minimizing environmental impact and improving agricultural production efficiency. Additionally, in Vigo, Spain, we explored vermiculture, which involves raising earthworms to produce worm humus, a high-quality organic fertilizer.

Manure

The use of manure as a biological input has been a fundamental agricultural practice since ancient civilizations, including the Egyptians, who understood its importance for improving soil fertility and maximizing crop yields. Manure, derived from animals such as cows, horses, pigs, and poultry, is rich in essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), which are primary macronutrients for plant development. It also contains micronutrients such as calcium, magnesium, zinc, and iron, essential for maintaining crop health and enriching soils. (Agroenlace, 2024)

Manure also plays a crucial role in improving soil structure. Its high organic matter content increases porosity, enhances water retention capacity, and fosters a more aerated soil environment, promoting root development and the activity of beneficial microorganisms.

As part of our research, we held virtual meetings with large-scale farmers in Poland, where strategic manure management as a bio-input was observed. These farmers, aware of manure's benefits for soil and crop productivity, have established partnerships with animal production facilities to ensure access to this resource. Such collaborations enable livestock waste to be efficiently utilized in agriculture, closing nutrient cycles and fostering synergy between the two sectors.

However, manure use requires proper management to avoid potential risks. These include contamination with pathogens such as Escherichia coli and Salmonella present in fresh manure, which can affect food safety if precautions are not taken during application. Additionally, uncontrolled use can lead to negative environmental impacts, such as nutrient leaching into groundwater or surface water, contributing to contamination and eutrophication of aquatic ecosystems.

Amino Acids

Amino acids as biological inputs are essential in modern agriculture, playing a key role in plant growth, stress resistance, and nutrient optimization. Before starting the Nuffield journey, we initiated a research project in Chile to develop agricultural amino acids from poultry industry waste, aiming to sustainably utilize these by-products. However, the amino acid profile analysis revealed an unfavorable composition for agricultural use, highlighting the importance of selecting appropriate raw materials and extraction methods. (Fagro, 2020)

In amino acid production, hydrolysis methods—chemical or enzymatic—directly affect the product's quality and effectiveness. Chemical hydrolysis, using strong acids or bases, is quick and cost-effective but tends to generate D-type amino acids, which are not easily absorbed by plants. This method can also degrade sensitive bioactive compounds and leave chemical residues, limiting its effectiveness. In contrast, enzymatic hydrolysis, performed with specific enzymes, preserves the natural configuration of amino acids in their L-form, which is highly efficient in plant metabolic processes. It also ensures the preservation of bioactive compounds and avoids chemical contamination.

A critical aspect of amino acids as bio-inputs is the size of peptides resulting from the hydrolysis process. Smaller peptides, or oligopeptides, are particularly important because they can be absorbed more easily by plant leaves and roots. Their smaller size allows them to cross cell membranes more efficiently, facilitating rapid translocation to tissues where they are needed. Additionally, smaller peptides require less energy to break down into individual amino acids, making them more effective during periods of high metabolic demand, such as environmental stress or critical growth stages. (Paungfoo- Lonhienne et al., 2008).

Biochar

Biochar is the product of the thermal decomposition of organic materials (biomass) with little or limited oxygen supply (pyrolysis), at relatively low temperatures (below 700 ºC), and it is intended for agricultural use. This distinguishes it from charcoal used as fuel and activated carbon. The International Biochar Initiative (IBI, 2012), in its Standardized Product Definition and Product Testing Guidelines for Biochar that is Used in Soil, defines biochar as "a solid material obtained from the thermochemical conversion of biomass in a limited oxygen environment." (Escalante Rebolledo, A., 2024)

In agriculture, its application has proven to be an effective tool for improving soil health, optimizing nutrient and water retention, and enhancing biological activity. Its ability to sequester carbon makes it a key element in climate change mitigation strategies, as the carbon in biomass is stabilized in a recalcitrant form capable of remaining in the soil for centuries. At facilities such as SITOS in Monterey, biochar is produced from forestry and agricultural residues, and then is mixed with compost to be applied on the farms.

