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Designing and managing cacao systems

Lessons from a 20-year comparison trial in the Bolivian Amazon



Imprint

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Why this document?

Over the past two decades, the SysCom Bolivia project has generated a large body of scientific evidence on cacao cropping systems. Through long-term comparisons of monoculture, agroforestry and dynamic agroforestry systems under different management approaches, SysCom Bolivia has produced numerous peer-reviewed publications addressing topics ranging from cacao genetics and tree architecture to soil fertility, biodiversity, climate resilience and farm economics.

While these studies provide valuable insights individually, many of the most important lessons emerging from SysCom only become apparent when results are analysed together. Understanding the long-term performance of cacao systems requires connecting agronomic, economic and environmental findings and considering how they interact within the same cropping system.

This document therefore aims to synthesise nearly two decades of research into a coherent set of lessons for farmers, technicians, cooperatives, value-chain actors, researchers and policy makers. Rather than reviewing individual practices in isolation, it focuses on the broader understanding that has emerged from the project: how system design influences productivity, livelihoods, environmental sustainability and resilience over time.

By bringing together evidence generated across disciplines and years of observation, this synthesis seeks to support informed decision-making, identify practical implications of the research and highlight priorities for future innovation and development.

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Executive Summary

Cacao cultivation faces growing agronomic, socioeconomic and climatic challenges. The SysCom Bolivia long-term experiment, established in 2007-08, provides one of the most comprehensive evidence bases globally for understanding how different cacao cropping systems influence productivity, livelihoods, environmental sustainability and climate resilience. Nearly two decades of research comparing monoculture, agroforestry and dynamic agroforestry systems reveal a central lesson: long-term performance depends less on individual practices than on the design and management of the cropping system as a whole.

A first major finding is that genetics, tree architecture, canopy management and cropping-system design are major determinants of cacao productivity. Locally adapted clones consistently outperformed most internationally introduced planting materials, while canopy management proved crucial for regulating the balance between light availability, productivity and climate buffering. Although agroforestry systems generally produced lower cocoa yields than monocultures, they maintained competitive production when shade was actively managed.

A second major finding is that diversification fundamentally changes how farms generate value. While monocultures concentrated production and income on cocoa alone, agroforestry systems combined cacao with food crops, fruit trees, timber species and other associated products. Diversified systems have the potential to generate additional food, income opportunities and ecosystem functions, demonstrating that farm performance should not be assessed through cocoa yields alone.

A third major finding is that agroforestry system design underpins environmental sustainability and climate resilience. Diversified systems increased biodiversity, carbon storage and soil biological activity while improving energy and water-use efficiency. Across many indicators, environmental outcomes were more strongly influenced by vegetation structure and biomass dynamics than by the distinction between organic and conventional management alone.

Taken together, the SysCom results show that productivity, livelihoods, environmental sustainability and resilience are not necessarily competing objectives. Different systems optimise different outcomes, and no single model consistently performs best across all dimensions. Rather than seeking a universally optimal cropping system, the challenge is to design and manage cacao systems that balance these objectives according to local conditions, farmer priorities and future uncertainties. Diversified cacao agroforestry therefore represents not a fixed cultivation model, but a flexible pathway towards more resilient and multifunctional agricultural landscape.

Key messages for practitioners



Start with the right genetic material

- Prioritise locally adapted, high-performing clonal material, and use a mix of genetic material on the field to ensure long-term productivity potential.
- Select genetic material not only for yield potential, but also for disease tolerance, adaptation to local climatic conditions, and targeted quality.
- Strengthen access to quality grafted plants through local nurseries and farmer-led propagation initiatives.



Manage cacao tree architecture as a production asset

- Build and maintain a strong scaffold structure with 3 to 5 main branches to maximise productive wood and flowering sites.
- Use simple architectural indicators such as scaffold branch number, branch diameter and productive branch length to guide pruning decisions.
- Maintain a balance between productive woody structures and a healthy photosynthetic canopy through regular renewal pruning.



Design and regulate shade for productivity and resilience

- Design agroforestry systems around light management, using appropriate spacing, canopy stratification and functionally complementary tree species.
- Maintain shade levels that support both productivity and climate buffering, avoiding excessive canopy closure during key flowering periods.
- Adapt pruning and thinning to regulate light availability, improve ventilation and minimise conditions that encourage disease.



Build soil fertility through biomass turnover

- Increase internal nutrient cycling and reduce soil erosion through inclusion of cover crops, use of biomass producing species to prune and mulch and spreading empty cocoa pods in the plot.
- Consider fertilisation in agroforestry as a complementary tool, as responses to nutrient application are strongly influenced by light availability and litter turnover.



Reduce risks through integrated system management

- Combine locally adapted varieties, sanitation pruning and shade management to reduce pest and disease pressure.
- Use canopy regulation to improve airflow and minimise humid microenvironments that favour disease development.
- Manage ground vegetation to balance soil protection, water conservation and competition for resources.



Diversify for resilience and livelihood

- Combine cacao with food crops, fruit trees, timber species and/or other complementary products that contribute to household nutrition and income.
- Select associated species according to their productive, ecological and economic functions within the system.
- View diversification as a long-term strategy for spreading risk and improving overall system performance, rather than as an environmental add-on.

Key messages for cocoa value chain actors



Strengthen access to improved genetic material and technical services

- Support decentralised, quality-controlled nurseries producing locally adapted clonal material for cacao and companion species.
- Strengthen farmer-led grafting initiatives, seed collection and nursery networks.
- Invest in extension services, lead farmers and cooperative technicians specialised in architecture-based cacao management, adaptive shade regulation and agroforestry design.



Develop markets for diversification

- Promote farm business models that embed diversification and combine cacao with fruits, plantains, timber and other agroforestry products.
- Strengthen value chains, market information systems and commercial partnerships for secondary agroforestry products.
- Support diversified marketing opportunities to reduce farmers' dependence on cocoa as a single source of income.



Reward food production for local communities and ecosystem services

- Support farmers in setting production, livelihood and environmental goals and in designing agroforestry systems accordingly.
- Develop sourcing schemes and long-term purchasing arrangements that recognise the value of food production, ecosystem services and resilience benefits, in addition to cocoa.
- Promote sustainability standards that evaluate whole-system performance rather than cocoa yields alone.
- Explore mechanisms that reward biodiversity conservation, carbon sequestration, climate adaptation and diversified farm outputs while preserving farmers' freedom to shape their own cropping systems.



Increase local value addition and organisational capacity

- Strengthen local collection, fermentation, drying and processing infrastructure to improve product quality and retain value in producing regions.
- Support farmer organisations and cooperatives as key actors for mutual support, collective marketing, knowledge exchange and technical assistance.
- Facilitate partnerships among producer organisations, private companies and research institutions to accelerate innovation and market development.

Key messages for policy makers



Recognise agroforestry as a strategic development pathway

- Integrate cacao agroforestry into climate adaptation, climate mitigation, biodiversity and rural development policies.
- Promote diversified agroforestry systems as a pathway to reconcile production objectives, livelihood development and environmental stewardship.
- Incorporate agroforestry into national agricultural, forestry and landscape-restoration strategies.



Support transition and long-term investment

- Strengthen land-tenure clarity for smallholders to enable long-term investment in tree-based systems.
- Establish incentives that reduce the financial risks associated with the transition to agroforestry systems.
- Provide grants, preferential credit schemes and other financial instruments that support long-term investments in tree-based cropping systems.
- Prioritise support during the establishment phase when benefits remain limited, but investments and management requirements are highest.



Invest in knowledge, innovation and evidence generation

- Maintain support for long-term research platforms that generate evidence on productivity, resilience and sustainability.
- Strengthen extension systems, vocational training and digital decision-support tools focused on agroforestry design, canopy management and climate adaptation.
- Foster collaboration among researchers, extension services, producer organisations and the private sector.



Build inclusive and enabling rural conditions

- Improve rural infrastructure, market access and processing opportunities for diversified farm products.
- Support the participation of women, youth and local organisations in agroforestry development, innovation and value-chain governance.
- Strengthen producer organisations as key actors in local economic development, innovation and knowledge exchange.

Introduction

The SysCom Bolivia project has generated one of the most comprehensive long-term evidence bases on cacao cropping systems available in the humid tropics. Established in 2007-08, the SysCom Bolivia Long-Term Experiment (LTE) compares monoculture, agroforestry and dynamic agroforestry systems under organic, conventional and no-input management. Over nearly two decades, this unique research platform has continuously monitored agronomic, economic and environmental indicators, providing an uncommon opportunity to assess how cacao cropping systems evolve through time.

A distinctive feature of the programme is its systems approach. Rather than evaluating individual practices in isolation, SysCom investigates how planting material, tree architecture, canopy structure, biodiversity, soil processes, labour allocation and management decisions interact to shape productivity, livelihoods and environmental performance. This approach makes it possible to move beyond short-term responses and identify the processes that determine long-term system functioning.

The evidence generated by SysCom Bolivia highlights the importance of understanding cacao plots as integrated systems. Across agronomic, economic and environmental dimensions, outcomes consistently emerged from the interaction of multiple components rather than from single interventions. As a result, the project provides insights not only into whether specific practices work, but also under which conditions and through which mechanisms they contribute to productive, resilient and sustainable cacao systems.

This synthesis brings together these lessons through three complementary perspectives. The first examines the agronomic foundations of cocoa cultivation, including planting material, tree architecture, canopy management, pest regulation and soil processes. The second explores how diversification influences food security, economic performance and labour requirements. The third addresses biodiversity, environmental sustainability and climate resilience. Together, these perspectives provide an integrated understanding of how cacao systems can be designed and managed to balance productivity, livelihoods, environmental stewardship and adaptation over the long term.