In Chile, we are exploring two projects related to biochar that integrate innovative and sustainable approaches. One involves biochar production using modified biomass boilers designed to optimize the pyrolysis of agricultural and forestry residues, generating high-quality biochar. The second project involves establishing biochar plants for the controlled combustion of wood waste from the mining industry, with the goal of incorporating this material into soils to improve their properties. These initiatives aim not only to mitigate the environmental impacts of waste but also to promote the reuse of materials in agricultural and non-agricultural systems.

In agriculture, biochar stands out for its ability to improve degraded or low-performance soils, increasing their fertility by acting as a reservoir of essential nutrients such as nitrogen, phosphorus, and potassium. It also enhances water retention in light soils, promoting more stable and resilient plant growth under adverse conditions such as drought. At vineyards managed by Nuveen in California, we observed its application combined with compost, which improves soil physical properties and also optimizes fertilizer use by reducing nutrient leaching.

The effectiveness of biochar depends on several factors, such as the type of biomass used in its production, specific pyrolysis conditions, and the characteristics of the receiving soil. Additionally, the dose and application method must be carefully adjusted to avoid negative effects, such as excessive soil pH alterations. Practical experiences visited in California, and ongoing projects in Chile highlight biochar's potential as a versatile and innovative solution for addressing current agricultural challenges, from soil improvement to climate change mitigation.

Figure 6. Visiting the Sitos biochar facility in Monterrey, California, during an individual trip in 2023

Figure 7. Observing compost and biochar applications in Nuveen vineyards, California, during an individual trip in 2023

Liquid Worm Humus

Liquid worm humus, derived from the composting activity of earthworms, is an increasingly valued bio-input in sustainable agriculture. It is a nutrient-rich liquid fertilizer containing a wide range of beneficial microorganisms, enzymes, and organic compounds that promote soil health and plant growth. Unlike synthetic fertilizers, liquid worm humus enhances the biological activity of the soil, improving its fertility over time rather than depleting it. Its ease of application and compatibility with various agricultural systems make it an effective and sustainable solution for modern farming practices.

During our individual trips to Spain, we explored innovative models of liquid worm humus production and application. These systems emphasized the integration of vermiculture with broader waste management strategies, turning organic residues into high-quality bio-inputs. The Spanish operations demonstrated how liquid worm humus improves soil structure and nutrient availability and also boosts plant resilience to environmental stresses. One notable example was the use of liquid humus in vineyards, where its consistent application led to healthier crops and reduced dependency on chemical inputs. These practices showcased how liquid worm humus can play a central role in regenerative agriculture.

Inspired by these experiences, we have begun replicating these models in Chile, adapting them to local agricultural conditions. The results so far have been highly encouraging, with farmers reporting significant improvements in crop health, yield, and soil quality. By integrating liquid worm humus into their farming systems, Chilean producers are enhancing nutrient release from the soil to the roots, especially when they combine compost with liquid worm humus.

Organic-liming Compost

Compost made from shellfish shells is an innovative and sustainable product designed to utilize organic waste and contribute to soil improvement. This compost stands out for its high liming power, making it an effective solution for correcting the pH of acidic soils and enhancing their fertility.

During our visit to Spain, we had the opportunity to observe the production process of this compost in detail. It is made from a balanced mix of poultry manure, organic residues, and mussel shells, which are rich in calcium carbonate. This natural component provides the ability to gradually and sustainably raise soil pH, neutralizing acidity over time.

The composting process combines these ingredients in precise proportions, allowing for controlled decomposition under optimal conditions. The result is a high-quality compost, rich in essential nutrients, that not only improves soil structure and water retention capacity but also promotes the development of beneficial microorganisms, which are key to the health of the soil ecosystem.

We discussed these methodologies with Sergio Quiroga from Celtacal, an expert in the field, who shared valuable insights about its development and application. However, we have not found formal publications supporting these practices, although the observed results are promising. This product has been widely used in vineyards in northern Spain, achieving remarkable effects in both pH correction and crop productivity.

This type of compost represents an excellent alternative for waste management and the sustainable management of agricultural soils, especially in areas where soil acidification is a significant challenge.

Figure 8. Winter vineyard in Galicia, Spain, 2023: Discussion with an expert advisor on mussel shell compost, highlighting its impact on productivity and pH correction, with visible grass growth differences.