Brief trial description

The SysCom Bolivia Long-Term Experiment (LTE) was established in 2007-08 in Sara Ana, Alto Beni, Bolivia. The experiment compares five cacao cropping systems: conventional and organic monocultures, conventional and organic agroforestry systems, and a dynamic agroforestry system managed without any external inputs. In parallel, it evaluates the performance of twelve cacao genotypes, including locally selected clones from the Bolivian cooperative El Ceibo, internationally used clones, and full-sib hybrid families, allowing the assessment of interactions between genetic material and cropping system design.

A key feature of the LTE is its gradient of planned diversification. While the monoculture treatments contain only cacao, the agroforestry systems combine cacao with banana, fruits, timber, coffee and shade-tree species at varying levels of structural complexity. The dynamic agroforestry treatment includes an even broader range of associated species which varied depending on age of the plots, including additional timber, biomass and shade trees as well as understory crops such as ginger and turmeric.

The trial covers approximately 5.5 ha and follows a split-plot design with four replicated blocks. Each experimental plot measures 48 × 48 m and contains 144 cacao trees planted at a spacing of 4 × 4 m. Scientific measurements are conducted within a central sampling area of 24 × 24 m comprising 36 cacao trees, while surrounding buffer rows minimise edge effects. The five systems, together with fallow reference plots, are repeated across the four blocks. In addition, around 3.5 ha of simple agroforestry systems have been established between the experimental plots for demonstration and training purposes.

More details are available in Rüegg et al. (2025)

Box 1. The SysCom Bolivia trial layout

The SysCom Bolivia Long-Term Experiment (LTE) compares five cacao cropping systems arranged across the landscape in a controlled experimental design. The simplified layout (Figure 1a) highlights the spatial distribution of the systems, with orientation and scale preserved to reflect plots' real-world configuration (Figure 1b).

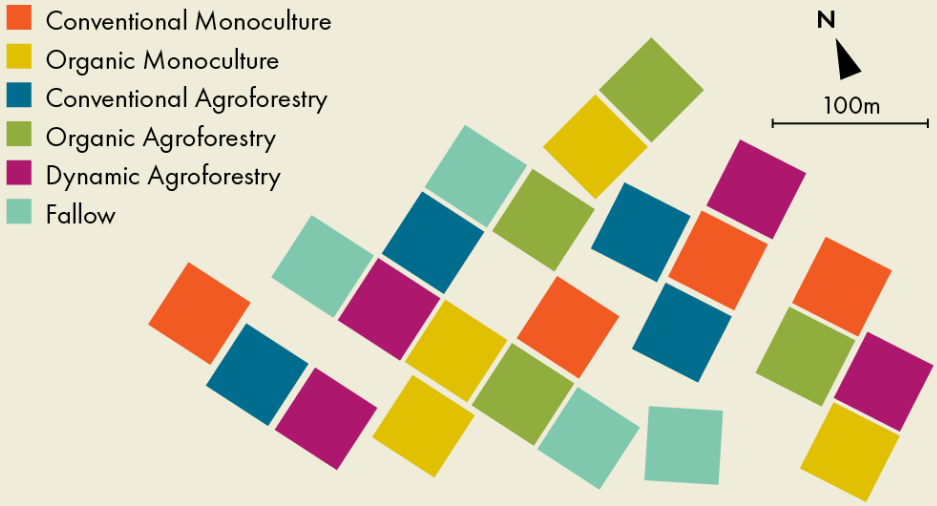


Figure 1a. Plot layout of SysCom Bolivia long-term trial.



Figure 1b. Trial 400m height drone view (2026), © L. Descarpontriez (ECOTOP)

Chapter 1 Improving cacao cropping performance

The productivity and long-term performance of cacao cropping systems depend on interactions among cacao planting material, cacao tree architecture, shade canopy structure, climatic patterns, water availability, soil processes, and management practices. Drawing on nearly two decades of research from the SysCom Bolivia long-term experiment, this chapter examines how these factors influence cocoa production under monoculture and agroforestry systems.

It synthesises the main agronomic lessons regarding cacao cropping emerging from the trial, from genotype selection and shade canopy management to soil fertility and pest regulation, highlighting how system design shapes long-term productivity.

1.1 Selecting performing and available cacao varieties

Planting material is one of the strongest levers for cacao productivity. Long-term data from SysCom Bolivia show that locally adapted clonal material substantially outperforms seedling cacao and widely disseminated international clones: locally selected clones delivered two- to five-fold higher yields, and exhibited lower pod index values (the number of cocoa pods required to produce 1 kg of dry cocoa beans), indicating superior reproductive efficiency under field conditions (Armengot et al., 2023). Two local clones were doing particularly well in the trial: IIa22 and III-06. Since 2018, they are producing on average between 2.4 and 3.2 kg of cocoa (dry bean weight) per tree and year. The best international clone, ICS 6, produced between 1.5 and 2.3 kg during the same period.

Besides, these highest-performing cacao clones remained among the best performers across all cropping systems and management approaches (Armengot et al., 2023). This consistency suggests that selecting superior planting material is a robust strategy, regardless of whether farmers adopt monoculture, agroforestry or dynamic agroforestry systems.

Independent evidence from western Colombia and Central Cameroon points to the same conclusion: cacao clone selection remains a major determinant of productivity across a wide range of agroforestry conditions (Escobar Ramirez et al., 2022; Jagoret, 2011). While some clones consistently achieved higher yields under different shade regimes, locally adapted planting material also proved capable of maintaining productivity in complex multispecies systems over the long term, highlighting the importance of selecting genetic material suited to local conditions.

1.2 Managing cacao architecture through pruning

Cocoa is unusual among fruit crops because flowers and fruits develop directly on the trunk and main branches (cauliflory). As a result, productivity is closely linked to tree size and crown architecture. In the SysCom trial, two easily observable characteristics, the number of scaffold branches and the diameter of the largest scaffold branches, explained a large share of the variation in annual pod production, even after accounting for differences among clones and cropping systems (Saj et al., 2026). These findings highlight the importance of tree structure as

both a determinant of productivity and a practical indicator for pruning and canopy management.

Tree architecture reflects the combined influence of genetics and growing conditions. In the agroforestry systems, cacao trees generally developed more slowly and carried fewer and thinner scaffold branches than in monocultures, suggesting stronger competition for light and a reduced development of productive woody structures. This contributes to the lower cocoa yields often observed in shaded systems (Saj et al., 2026).

Because tree structure strongly influences productivity, pruning is a key management tool for shaping tree architecture. Evidence from other cacao-growing regions shows that pruning can stimulate branch renewal, improve light distribution within the canopy and modify crown structure, although its effects depend on tree size, initial crown architecture and competition from neighbouring trees (Hall et al., 2025; Tosto et al., 2022, 2023).

Taken together, these findings suggest that the objective of pruning should be to maintain a balance between productive branches that bear flowers and pods and a healthy leafy canopy that supplies the carbon needed for fruit development. A compact, well-structured crown with regular branch renewal is more likely to sustain flowering, pod set and fruit development over time. In agroforestry systems, where competition for light is greater and scaffold branches tend to be smaller, pruning should focus on preserving healthy scaffold branches and avoiding excessive canopy removal, which can further limit growth and production (Hall et al., 2025; Saj et al., 2026).

Beyond its effects on productivity, pruning also contributes to pest and disease management. Structural and sanitary pruning improve air circulation and light penetration within the canopy, thereby reducing humidity and limiting conditions favourable to the development of fungal diseases (see Section 1.4).



Figure 2. An ICS1 clone from the SysCom trial. Note the strong and numerous scaffold branches, primary drivers of the tree production potential © L. Descarpontriez (ECOTOP)

Box 2. Renewed tree architecture management

The SysCom trial demonstrated that cacao yield is strongly influenced by tree architecture, a factor that has received relatively little attention in conventional pruning recommendations. Trees with three or more scaffold branches produced 10-50% higher yields than trees with only one or two scaffold branches, depending on genotype and cropping system (Figure 2). In addition, the number of scaffold branches and their diameter were closely associated with annual pod production, highlighting the importance of maintaining a well-developed crown structure. To rapidly assess the productive potential of a tree in the field, it is recommended to combine measurements of trunk diameter with simple observations of scaffold branch number and estimating the linear metres of productive wood beneath the leafy crown.



Figure 3. Cacao with only two scaffold branches (left) generally have fewer higher-order productive branches than trees with four scaffold branches (right) and therefore a lower production potential.

Pruning recommendations

1. Establishing the tree architecture (young plantations)

The first years after planting are critical for building a robust and productive tree architecture.

- ***Develop a strong scaffold structure***. Aim for three to five well-distributed scaffold branches. Trees with fewer scaffold branches generally develop less productive wood, while too many scaffold branches can increase self-shading and internal competition. This objective can be facilitated by using longer scions with four to five viable buds or, where appropriate, by grafting two scions onto the same rootstock.
- ***Carry out formative pruning***. Once the selected scaffold branches are well established, remove the terminal shoot ("tipping") to break apical dominance. This stimulates the development of lateral branches and promotes the formation of the next branching order, increasing the future fruit-bearing surface.

2. Maintaining productivity in mature plantations

Once the basic architecture has been established, pruning should focus on maintaining productivity, facilitating field operations and preserving tree health.

- ***Maintain structural balance and control tree height.*** Tree height should be controlled to facilitate harvesting, removal of deceased pod and branches and pruning operations. Pruning should maintain a balance between productive branches that bear flowers and pods and a

leafy canopy that provides the photosynthetic capacity required for fruit development. As a practical rule, the depth of the leafy crown should represent approximately 30-40% of the total tree height.

- ***Improve light penetration, airflow and avoid excessive investment in wood production.*** Thinning pruning, typically conducted once or twice per year depending on tree growth, involves removing suckers and poorly positioned, crossing or intertwined branches. This improves light distribution within the canopy, enhances air circulation and facilitates harvesting and phytosanitary management.
- ***Remove dead, damaged and diseased wood***. Sanitary pruning should be integrated into every pruning operation. The systematic removal of dead, damaged or diseased branches reduces sources of infection and contributes to maintaining tree vigour and productivity.

1.3 Agroforestry complexity, canopy design and management

Cacao agroforestry systems vary widely in species composition, tree density, and structural complexity. These characteristics strongly influence cocoa productivity, system resilience, and environmental and social outcomes. Evidence from multiple regions shows that simple agroforestry systems with low to moderate shade levels can achieve cocoa yields comparable to those of monocultures (Blaser et al., 2018; Mattalia et al., 2022). As agroforestry systems become more complex and shade levels increase, cocoa yields generally decline, while benefits related to biodiversity conservation, climate resilience, resource-use efficiency and other ecosystem services tend to increase (Niether et al., 2020).

The SysCom results are consistent with this broader pattern. Across the study period, cocoa yields in the agroforestry systems averaged 56% of those recorded in monocultures. Among the agroforestry treatments, the dynamic agroforestry system, characterised by the highest structural complexity and shade levels, consistently produced the lowest cocoa yields. Nevertheless, these highly diversified systems still achieved dry bean yields exceeding 700 kg ha^{-1} during the full-production phase, with some plots surpassing 1,000 kg ha^{-1}. Organic and conventional management resulted in comparable cocoa yields, except during the establishment phase of the monocultures (Rüegg et al., 2025).

The main mechanism underlying these productivity differences is light availability. Because cocoa productivity depends directly on photosynthesis, the amount of light reaching the cocoa canopy is often the primary factor limiting yield in diversified agroforestry systems, even before nutrients or water become limiting (Niether et al., 2018; Saj et al., 2025). However, light availability is not determined by tree density alone. It results from the interaction between tree spacing, species composition, crown architecture, vertical stratification and leaf phenology. Consequently, agroforestry design is one of the most important management decisions influencing long-term system performance (Somarriba et al., 2023).

In addition to regulating light availability, shade trees influence water dynamics within cacao agroforestry systems. By reducing incoming solar radiation, air temperature and vapour pressure deficit, shade tree canopies lower atmospheric water demand and may improve

water-use efficiency. However, these benefits depend strongly on canopy structure and management, as excessively dense canopies can increase competition for water while simultaneously restricting light availability. Consequently, shade management should seek to balance climate buffering, resource competition and cocoa productivity (Kohler et al., 2014; Niether et al., 2018).

The selection of associated tree species is therefore critical. Tree characteristics such as crown depth, lateral expansion, branching pattern and leaf habit determine both the quantity and seasonal distribution of light reaching the cocoa layer. Species that shed their leaves during part of the year may be particularly valuable because they increase light transmission during critical periods while continuing to provide ecosystem services and additional products. Long-term observations from Central Cameroon further demonstrate that associated tree species differ markedly in their functional contributions depending on their crown architecture and phenology, highlighting the importance of matching tree traits to the objectives and constraints of the cacao cropping system (Saj et al., 2017).



Figure 4. Shade tree pruning by trained arborist and team member Elver Mamani in the dynamic agroforestry system of the SysCom long-term trial. © Marco Picucci (FiBL)

Once the system has been established, shade-tree pruning became the principal tool for maintaining a productive canopy structure in the dense agroforestry systems of the SysCom trial (

Figure 4). Regular pruning prevents complete canopy closure, maintains a heterogeneous shade environment and improves light penetration into the cocoa canopy. At the same time, it preserves many of the ecological functions provided by associated trees, including microclimate regulation, nutrient cycling, biodiversity support and future timber production.

Results from the SysCom trial showed that structured (strata separation) pruning effectively reduced canopy closure and increased cocoa yields (Saj et al., 2025).

The timing of shade canopy pruning is also important. Pruning interventions should be adapted to both local climatic conditions and cacao phenology. Heavy pruning immediately before the hottest and driest months may expose cocoa trees to heat and drought stress, whereas increased light availability before flowering can favour carbon accumulation and reproductive development. However, where canopy closure becomes excessive, yield limitations may persist even after substantial pruning because too little light reaches the cacao canopy (Esche et al., 2022; Saj et al., 2025). For this reason, agroforestry design should not rely exclusively on subsequent pruning to regulate shade. Species selection, planting density and spatial arrangement need to be considered from the beginning.

Box 3. Principles of cacao agroforestry shade canopy management

1. Plan and manage shade levels

High cocoa productivity is incompatible with dense shade. System design and shade tree pruning or thinning aim to achieve an acceptable level of canopy cover even in high density agroforestry systems. Management aims to balance the benefits of shade and associated species with creating good conditions for cacao flowering and fruiting. In the SysCom trial, canopy cover levels of 20-30% during the main flowering season were associated with 800-1000 kg ha^{-1} of marketable cocoa.

2. Design a stratified, multi-species canopy

Effective management is based on a deliberate design of the canopy in multiple vertical layers, or strata, to optimise the use of space and light. Perennial species should be given a specific stratum and a defined role. In the SysCom trial, it comprises an emergent (e.g. timber), high (e.g. nitrogen-fixing), middle (e.g. fruit), and low (cacao) stratum. Each tree type receives specific management tailored to its role and position, targeting a separation of 3-4 metres between canopy layers (Figure 5).

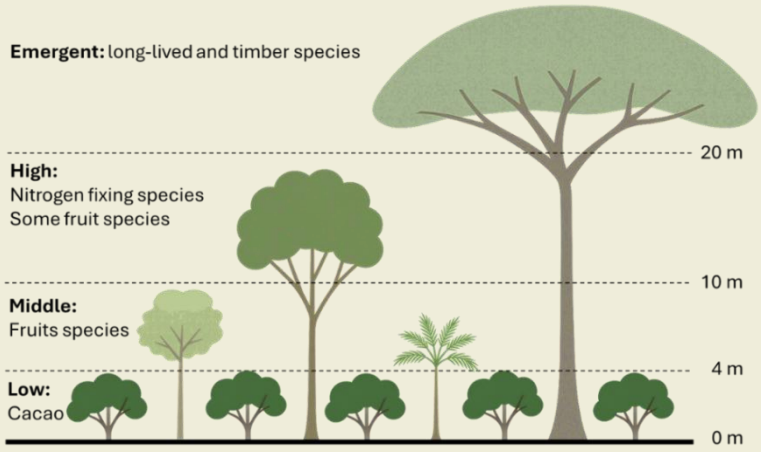


Figure 5. The four different strata managed in the agroforestry systems of the SysCom trial.

3. Practise dynamic and synchronised pruning and/or thinning

In the SysCom trial, a two-stage pruning strategy was applied. First, a severe "*flowering pruning*" is carried out before the rainy season to maximise light penetration and stimulate strong flowering of cacao. This may be followed by a lighter "*ripening pruning*", mainly targeting branches that grow laterally and can be reached from the ground, after the rains to improve ventilation, reduce the risk of fungal diseases and support healthy pod development. SysCom data, however, show that pruning needs further fine-tuning to improve economic efficiency. In addition, the data indicate that yield gains from shade-tree pruning at targeted canopy cover levels above 50% are likely to be minimal.

4. Manage for the entire lifecycle of the plot

Finally, shade management is a long-term strategy that begins well before the first pruning saw is used. It starts with the initial plot design, where foundational decisions about species composition, population density and planting patterns determine the system's potential. Canopy naturally evolves with tree growth, planned thinning or natural disturbances. Therefore, management needs constant adjustments to maintain optimal conditions throughout the entire life of the plantation.

1.4 Integrated strategies to reduce pest and disease pressure

Cacao pests and diseases represent a major constraint to cocoa cultivation worldwide. Their importance varies among regions and depends on factors such as pathogen pressure, climatic conditions, plantation age, management practices and the genetic characteristics of the planting material. Agroforestry systems are often assumed to increase pest and disease risks because their denser canopies can create more humid microclimatic conditions, while organic cultivation limits the use of synthetic pesticides, which may be seen as a management constraint.

The results from the SysCom trial challenge this view. Across ten years of monitoring (2015-2024), the average proportion of diseased pods remained close to 10%, with no significant differences between monocultures and agroforestry systems or between organic and conventional management. Frosty pod rot (*Moniliophthora roreri*) was the dominant disease throughout the study period and accounted for approximately 70% of all diseased pods (Figure 6). Nevertheless, overall losses remained relatively low compared with values commonly reported from other cocoa-producing regions. These results indicate that effective crop management, including regular structural and sanitary pruning, weed control and the fortnightly removal of infected pods, can substantially limit disease development and compensate for potential increases in humidity associated with agroforestry systems (Armengot et al., 2020; Saj et al., al. submitted).