Phosphate rock

Phosphate rocks, also known as phosphorites, are sedimentary minerals rich in phosphorus, essential for agriculture as a key nutrient source for pastures and crops. These rocks, originating from ancient deposits like those in Bahía Inglesa, Caldera, Chile, primarily contain tricalcium phosphates. While they have low water solubility, they are soluble in weak acids such as citric acid, making them suitable for acidic soils. In such soils, organic acids present in soil organic matter or secreted by plant roots can release the phosphorus contained in the rocks and make it available to plants (Carlos Sierra, 1990).

Solubility is a critical factor in determining the effectiveness of phosphate rocks as fertilizers. While water-soluble phosphate fertilizers provide a quick release of phosphorus, phosphate rocks allow for a more controlled release, reducing the initial fixation problems in the soil. Among the rocks evaluated, the Bifox rock from Caldera stands out for its higher solubility in citric and formic acid compared to others, such as those from Sechura and North Carolina, positioning it as a high-quality material for improving acidic and calcium-poor soils (Carlos Sierra, 1990).

During an individual trip to Bifox facilities in Caldera, the process of extracting and processing these phosphate rocks was observed in detail. This visit provided valuable insights into how a millennia-old natural resource is transformed into a key bio-input for sustainable agriculture. This approach contributes to agricultural productivity because many farmers are trying to find alternatives sources of Phosphorus.

From a bio-input strategy perspective, phosphate rocks represent an economically and environmentally responsible alternative to conventional fertilizers. Their use is particularly relevant in agricultural systems aiming to reduce dependency on synthetic inputs, promote natural nutrient cycles, and enhance soil quality. Additionally, their calcium content offers advantages in balancing highly acidic soils, a common characteristic in many agricultural regions.

Figure 9. Bifox facilities, Caldera, November 2023: Extraction process overview

Compost:

Since compost was identified as a comprehensive solution for soil improvement and nutrient management, the decision was made to participate in the International Compost Congress in Daytona, United States. This decision marked a milestone in the exploration process, as it allowed access to global experiences, innovative technologies, and strategic approaches to composting. Participation in this congress expanded knowledge about compost and also provided practical tools to address challenges such as logistics, production efficiency, and communicating the value of certified compost.

Key Learnings from the International Compost Congress

The International Compost Congress stood out as a comprehensive experience that combined theory and practice. During the event, participants visited fields, facilities, and composting plants where advanced technologies and innovative methodologies were showcased. A central focus was the presentation of odor management technologies, a recurring challenge in the composting industry. Among the highlighted solutions were Gore™ covers and air injection systems, which proved to be highly effective tools for controlling emissions and meeting stringent environmental standards.

The congress also explored pile-turning technologies, essential for ensuring proper aeration and decomposition of organic materials. Equipment from companies such as Brown Bear (brownbearcorp.com), Aeromaster Composting Equipment, and Rectec Compost Turners (jt-rectec.com) stood out for their efficient design and ability to handle large volumes of material. Additionally, real-time temperature monitoring systems, like those offered by Reotemp, were presented. These systems integrate advanced dashboards to supervise and adjust composting conditions, enhancing the quality of the final product.

Another significant advancement was the analysis of aeration systems, such as those developed by Bactee Systems (bactee.com), which offer specific solutions for odor control and process optimization.

Certifications and Quality Assurance

The congress emphasized the importance of certifications, such as the STA (Seal of Testing Assurance) program, to ensure the quality of marketed compost. This program is based on principles of clarity, consistency, and trust:

Clarity: Providing precise technical information about compost ingredients, analysis results, and usage recommendations.

Consistency: Establishing uniform controls among laboratories and participants to ensure standardized procedures.

Confidence: Offering consumers transparent data about the properties and origin of the compost.

This approach raises quality standards in the industry and encourages other countries to adopt similar practices. Additionally, the STA program promotes effective communication of compost value through educational and commercial strategies, positioning it as a key solution in sustainable agriculture (Composting Conference, 2023).

Innovations in Design and Sustainability

Proper project design is essential to maximize the positive impact of composting. During the congress, various design firms, including Aldea Verde, demonstrated how efficient design can reduce operating costs, optimize resources, and ensure consistent results.