Figure 6. Damages on pods due to the major causes of yield loss in the SysCom Bolivia trial © in Saj et al. (submitted)

Three complementary mechanisms likely contributed to these low levels of pest and disease pressure. First, genetic and biological diversity can enhance system resilience. The use of

tolerant cacao clones reduces susceptibility to disease, while cultivar mixtures and the greater plant diversity typical of agroforestry systems may contribute to natural pest regulation and support beneficial organisms (Huang et al., 2024; Pumariño et al., 2015; Ratnadass et al., 2012). Second, effective crop and plot management plays a central role. Regular pruning improves air circulation and reduces humidity within the cacao canopy, while frequent sanitary harvests and the removal of infected pods interrupt disease cycles and limit pathogen spread. The absence of major differences among cropping systems in the SysCom trial suggests that management quality may be more important than the system itself. Third, shade structure and canopy organisation appear to be more important than shade per se. Recent studies show that pest and disease dynamics are influenced by canopy architecture, tree distribution and ventilation patterns. Well-distributed and regularly pruned shade trees can maintain favourable microclimatic conditions while reducing the risk of frosty pod rot and other fungal diseases (Gidoin et al., 2014; Ramos et al., 2024).

The pod-loss analysis also highlights the importance of genotype selection (Saj et al., submitted). Differences among cacao genotypes were often larger than differences among cropping systems, with some clones consistently showing greater susceptibility to frosty pod rot and other causes of yield loss (e.g. IIa 58, ICS 95). Taken together, these findings indicate that combining adapted planting material with appropriate shade management in agroforestry systems, regular cacao pruning and rigorous sanitary practices constitutes the most effective integrated strategy for reducing pest and disease pressure in cacao systems.

More broadly, the SysCom results demonstrate that high levels of pest and disease control can be achieved with minimal reliance on pesticides. Even in the conventional systems, pesticide use was limited to only a few applications over the entire study period, suggesting that preventive and ecological management measures can play a much greater role in disease regulation than is often assumed

1.5 Sustaining soil health and function

Soil degradation, insufficient nutrient replenishment and extensive management are among the major factors limiting cocoa productivity worldwide (Amponsah-Doku et al., 2022; Wessel & Quist-Wessel, 2015). Agroforestry systems offer an opportunity to improve soil fertility through ecological processes rather than relying exclusively on external inputs. In particular, the integration of trees and other biomass-producing species can enhance nutrient cycling, increase organic matter inputs and support the long-term functioning of the soil. This is especially relevant in cocoa-growing regions where manure, compost and other organic fertilisers are often scarce or costly to obtain.

The SysCom trial provides a unique opportunity to assess how long-term differences in system design influence soil health. A key finding is that soil functioning depended more strongly on biomass inputs and vegetation structure than on whether a system was managed as conventional, organic or with no external inputs. By comparing monocultures with highly diverse agroforestry systems characterised by substantial litter production and regular shade-tree pruning, SysCom highlights the central role of biomass flows in sustaining soil processes (Figure 7).

Across the trial, indicators of soil quality generally decreased along the gradient from fallow to agroforestry to monoculture. Soil organic matter content and enzyme activities were highest in fallow vegetation, intermediate in agroforestry systems and lowest in monocultures, while differences between organic and conventional management remained relatively small. Rapid decomposition rates, exceeding 80% of carbon and 95% of phosphorus within one year, further demonstrated the efficiency of nutrient cycling across all systems (Morales-Belpaire et al., 2024).



Figure 7. Soil covered by litter and pruning residues in one of the SysCom agroforestry plots. © S. Saj (FiBL)

Biological indicators revealed even stronger differences among systems. Soil organic carbon, total nitrogen, labile carbon fractions and microbial respiration tended to increase from monocultures to agroforestry systems, with the highest values recorded in the dynamic agroforestry treatment (Lori et al., 2022). These patterns reflect the larger and more diverse organic matter inputs generated by litterfall, root turnover and pruning residues, which support soil microbial communities and contribute to maintaining soil structure and biological activity (Schneidewind et al., 2019).

Differences between fertilisation strategies were also observed, particularly during the establishment phase of the plantations. In monocultures, mineral fertilisers accelerated early cocoa growth, whereas compost applications gradually increased soil organic matter and nutrient reserves. As the plantations matured and cocoa canopies closed, however, these yield differences diminished and productivity tended to converge (Rüegg et al., 2025). Synthetic fertilisers generally increased exchangeable potassium and magnesium levels, whereas

compost contributed more strongly to the accumulation of organic carbon and biologically active nitrogen pools. Nevertheless, many of these effects were relatively modest compared with the influence of vegetation structure and biomass recycling (Morales-Belpaire et al., 2024).

In agroforestry systems, nutrient dynamics are strongly influenced by internal recycling processes. Pruning residues, fallen leaves and root turnover continuously return nutrients to the soil, reducing dependence on external inputs. In the SysCom systems, nutrient recycling through organic residues, including the cacao pod husks, contributed quantities of nitrogen and potassium comparable to, and in some cases exceeding, annual fertiliser inputs, whereas phosphorus remained the nutrient most likely to limit productivity in mature agroforestry systems (Morales-Belpaire et al., 2025; Sauvadet et al., 2020; Schneidewind et al., 2019). At the same time, the positive effects of fertilisation may be constrained when excessive shade limits cocoa growth and nutrient uptake, highlighting the close interaction between canopy management and soil fertility (Rüegg et al., 2025; Saj et al., 2025).

Among the systems evaluated, dynamic agroforestry showed the strongest capacity to support long-term soil functioning. High biomass production, frequent pruning, extensive root activity and continuous organic matter inputs promoted greater carbon storage, enhanced biological activity and more efficient nutrient cycling than in the other systems (Krause et al., 2025). Taken together, the SysCom results suggest that sustaining soil health depends less on the use of particular input types and more on maintaining active biomass production and nutrient cycling within the system. Agroforestry systems designed to maximise organic matter flows can therefore make an important contribution to long-term productivity, resilience and soil conservation.

Chapter 2 Diversification for enhanced livelihoods

Chapter 1 showed that long-term agronomic performance depends strongly on the design and management of cacao cropping systems. However, farmers rarely manage their farms solely to maximise cocoa yields. Cropping systems also provide food, income, employment opportunities and a range of social and environmental benefits that contribute to household wellbeing. Consequently, the performance of a farm producing cocoa cannot be assessed through its cocoa production alone. It must also consider the broader set of outputs and functions generated by the farm. Diversification plays a central role in this perspective. Through the integration of food crops, fruit trees, timber species and other useful plants, agroforestry systems create multiple sources of production and value. This chapter examines how diversification influences food security, economic resilience and labour requirements, and explores the conditions needed for diversified cacao agroforestry systems to translate ecological complexity into tangible livelihood benefits.

2.1 Diversification beyond cocoa: food, nutrition and wellbeing

Diversification can contribute directly to household wellbeing by increasing the range of products available for consumption. Across tropical cacao-producing regions, companion crops such as bananas, fruits, root crops, palm products and timber provide both marketable outputs and food for household use. This diversity can enhance food security, reduce dependence on purchased foods and strengthen household autonomy (Cerda et al., 2014).

Importantly, the value of diversification is not fully captured by monetary indicators. Products retained for household consumption contribute to nutrition and generate savings by substituting for purchased goods, thereby providing benefits that remain largely invisible in conventional economic assessments.

The SysCom trial illustrates the productive potential of diversified cacao agroforestry systems. Throughout plantation development, companion crops generated both staple foods and marketable products, demonstrating that cocoa production and food production can occur simultaneously (**Figure 7**). Total harvested biomass in agroforestry systems was up to 6.9 times greater than in monocultures. In the dynamic agroforestry system, 22 different products were harvested over the first 15 years, including in early years crops like cassava, maize and pineapple accounting for approximately one-third of total marketable biomass produced (Rüegg et al., 2025).

These observations are consistent with broader evidence indicating that diversified cacao agroforestry systems can maintain productive performance while providing a greater diversity of useful products than monocultures (Niether et al., 2020). In coastal Ecuador, farmers adopting successional cacao agroforestry identified food autonomy, access to diverse and healthy food, and improved household wellbeing among the major benefits associated with diversification (Rodríguez et al., s. d.).

Taken together, these findings suggest that diversified cacao systems should not be evaluated exclusively through their contribution to cash income. By generating food alongside cocoa, agroforestry systems can strengthen food sovereignty, improve dietary diversity and reduce

dependence on external food markets. This broader perspective is particularly important given that cocoa revenues often support household food production and food purchases, creating strong links between cash-crop production and food security (Hashmiu et al., 2022). These often-overlooked benefits represent an important component of household resilience and wellbeing.



Figure 7. Different associated crops from the SysCom agroforestry plots produced in the mature phase. From top-left to bottom-right: copoazú, different banana varieties, açai, peach palm, coffee, ginger. © Laura Armengot, Johanna Rüegg (FiBL)

2.2 Diversification as a strategy for reducing economic risk

While diversification contributes to food security, it also provides important economic benefits. A central advantage of diversified cropping systems is the reduction of dependence on a single commodity. In cacao-dominated systems, household income is highly influenced by fluctuations in cocoa prices, climatic conditions and production risks. Diversified systems distribute production among multiple crops and products that can be harvested, consumed or marketed at different times of the year.

As a result, diversification spreads risks across products, markets and seasons, thereby increasing the capacity of farming households to cope with economic and environmental shocks. Successful diversification strategies have been documented in several cocoa-producing regions. In Côte d'Ivoire, households combining cacao with food crops and other perennial species achieved higher total incomes and showed greater resilience to market and production fluctuations (Tokou et al., 2025).

Evidence from Ecuador similarly suggests that dynamic agroforestry systems can maintain cocoa production and income while simultaneously increasing the abundance of fruit and timber trees. As these associated species mature, they may generate additional productive and economic opportunities without necessarily reducing cocoa performance (Allen et al., 2024).

The SysCom results support these observations. Although cacao remained the dominant source of potential revenue across all cropping systems because of its relatively high market value, agroforestry systems generated a substantially broader portfolio of products. In the long-term trial, the agroforestry system combined cacao with crops destined for local and national markets, such as banana and coffee, while fruit trees provided additional products for household consumption. Dynamic agroforestry systems further diversified production through temporary shade crops, including maize, cassava, and pineapple, which were marketed locally. Other crops, such as ginger, were cultivated experimentally and generated occasional income as well as products for self-consumption. When a market value was assigned to all harvested companion crops, they accounted for approximately one-third of the total marketable value in organic agroforestry systems and about one-half in dynamic agroforestry systems (**Figure 8**, Rüegg et al., in preparation). Although cacao remained the main economic driver, the contribution of companion crops increased markedly with system complexity, highlighting the role of diversification in broadening livelihood opportunities and reducing dependence on a single commodity.

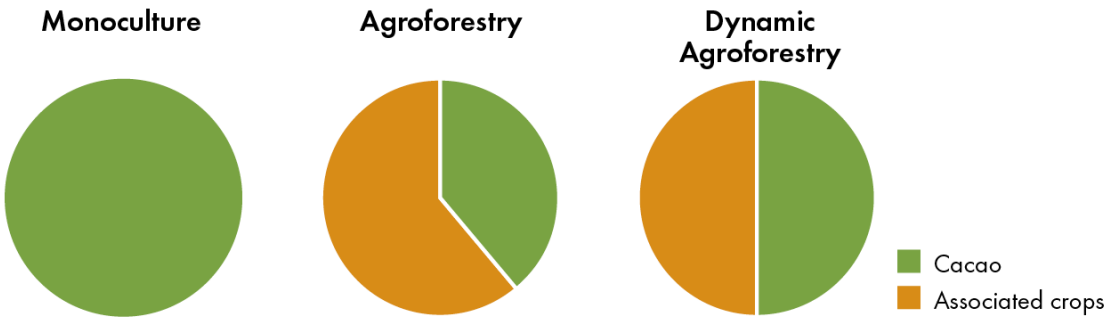


Figure 8. Share of the potential economic value at farm gate of agricultural products in the SysCom Bolivia long-term trial depending on the cropping system.

Diversification therefore changes not only what is produced, but also how risks are distributed within the farm. By reducing dependence on a single commodity, diversified systems provide greater flexibility and potentially greater resilience in increasingly uncertain economic and climatic contexts.

However, these benefits are not obtained without costs. Producing, managing and harvesting a wider range of crops requires additional labour, investments and technical skills. Understanding these requirements is essential when assessing the overall performance and adoption potential of diversified systems.

2.3 Labour and investment: the overlooked costs of diversification

Cacao cropping is inherently labour-intensive, but different cropping systems allocate resources in different ways. Monocultures and conventional systems tend to rely more heavily on purchased inputs such as fertilisers and crop-protection products. By contrast, agroforestry

systems depend more strongly on biological processes, biomass management and human labour.

The SysCom results clearly illustrate this trade-off. Direct costs for inputs and materials were highest in conventional monocultures. Dynamic agroforestry systems incurred the lowest management costs but the highest establishment costs because of their greater species diversity and more complex initial design (Rüegg et al., in preparation). Thus, cropping systems differ not only in total costs but also in how these costs are distributed between external inputs and labour.

Total labour requirements were generally higher in agroforestry systems than in monocultures, particularly in dynamic agroforestry, where shade tree pruning was very labour intensive (Rüegg et al., in preparation). While labour demand in monocultures was concentrated on cacao management, harvesting, and post-harvest activities, agroforestry systems required additional labour for the management and harvest of companion crops, particularly coffee (**Figure 9**). This distinction is important when evaluating overall system performance. Excluding labour associated with companion crops, labour requirements for cacao production were comparable to, or even lower than, those observed in monocultures. Much of the additional labour associated with diversification therefore reflected the production of additional food and marketable outputs rather than a higher labour demand for cacao itself.

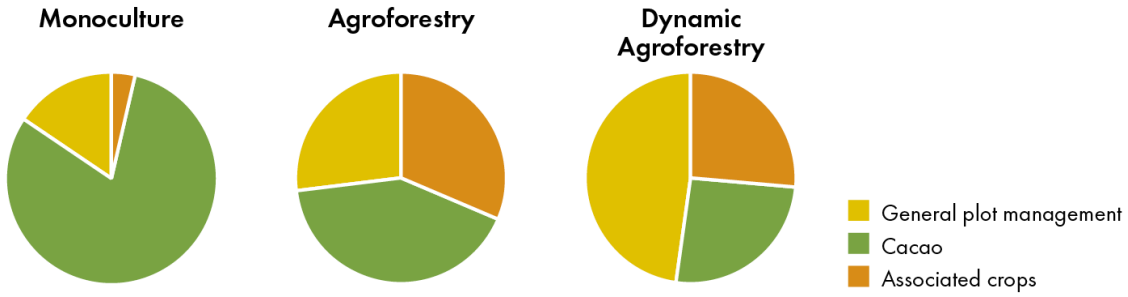


Figure 9. Distribution and amount of labour in different cropping systems of the SysCom Bolivia long-term trial between 2008 and 2021. General plot management includes weeding and shade tree pruning, Cacao includes planting, management (fertilization including preparation of compost, pruning, pest and diseases) and harvest and post-harvest, Associated crops include planting, management, harvest and post-harvest of all other crops. Rüegg et al., in preparation.

From a farmer's perspective, labour should therefore not be viewed solely as a production cost. It also represents an investment capable of generating additional sources of food, income and resilience. Whether this trade-off is attractive depends on household objectives, labour availability and costs as well as on prices for cocoa and associated commercialized crops.

Labour availability nevertheless remains an important constraint to adoption. Evidence from Peru identifies labour requirements among the principal barriers limiting transitions towards more diversified agroforestry systems, particularly where labour is scarce or expensive (Quaedvlieg & Lagneaux, 2026). Farmers also frequently report that complex agroforestry systems require greater management skills and technical knowledge than monocultures.

2.4 Economic performance emerges from system design

The previous sections show that diversification influences food availability, risk distribution and labour requirements. Economic performance therefore depends not only on cocoa yields but on how different components are combined within the farm production system.

In cacao agroforestry systems, system design determines how production, labour and revenues are distributed throughout the lifespan of the plantation (Merot et al., 2026). Different species occupy different productive and economic niches and become productive at different moments. Annual crops and plantains often used as temporal shade for the small cacao plants provide food and income during the establishment phase, while cocoa becomes increasingly important as plantations mature. Fruit trees may contribute intermediate revenues, whereas timber species generate value over much longer time horizons.

The SysCom results illustrate these dynamics clearly. During the first years following establishment, companion crops played a critical role in generating production and revenues while cocoa trees remained largely unproductive. Earlier analyses showed that this diversification strategy generated labour returns approximately twice as high as those observed in monocultures during the establishment phase (Armengot et al., 2016). These early returns help bridge the economically vulnerable years before cacao enters production. In dynamic agroforestry systems, the combination of low production costs and high early yields and potential revenues from companion crops resulted in a substantially shorter payback period than in the other systems when labour was considered unpaid family labour (Rüegg et al., in preparation). As a result, diversified systems can reduce the financial vulnerability associated with the delayed economic returns of cacao (Rüegg et al., in preparation).

As plantations mature, cacao progressively contributes a larger share of total revenues and increasingly drives overall economic performance, thereby influencing results over the entire study period. Over the first fifteen years, the SysCom trial showed that, although cacao yields were lower in agroforestry systems, potential revenues from companion crops largely compensated for these yield reductions. Combined with lower production costs, this resulted in net margins at the whole-system level that were comparable to those of monocultures when labour was considered unpaid family labour (Rüegg et al., in preparation). However, returns to labour (net margin per labour day) were higher in monocultures than in agroforestry systems. This difference was primarily related to the labour productivity of the companion crops integrated into the diversified systems.

These findings highlight a central lesson: economic performance emerges from the design of the entire cropping system rather than from cacao productivity alone. Species selection, crop density, temporal complementarity, labour requirements and costs, as well as market opportunities, all influence profitability. Consequently, successful agroforestry systems strategically combine species with complementary productive, ecological, and economic functions that match the objectives, resources, and constraints of individual farms. Equally important, diversification pathways must be carefully planned and managed over time, as the composition, productivity, labour demands, and economic contributions of individual components evolve throughout the different stages of system development.

Box 4. Diversification pathways in the SysCom trial

The SysCom trial explored how diversification can be progressively integrated into cacao cropping systems through the combination of species with different functions, growth patterns and production cycles. Rather than representing a fixed agroforestry model, the systems were designed as examples of how farmers may combine productive, ecological and economic objectives within the same plot.