Incorporating these lessons into future projects will allow composting technologies and strategies to be adapted to local needs in Chile, a country where soils show great potential for improvement through compost. From proper organic waste management to the production of high-quality compost, design and planning will be critical for scaling these practices in the agricultural sector.

Compost as a Comprehensive Tool

After analyzing various alternatives, compost has emerged as one of the most complete and effective tools for sustainable agriculture in Chile. Its ability to improve soil structure, increase water retention, and provide essential nutrients makes it a comprehensive solution.

The experience gained at the International Compost Congress, along with visits to successful facilities and projects, provided a solid foundation for implementing these practices in local contexts. As advanced technologies are integrated and quality standards are strengthened, compost has the potential to transform agricultural management and significantly contribute to the country's sustainable development.

Figure 10. Receiving "The Compost Handbook" directly from the author Robert Rynk at the Compost Congress, Daytona, 2023

Innovative Solutions for Organic Waste Management, Fertilization, and Soil Improvement

During the exploration of advanced technologies and sustainable strategies, several innovative solutions were identified that are transforming organic waste management, fertilizer production, and soil quality enhancement.

Ecodrum Composters

The technology offered by Ecodrum (ecodrumcomposters.com) provides an efficient solution for organic waste management. These composters are designed to process waste quickly and effectively, converting it into high-quality compost. Their automated and enclosed approach minimizes odors and accelerates decomposition, making them ideal for agricultural and industrial applications.

N2 Applied Plasma Technology

N2 Applied (n2applied.com) has developed a plasma technology that addresses some of the planet's most pressing environmental challenges. Its patented process closes the nitrogen cycle by producing sustainable fertilizers directly on farms, offering an alternative to the traditional Haber-Bosch process for nitrogen fertilizer production.

Nitrogen-Fixing Bacteria

The use of nitrogen-fixing bacteria represents another significant innovation in sustainable agriculture. Bacteria such as Rhizobium, Azospirillum, and Azotobacter can capture atmospheric nitrogen and convert it into forms usable by plants, reducing dependence on chemical fertilizers. While it is well-known that these biological technologies work effectively with legume crops, recent research is focusing on the innovative potential of applying them to other types of crops. This approach offers a powerful tool for enhancing soil fertility and reducing the environmental footprint of agriculture..

Pelletized Compost

Pelletized compost has emerged as a practical and efficient alternative for organic fertilization. Processing compost into pellets increases its density and nutrient concentration, simplifying its transport and application in fields. This technology is especially beneficial in regions where access to fertilizer is limited or expensive. (Biosafesa, Fertiplus)

Shell-liming compost

Shell lime represents another innovative solution, particularly in regions with acidic soils. Derived from marine shells, this material is a natural source of calcium carbonate that can significantly improve soil quality by neutralizing acidity and supplying calcium, an essential nutrient for crops.

Conventional agriculture: learning from experience rather than reinventing everything.

During the trip, many conventional agricultural operations were visited, showcasing practices that do not incorporate regenerative techniques. However, it is crucial to learn from these experiences, as they often include rigorous management strategies worth highlighting. For example, the interpretation of classical soil chemistry is a key aspect to understand. Plants feed on ions, which conventional agriculture provides through salts. In regenerative practices, these ions are delivered in organic forms but eventually transition to ionic states. This foundational knowledge of soil chemistry should not be overlooked in regenerative agriculture. Conventional agriculture has achieved consistent high yields for decades, and there are valuable lessons to be learned from its precision.

Notable examples include the greenhouses visited in the Netherlands, where fertigation is practiced with remarkable precision, even in the absence of soil. This level of accuracy in nutrient delivery is something regenerative agriculture can learn from. Similarly, research trials like those seen in Kununurra, demonstrated the results of varying fertilization doses, showcasing the importance of data-driven decision-making.

There is a trend in regenerative agriculture to take a holistic approach, interpreting entire cycles and processes, often emphasizing biology over chemistry. However, this shift sometimes leads to oversimplification. For instance, some farmers assume that compost alone provides everything, overlooking critical aspects of soil chemistry. The Dutch greenhouse systems exemplify the value of technical precision and chemical management, which are essential for high productivity. Regenerative agriculture must embrace this level of precision to remain economically viable while balancing holistic practices with solid scientific principles.

During the Nuffield study, a research project was conducted in collaboration with INIA and Dr. Juan Hirzel. This study specifically translated the concept of nutrient release from conventional fertilizers to organic amendments. The results, presented in the table, highlight the nutrient availability rates compared to a control treatment.

Nutrient	Availability Rate (%)
Nitrogen	145
Phosphorus	36
Potassium	1061
Calcium	351
Magnesium	518

Figure. 11. This table illustrates the availability rates of key nutrients in composted organic fertilizer, highlighting its superior release rates compared to conventional fertilizers. For example, the availability rate of nitrogen in composted organic fertilizer is 145%, significantly higher than standard fertilizers. Similarly, phosphorus, potassium and magnesium demonstrate exceptional availability rates, emphasizing the efficiency of composted organic amendments in improving soil fertility. Extracted from a 2024 study conducted by INIA, Juan Hirzel, and Abonos San Francisco.

Figure 12. Visit to Matt Stott, 2008 Scholar, Kununurra: Growing cotton and maize on 800 irrigated hectares, showcasing fertilizer dose trials

The role of genetics

The role of genetics is critical in maximizing productive potential, as highlighted during our visit to the variety trials for Delaware potatoes alongside experts from the University of Delaware's extension department. While this topic may not directly relate to bio-inputs or regenerative agriculture, it is essential to emphasize how genetics contribute significantly to productivity. Selecting the right varieties ensures optimal adaptation to environmental conditions and management practices, reinforcing the importance of integrating genetic advancements into agricultural systems to achieve sustainable and high-yield outcomes.

How do we measure it?

To successfully transition to regenerative agriculture and identify which bio-inputs or practices work best, it is essential to incorporate robust measurement systems. During the journey, we explored various tools and methodologies for data collection, such as laboratory analyses, microbiometer tools, and sap analyses, as observed in California. These methods provide critical insights into soil health, crop nutrition, and the overall effectiveness of regenerative practices, allowing farmers to make informed decisions.

A remarkable example is Braga Fresh, a leading operation dedicating 70 hectares to regenerative agriculture trials on crops like broccoli, cabbage, leafy greens, kale and lettuce. They use cutting-edge technologies to measure soil respiration, analyze soil microbiomes, and identify microorganisms present. Their findings reveal a significant increase in microbial diversity and abundance under regenerative management practices. Additionally, they conduct soil, foliar, and sap analyses (xylem and phloem) to monitor crop nutrition and performance comprehensively.

The research mentioned earlier, which we conducted in parallel with the Nuffield study, is also important to highlight here, as it reinforces the critical importance of measurement for farmers. Some other key conclusions from this study include:

- The composted organic fertilizer activates soil biomass, releasing 45% more nitrogen than it initially provides.
- It liberates 36% of available phosphorus, significantly outperforming traditional fertilizers like triple superphosphate, which typically release 8-10%.
- By contributing calcium, the composted organic fertilizer displaces weakly retained potassium in the soil, improving its availability to plants by a factor of 10.

These findings highlight the transformative potential of regenerative practices when paired with precise measurement tools. Advanced measurement systems, such as those employed by Braga Fresh and in the INIA trials, are essential to bridging the gap between conventional and regenerative agriculture. By quantifying outcomes, farmers can validate the benefits of regenerative practices, adjust their management strategies, and build confidence in the transition process. Ultimately, data-driven approaches empower farmers to adopt sustainable methods while ensuring economic viability and environmental health.