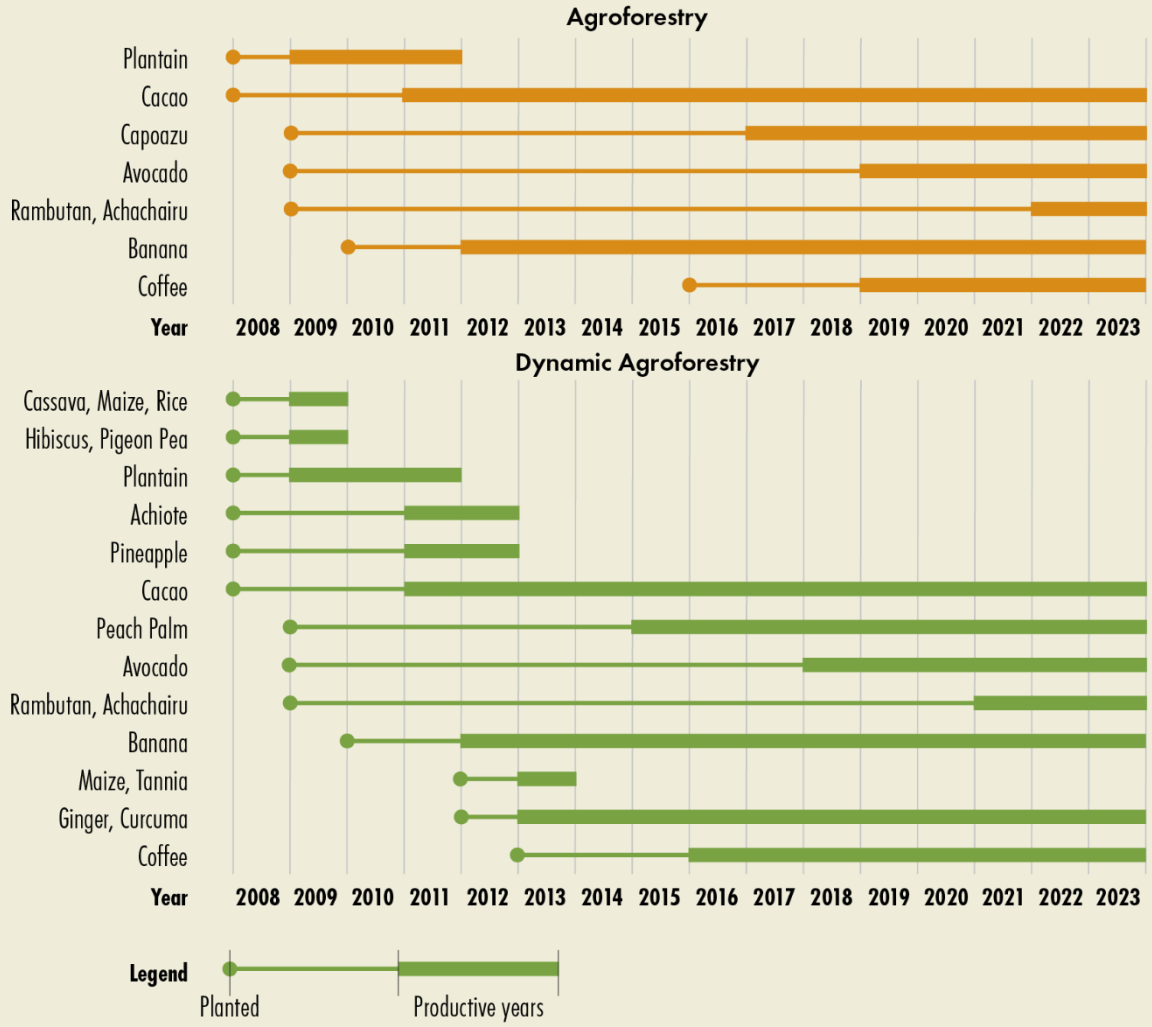


Figure 10. Succession of crops in agroforestry and dynamic agroforestry plots in the SysCom LTE. Most crops were planted from the beginning, but others were integrated later on as the systems evolved.

Chapter 3 Agroforestry for environmental sustainability and resilience

The design of cacao cropping systems affects far more than crop yields. By altering vegetation structure, biomass production and species diversity, design and management decisions influence biodiversity conservation, resource-use efficiency, carbon storage and resilience to climatic stress. Understanding these multiple environmental dimensions is increasingly important as agriculture is expected to contribute simultaneously to food production, climate adaptation and ecosystem conservation.

This chapter synthesises evidence from the SysCom Bolivia long-term experiment on how diversification shapes ecological functioning, environmental impacts and climate resilience. Together, these findings provide a systems perspective on the environmental opportunities and limitations of cacao agroforestry

3.1 Enhancing biodiversity for functional benefits

Ecological performance in cacao landscapes emerges from the coupling of community composition, vegetation structure and functional processes that govern soils, microclimate and plant physiology. While agroforestry systems generally support higher levels of plant and associated biodiversity than monocultures, they remain substantially less diverse than natural tropical forests. Biodiversity conservation in cacao landscapes therefore depends on both the maintenance of diverse agroforestry systems and the protection of remaining natural forests, which continue to harbour the highest levels of biodiversity (Maney et al., 2022; Mortimer et al., 2018).

SysCom reveals consistent compositional shifts along the management gradient: from dynamic agroforestry and agroforestry to conventional monocultures. While species richness may remain relatively stable for some taxonomic groups, community composition, structural complexity and habitat heterogeneity decline predictably along the intensification gradient (Limachi et al., 2018; Maney et al., 2022; Marconi & Armengot, 2020; Naoki et al., 2017; Zegada Herbas et al., 2020). Broader literature shows that tree diversity and canopy architecture are key determinants of biodiversity in cacao agroforests (Mortimer et al., 2018; Solarte-Soto et al., 2025).

In the herbaceous layer, agroforestry systems maintain plant communities characterised by forest-associated and shade-adapted species, whereas monocultures, especially under conventional herbicide-based management, are increasingly dominated by disturbance-adapted and herbicide-tolerant taxa. These compositional shifts are indicative of ecological homogenisation and reduced habitat complexity (Marconi et al., 2022; Marconi & Armengot, 2020). Ant communities mirror this pattern: specialist guilds are more strongly associated with dynamic agroforestry systems and secondary forests, reflecting their dependence on litter depth, moisture, and structural heterogeneity, all of which are indicators of greater ecological complexity and habitat quality (Durot et al., 2023; Limachi et al., 2018).

Box 5. Why diversification matters: biomass, functions and species

Diversification influences agroecosystem performance through several complementary dimensions. While these dimensions are often correlated, they represent distinct ecological properties and contribute differently to productivity, resilience and sustainability at both plot and landscape scales.

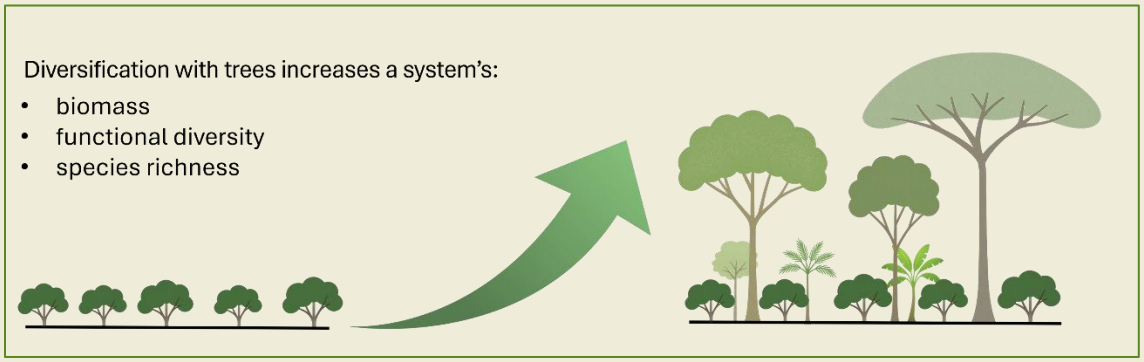


Figure 11. Three effects of plot diversification.

1. Biomass: building larger resource stocks

Biomass refers to the total amount of living plant material within a system. Through its multi-strata structure, agroforestry captures more sunlight and generally produces more biomass than monocultures. This biomass acts as a reservoir of water, nutrients and organic matter.

Leaf litter, root turnover and pruning residues continuously transfer organic matter to the soil, where they support nutrient cycling, soil structure and moisture retention and offer erosion protection. Biomass-producing species such as Inga and Erythrina can be actively managed through pruning to recycle nutrients and maintain soil cover. Greater biomass also creates opportunities for additional production, including fruits, timber, fuelwood, spices and other marketable products.

2. Functional diversity: combining complementary ecological roles

Functional diversity refers to the variety of ecological functions performed by the organisms present in a system. Different species influence resource acquisition, nutrient dynamics and environmental regulation in different ways. For example:

- Nitrogen-fixing species contribute to nutrient cycling;
- Deep-rooted trees can access water and nutrients from deeper soil layers;
- Biomass-producing species contribute organic matter and mulch;
- Shade trees regulate temperature, humidity and light availability;
- Flowering plants support pollinators and beneficial insects.

3. Species richness: increasing resilience and conservation value?

Species richness refers to the number of species present within a system. A species-rich agroforestry system is more likely to contain a broader range of functions and responses to environmental disturbances. Higher species richness can increase functional redundancy, meaning that several species may perform similar ecological roles. If one species declines because of drought, pests or disease, others may partially compensate, helping maintain ecosystem functioning. Species-rich systems can therefore be more resilient to environmental and economic shocks. Species richness also contributes directly to biodiversity conservation. In cacao agroforests, maintaining native trees and natural regeneration can support local flora and fauna while increasing habitat connectivity within agricultural landscapes.

Bird use of habitat rises with structural complexity (from monocultures to agroforestry, dynamic agroforestry and fallow). Forest-linked birds are scarce in monocultures but frequent in dynamic agroforestry systems, indicating functions such as seed dispersal and insect predation may be better provided in and around more complex systems (Naoki et al., 2017).

Even floral visitor assemblages associated with cacao flowers differ among systems. Dynamic agroforestry tends to support higher abundances of thrips, likely as a result of greater resource availability and more diverse microhabitats, further illustrating the influence of system design on biodiversity patterns (Zegada Herbas et al., 2020).

Functional metrics track these patterns: diversified vegetation and organic management increase soil organic N, labile C, basal respiration and mineralisation rates, with enzyme activity gradients typically on the same gradient (Lori et al., 2022; Morales-Belpaire et al., 2024). Independent studies document richer, more functionally diverse soil microbiota under diversified cacao (Buyer et al., 2017; Nahon et al., 2024).

Overall, the SysCom results indicate that management intensification influences not only biodiversity patterns but also the ecological functions supported by cacao systems. Although directly linking biodiversity changes to ecosystem functions remains challenging, the consistent shifts in community composition and soil functioning suggest important differences in ecological processes among systems. These findings should also be interpreted in their landscape context, as the heterogeneous mosaic surrounding the trial likely mitigates some impacts of intensification; effects may be stronger in more extensive monoculture-dominated regions with limited forest connectivity.

3.2 Lowering environmental impacts

SysCom assessments indicate that cropping system design (monoculture versus agroforestry) is the primary driver of environmental performance. Across indicators such as cumulative and fossil energy demand, water use, greenhouse gas emissions and carbon storage, agroforestry systems consistently exhibit lower environmental impacts than monocultures. By comparison, differences between organic and conventional management are generally smaller and often become secondary when impacts are expressed per functional unit and assessed across the entire plantation cycle (Gonzalez-Socorro et al., 2026; Pérez-Neira et al., 2020).

However, environmental performance depends strongly on the functional unit considered, whether impacts are expressed per hectare, per kilogram of cacao, or per kilogram of total harvested production. This distinction is particularly important in diversified agroforestry systems, where companion crops contribute substantially to total output.

Energy demand and efficiency

Agroforestry systems were consistently more energy-efficient than monocultures (Pérez-Neira et al., 2020). When expressed per hectare, total energy demand, including the production of inputs, tools, machinery and labour requirements, was approximately twice as high in monocultures as in agroforestry systems. Agroforestry systems also relied less on non-renewable energy sources (like fossil fuel-derived fertilisers), reflecting their lower dependence on external inputs.

When impacts were expressed per kilogram of cacao, the higher cacao yields obtained in monocultures partially compensated for their greater input use. However, when total system production was considered, including cacao, banana, plantain and other companion crops, non-renewable energy demand was 7.4 times higher in monocultures than in agroforestry systems. Consequently, the energy return on investment was up to 4.8 times higher in agroforestry systems. In addition, both labour productivity and the productivity per unit of labour energy invested were higher in agroforestry systems than in monocultures (Pérez-Neira et al., 2020).

Carbon footprint and water use

The same general pattern emerged for greenhouse gas emissions. During the establishment phase (2010-2016), monocultures displayed the highest carbon footprints per kilogram of cocoa (> 2 kg CO_2-eq kg^{-1}), whereas agroforestry systems performed markedly better during the mature production phase, with dynamic agroforestry reaching values as low as approximately 0.38 kg CO_2-eq kg^{-1} (González-Socorro et al., 2026).

Water footprints also declined substantially with increasing diversification. In mature agroforestry systems, water use per kilogram of total harvested production was more than 95% lower than in monocultures. These reductions were associated with improved microclimatic regulation through shade and higher soil organic matter contents that enhanced water retention and system efficiency (Colmenares-Quintero et al., 2025; Gonzalez-Socorro et al., 2026; Pérez-Neira et al., 2020).

Implications for sustainable cacao production

Taken together, these results suggest that diversification improves environmental performance not only by reducing dependence on external inputs, but also by increasing the efficiency with which energy, water and other resources are converted into useful products. The environmental advantages of agroforestry become particularly apparent when the full range of outputs provided by the system is considered rather than cocoa production alone.

These findings are consistent with broader life-cycle assessments, which have identified the cacao cropping stage as the principal contributor to environmental impacts across cocoa value chains (Avadí, 2023; Wang & Dong, 2024).

3.3 Contributing to resilience and climate adaptation

Climate change is increasingly recognised as a major challenge for cacao production, with rising temperatures, changing rainfall patterns and more frequent climatic extremes affecting both productivity and stability. Within the SysCom trial, long-term climate monitoring reveals a gradual warming trend over the last 15 years (+1.7 °C), particularly in wet-season maximum temperatures, accompanied by declining annual precipitation (approximately -400 mm) and increasing climatic variability (Saj et al., submitted). These trends are consistent with broader changes reported across southern Amazonia and raise concerns about increasing abiotic stress for cacao production (Medina & Laliberte, 2017).

SysCom identified three key mechanisms through which agroforestry contributes to climate resilience in the Bolivian Amazon: shade canopy structure, adaptive shade regulation and leaf-level physiological plasticity.

Microclimate monitoring demonstrated that agroforestry substantially reduced heat exposure. Relative to exposed conditions, agroforestry systems buffered maximum temperatures by 4.4-5.1 °C, while adjacent forest fallows buffered temperatures by up to 9 °C (Saj et al., submitted). Analysis of eight years of microclimate measurements further shows that tree cover consistently reduces daytime temperature, vapour pressure deficit (VPD) and atmospheric water demand compared with monocultures. However, buffering effects on minimum temperatures are much weaker. Consequently, agroforestry effectively mitigates heat and evaporative stress during the day but provides only limited protection against cold events associated with regional "*surazos*" (cold southerly winds that can negatively affect cocoa production) (Saj et al., submitted).

Climate buffering depends not only on the amount of shade but also on canopy composition and structure. Some shade-tree species reduce VPD more effectively than others, demonstrating that canopy architecture and species traits are as important as overall canopy cover (Kohl et al., 2024). Shade management therefore requires a dynamic approach. Opening the canopy through pruning can improve light availability and flowering synchrony, but excessive canopy opening before hot and dry periods can increase water stress and expose cacao trees to sunburn damage. Resilience therefore depends on adaptive rather than maximal shade reduction.

Climate adaptation also operates at the level of cacao physiology. Leaf transpiration increases with temperature, whereas greater canopy cover and lower specific leaf area help limit water loss. In monocultures, cacao leaves tend to develop larger stomata and experience greater water losses, whereas shaded conditions improve water-use efficiency (Saavedra et al., 2020). Vertical stratification further contributes to resilience by combining upper-storey trees that buffer environmental conditions with a sheltered cacao layer operating under lower thermal and hydric stress (Saavedra et al., submitted).

Overall, SysCom results indicate that agroforestry should be viewed as a risk-mitigation strategy rather than a complete adaptation solution. Tree cover can substantially moderate thermal and atmospheric extremes, improve microclimatic conditions and reduce water stress, yet it cannot fully compensate for long-term regional warming or major shifts in climatic regimes. Moreover, several climate-impact studies suggest that climatic suitability for cacao may decline in parts of today's production areas during the coming decades, particularly where increasing temperatures and water deficits exceed the buffering capacity of agroforestry systems (Ariza-Salamanca et al., 2023; Igawa et al., 2022).

Consequently, adaptation strategies should not focus exclusively on increasing tree cover. Maintaining the long-term viability of cacao systems will require combining adaptive shade management with the selection of climate-resilient cacao genotypes, the use of associated tree species capable of performing under warmer and more variable conditions, and, in some regions, the gradual diversification towards alternative crops and systems better suited to future climatic conditions (Ariza-Salamanca et al., 2024). Agroforestry can therefore play a

central role in climate adaptation, but its effectiveness ultimately depends on the capacity of cropping systems to continuously adapt to changing environmental conditions.

Box 6. Microclimate buffering: what agroforestry really changes

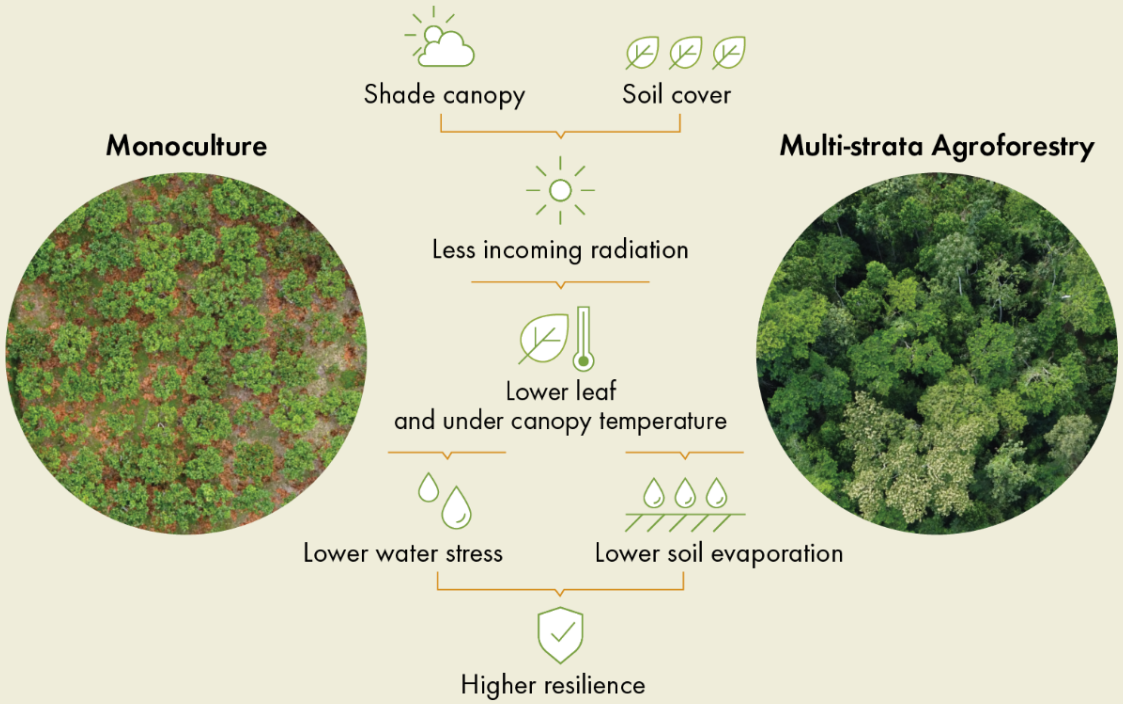


Figure 13. Soil cover and shade canopy helps agroforestry systems to be me resilient to heat stress. Pictures ©: L. Descarpontriez (ECOTOP)

Agroforestry modifies the microclimate experienced by cacao through multiple pathways: By intercepting solar radiation and reducing exposure to wind, shade trees lower air and leaf temperatures, while ground cover helps conserve soil moisture and limits evaporation losses. Together, these processes reduce the atmospheric demand for water and moderate climatic extremes within the plantation. Results from SysCom show that these buffering effects can substantially reduce heat and water stress, particularly during hot and dry periods.