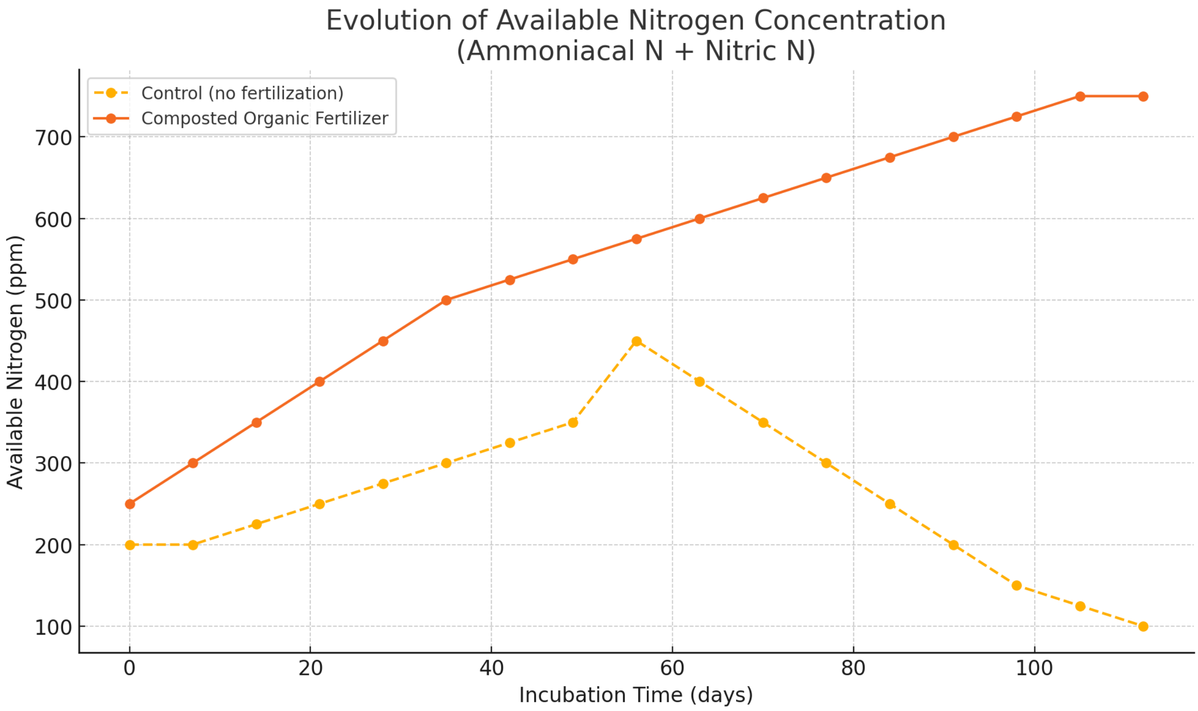

Figure. 13. Extracted from a 2024 study conducted by Juan Hirzel, INIA, and Abonos San Francisco, illustrating the impact of composted organic fertilizer on nitrogen availability during soil incubation.

Cultural aspects:

Transitioning to regenerative agriculture involves more than adopting new farming techniques; it requires a profound cultural shift among farmers and their communities. Understanding the psychological, economic, and cultural motivations behind farmer decision-making is crucial for designing effective investment and market strategies that support this transition. (Conservation Finance Network, 2020) This chapter addresses how education, public policies, the role of universities, associations, and investment funds, as well as market dynamics, contribute to advancing regenerative agriculture, or can become barriers to its development.

Education and Engaging New Generations

Education plays a crucial role in the transition to regenerative agricultural systems. A standout example is the agricultural school we visited in the Netherlands, where students actively participate in an educational dairy business. Founded in 2020, this initiative produces a wide range of dairy products, such as cheeses, yogurts, and butter, which are sold locally. Senior-year students take primary responsibility for the operation, allowing them to integrate technical knowledge with practical experience. This model demonstrates how engaging new generations promotes sustainability and also drives agricultural innovation.

Another remarkable example is the San Luis Obispo City Farm in California, which we visited during the individual trip. This farm welcomes school students to educate them on the importance of regenerative farming techniques. Through hands-on learning and exposure to sustainable practices, young minds gain a deeper understanding of agriculture's role in environmental stewardship and food production. City Farm SLO has stewarded 19 acres of the Calle Joaquin Agricultural Reserve in organic agriculture since 2013. Thirteen acres are subleased to small-scale, independent farmers and the remaining acreage is regeneratively farmed by the nonprofit during impactful youth education programs. (City Farm SLO, 2022).

Role of Institutional Investors

During visits to California, it became clear how the presence of investment funds can be a key driver in promoting regenerative practices in agriculture. These funds, by focusing on the responsible and long-term management of farmland, encourage an approach that combines economic profitability with environmental sustainability. Accordingly, responsible land management is essential to ensure future productivity and provide significant environmental benefits.

The participation of these funds not only brings capital but also strategic vision to implement innovative techniques that restore soil health and ecosystems. Furthermore, their long-term approach builds trust among farmers, who view these investments as support for adopting regenerative practices that might otherwise be perceived as risky. The ability of these funds to align conservation goals with sustainable economic outcomes is a clear example of how institutional capital can accelerate the transition toward more regenerative agriculture, contributing both to agricultural productivity and climate change mitigation.

Universities and Associations

A key strategy to promote the adoption of regenerative practices that increasingly incorporate the use of organic bio-inputs lies in the role of universities and their extension departments, as well as local associations. These institutions are essential players in disseminating knowledge and techniques that enable farmers to integrate sustainable practices into their operations. A notable example is the work of the Delaware Cooperative Extension, which collaborates with individuals, farms, and the agricultural industry to enhance economic and environmental integrity as well as food security.

Through extension programs and field trials, these institutions connect farmers with scientific and practical knowledge tailored to their specific needs. This approach provides reliable technical support that reduces the perceived risks associated with adopting new methods. Initiatives like these demonstrate that universities are bridges between science and agricultural practice, fostering an effective transition toward sustainability.

Organic inputs and Climate Change

Regenerative agriculture positions itself as a key solution in the fight against climate change, standing out for its ability to transform food systems into drivers of positive change. Food systems, which currently rank as the second-largest global emitter of greenhouse gases after the energy sector, have the potential to become net zero, nature-positive, and capable of nourishing the entire population (World Economic Forum, 2024). Achieving this requires an approach that prioritizes regenerative and climate-smart agricultural practices, placing farmers at the center of these initiatives. These measures can improve crop yields and also turn farmlands and pastures into carbon sinks, optimize the use of nitrogen-based fertilizers, and promote sustainable supply chains.

Furthermore, through natural climate solutions (NCS), food systems could contribute up to 37% of the climate change mitigation required to meet 2030 targets. Despite this potential, less than 2% of global climate financing is allocated to agri-food solutions, revealing a missed opportunity. In the European Union, a recent report highlighted that if just one-fifth of farmers received support to transition to net-zero practices, greenhouse gas emissions could be reduced by 6% annually. This transition would simultaneously improve soil health and generate significant economic benefits for farmers (World Economic Forum, 2024).

It is imperative to recognize that transforming food systems through regenerative agriculture combats climate change and generates environmental, economic, and social benefits. Investing in this transition is one of the most effective strategies to ensure a sustainable future, aligned with global climate goals and the well-being of future generations.

Connection with markets

Many experiences have demonstrated how regenerative practices can be profitable by connecting farmers directly with target markets. In the United States, examples like Fifer Orchards show how diversified production of fruits, vegetables, and other products can be marketed directly to consumers through markets and online platforms. Similarly, in Darwin, farmer Bluey Stoldt specialized in composting and direct sales of vegetables online, improving his soils with organic inputs and achieving a sustainable business model.

Figure 14. City Farm SLO: Stewarding 19 acres with organic and regenerative farming, supporting small farmers and youth education since 2013.

Discussion:

Using high-value organic inputs needs a clear plan that mixes sustainable methods with technical and economic solutions to improve soil health. This type of farming is a great chance to support sustainability while still being profitable. It improves soil health, helps capture carbon, and lowers environmental impact. However, adoption cannot depend only on political pressure. It should be a gradual process where farmers can test and adapt to changes without risking their profits. Agriculture cannot survive changes that harm its economic stability. Research and testing are essential to prove the effectiveness of regenerative methods and build farmers' trust in these practices.

One of the main challenges of this transition is the established trajectory and backing of conventional inputs, which are supported by a robust foundation of data and research validating their effectiveness. Additionally, there is a tendency to oversimplify regenerative agriculture, neglecting critical technical aspects such as soil chemistry. Practices like the use of compost often focus exclusively on biological factors, overlooking the necessary balance of chemical components to ensure high productivity.

Chile, with its productive challenges, and agriculture in general, must prepare for these global trends by developing strategies that promote sustainability without compromising profitability. It is crucial to foster a gradual transition that allows the soil to reach a natural balance before reducing the use of synthetic inputs. This process should be accompanied by applied research and educational programs involving new generations. Experiences like those from the Extension Department in Delaware, which has tested over 20 bio-inputs with promising results, provide a clear example of how research can guide the adoption of regenerative practices. Similarly, trials with bio-inputs conducted in California, USA, offer a model for developing soil improvement programs tailored to local needs.

In developing countries, this process must be approached cautiously, ensuring that regenerative practices are adapted to specific contexts and avoiding the replication of models without thorough analysis. Collaboration among farmers, extension centers, and international institutions is essential to ensure an effective and sustainable transition.

The correct implementation of soil improvement strategies based on local and high-value organic inputs represents an opportunity to transform agricultural systems by integrating regenerative principles with advanced techniques. This approach will improve sustainability and productivity without compromising profitability, while building resilient agricultural systems that benefit future generations.

Conclusion:

The transition toward regenerative strategies based on local, high-value organic inputs faces significant challenges but also offers key opportunities to enhance agricultural sustainability. For this transition to succeed, it is essential to rely on rigorous measurements and reliable data to make informed decisions and minimize risks. Learning from conventional agriculture in areas such as studies, data collection, and soil chemistry is crucial for adopting regenerative practices that are technically sound and productively viable.

Collaboration among farmers, universities, and other organizations plays a vital role in facilitating this transition, as it allows for the sharing of experiences, the validation of results, and the reduction of uncertainties. Globally, the need to tackle climate change and agriculture's impact has increased interest in regenerative practices and sustainable bio-inputs. This context underscores the importance of combining precision agriculture with regenerative approaches, integrating technology, education for new generations, and practices that promote carbon sequestration.

However, one of the main obstacles lies in the perception that regenerative practices might compromise profitability. Agriculture has been pushed to its limits, and many farmers face economic difficulties. Therefore, any strategy promoting the use of organic inputs must ensure that they contribute to increased profitability rather than reducing it. This requires a comprehensive approach that combines education, rigorous measurement, and public policies aligned with the realities of farming.

Recommendations

This chapter presents recommendations based on the conclusions of the report, offering actionable steps to further develop, disseminate, and implement regenerative agricultural strategies using local and high-value organic inputs. These recommendations aim to guide the transition toward sustainability while ensuring economic viability and leveraging ongoing practical applications.

One key recommendation is to develop and expand the use of proven bio-inputs. For instance, the project utilizing compost made from lime shell waste highlights the potential to repurpose local materials into effective and sustainable inputs. This initiative should be scaled up to enhance soil health and reduce dependence on synthetic fertilizers. Similarly, the production and commercialization of liquid worm compost fertilizer demonstrate a scalable solution that improves soil fertility and yields. Further efforts are recommended to validate its effectiveness, expand its market reach, and educate farmers on its proper application.

Another recommendation focuses on promoting biochar as an innovative soil amendment in Chile. This relatively new input offers significant benefits, such as carbon sequestration, improved soil fertility, and enhanced water retention. Pilot trials and guidelines tailored to local soil and crop conditions are necessary to ensure its effective adoption. Collaboration with international experts and organizations experienced in biochar use is encouraged to fast-track its implementation and optimize its benefits.

Investing in research and data collection is also recommended to overcome the current lack of reliable information, which makes it harder to adopt regenerative practices widely. Research should measure the long-term impacts of bio-inputs on soil health, productivity, and profitability. Precision agriculture techniques should also be integrated to ensure the efficient and effective application of these practices. Partnerships between universities, research institutions, and farmers are vital to generating actionable insights and disseminating findings.

Finally, Farmer education and capacity building remain critical components of these recommendations. It is essential to create workshops, demonstration farms, and online resources to teach the benefits and applications of bio-inputs, including compost, liquid fertilizers, and biochar. Additionally, involving younger generations through targeted educational programs will foster innovation and ensure the continuity of sustainable farming practices.

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