However, the benefits depend not only on the presence of trees but also on how they are arranged and managed. Species choice, vertical stratification, canopy density and pruning regimes determine the balance between light availability, productivity and climate protection. Soil characteristics, particularly texture and effective soil depth, also influence the system's capacity to store and supply water during dry periods. Well-designed agroforestry systems therefore act as a form of biological climate insurance, strengthening the resilience of cacao production under increasingly variable environmental conditions.

The path ahead

The SysCom Bolivia experiment demonstrates that productive, diversified and environmentally sound cacao systems can be maintained over the long-term while addressing multiple agronomic, socioeconomic and environmental objectives. However, translating these findings into large-scale change requires more than agronomic knowledge alone. Farmers, extension services, cooperatives, private companies, consumers and policy makers all contribute to shaping the conditions under which diversified systems can emerge and persist. This final chapter synthesises the broader lessons from SysCom and discusses the opportunities, challenges and priorities associated with the transition towards more diversified and resilient cacao cropping systems

3.4 Rethinking cacao cultivation through a systems lens

After nearly two decades of research, SysCom Bolivia delivers a clear message: the long-term performance of cacao farming depends less on individual practices than on the way cropping systems are designed and managed. Productivity, profitability, environmental sustainability and resilience emerge from interactions among planting material, vegetation structure, ecological processes, labour organisation, market opportunities and farmer decision-making.

This perspective challenges approaches that evaluate cacao systems primarily through cocoa yields. While yield remains an important indicator, it captures only one dimension of system performance. Food production, income diversification, labour requirements, resource-use efficiency, biodiversity conservation and resilience to climatic and economic shocks are equally important in determining the long-term viability of farming households and rural landscapes.

Rather than seeking to maximise a single objective, the SysCom results highlight the importance of managing trade-offs and synergies among multiple objectives. Diversified agroforestry systems generally rely more on ecological processes, adaptive management and farmer knowledge, and less on external inputs, than simplified cropping systems. Their success therefore depends not only on technical innovations, but also on the capacity of farmers and supporting organisations to manage increasing levels of biological and managerial complexity.

Ultimately, the challenge is not to identify a universally optimal production model, but to design systems that appropriately balance productivity, livelihoods, environmental stewardship and resilience according to local conditions and priorities.

3.5 Diversification as a strategy for resilience

One of the most consistent findings emerging from SysCom is the importance of diversification as a strategy for coping with uncertainty. Climatic variability, fluctuating commodity prices, evolving pest and disease pressures, and changing labour conditions all create risks for farming households. Systems that depend heavily on a single crop or market are generally more vulnerable to these shocks than systems that distribute risks across multiple products and functions (Allen et al., 2024; Niether et al., 2020; Tokou et al., 2025).

In SysCom, diversification increased the range of products and services provided by cacao systems. In the trial, agroforestry systems combined cacao with food crops, fruit trees, timber species and service plants. The dynamic agroforestry system produced 22 different crops, creating multiple sources of food, income and ecological functions throughout the lifespan of the plantation. However, diversification should not be confused with maximising species richness. The benefits observed in SysCom emerged less from the number of species present than from the combination of species performing complementary productive, ecological and economic functions. Productive species such as plantain, cassava, pineapple, copoazú or coffee contributed food and income, while species such as Inga and Erythrina supported nutrient cycling, biomass production and shade regulation.



Figure 12. Technicians discussing diversification and agroforestry design during a SysCom agroforestry course. © Barbora Tůmová, FiBL

Diversification also creates flexibility through time. In the dynamic agroforestry system, annual crops contributed during the establishment phase, cacao progressively became the dominant cash crop, and timber and perennial fruit trees represented longer-term investments. Such temporal complementarity reduces dependence on a single production period and increases the range of options available to farmers.

However, diversification does not eliminate trade-offs. More complex systems generally require greater labour inputs, management skills and adaptive decision-making than simplified systems. A high number of crops, for example, may lead to lower production volumes per crop and increase the effort required for harvesting, processing, and marketing. The challenge is therefore not to maximise diversity, but to design systems that balance productivity, livelihoods, environmental stewardship and resilience according to local conditions and priorities (

Figure 12).

As climatic and economic uncertainty continue to intensify, diversification is likely to become an increasingly important strategy for maintaining productive and resilient cacao landscapes. The critical question therefore becomes not whether diversification is desirable, but how farmers can successfully implement and manage diversified systems. This challenge is explored in the following section.

3.6 Enabling the transition towards diversification

Diversified cacao agroforestry systems offer opportunities to improve food security, spread economic risks and strengthen resilience. However, the benefits described in Chapters 2 and 3 are not automatic. Whether farmers can successfully establish and maintain diversified systems depends on access to supportive markets, enabling institutions, technical services and learning opportunities. The transition towards diversified cacao production therefore requires not only changes in farm design and management, but also investments in the broader systems that support farmers (**Figure 13**).



Figure 13. Facilitators and technicians attending to a demonstration of the positive effect of soil cover for water retention and erosion reduction during a SysCom agroforestry course. © Johanna Rüegg, FiBL

Markets, value chains and incentive mechanisms

The economic benefits of diversification are highly sensitive to market conditions for both cacao and companion crops. While cacao generally benefits from relatively well-developed value chains, many agroforestry products face important commercialisation constraints. Weak market access, limited processing opportunities, transportation costs and the absence of reliable buyers can prevent farmers from fully realising the value generated by diversified systems.

Research conducted in Ecuador identified access to stable markets and fair prices for agroforestry products among the highest priorities expressed by farmers and technicians involved in successional agroforestry systems. Similar observations have been reported from

Peru, where commercialisation constraints were identified as major barriers limiting the realisation of agroforestry benefits (Quaedvlieg & Lagneaux, 2026; Rodríguez et al., s. d.).

The SysCom results illustrate the importance of these enabling conditions. Companion crops contributed substantially to total system value, particularly in the more diversified systems, yet these benefits depend on whether products can be consumed, exchanged or marketed. In addition to their commercial value, many companion crops contribute directly to household food supplies, an often overlooked but important outcome of diversification (Hashmiu et al., 2022).

Collective action also plays an important role in enabling diversification. Farmer organisations and cooperatives can facilitate access to planting material, inputs, technical assistance, market information and marketing channels, while also reducing the individual risks associated with innovation. In Bolivia, organic farmers' organisations and cocoa cooperatives have contributed to the promotion of agroforestry practices and greater tree diversity among producers (Jacobi et al., 2014).

Additional support mechanisms, including premium prices for agroforestry-produced cacao, stronger value chains for companion crops, payments for ecosystem services, targeted services for farmers and policies promoting food sovereignty and rural livelihoods, could help create conditions under which diversification translates into tangible benefits for farming households. Successful transitions therefore depend not only on farm-level decisions, but also on the institutions, organisations and markets that shape farmers' opportunities.

Knowledge-intensive agriculture

The agronomic findings presented throughout this synthesis demonstrate that the performance of diversified cacao systems depends strongly on management decisions related to planting material, pruning, canopy regulation, species composition, soil fertility and crop interactions. As system diversity increases, management complexity typically increases as well. Diversified agroforestry systems should therefore be viewed as a form of knowledge-intensive agriculture. Unlike simplified systems that rely more strongly on external inputs, diversified systems require continuous management of species interactions, canopy dynamics, nutrient cycling and production trade-offs.

Successful diversification therefore depends on what could be termed system-management skills: the ability to regulate shade, manage complementarity and competition among species, anticipate the consequences of management interventions, and adapt production strategies to changing environmental and economic conditions. Recent work in Ecuador identified pruning, species selection, shade regulation and understanding ecological succession among the most important competencies required for successful agroforestry management (Rodriguez et al., preprint). More broadly, the results of SysCom suggest that future extension approaches should move beyond the transfer of standardised recommendations and increasingly focus on strengthening farmers' capacity to understand, monitor and manage system dynamics.

Box 7. From research to practice: the SysCom agroforestry curriculum

Building on nearly two decades of research and practical experience, the SysCom partners developed a modular training curriculum to support the transition towards diversified and organic cacao agroforestry systems. The curriculum targets producers, cooperative technicians, extension agents, vocational training centres and organisations promoting agroforestry.

Rather than transferring fixed recommendations, the curriculum relies on participatory methods, field observations, demonstration plots, peer-to-peer exchange, videos, posters and practical exercises to strengthen farmers' capacity to analyse, adapt and manage increasingly complex agroecosystems. A central objective is to foster long-term learning processes and communities of practice among farmers, technicians and organisations.



Figure 14. Cover page and credentials of the manual for trainers

The curriculum is organised around the following themes:

- Introduction to agroforestry systems
- Biodiversity
- Climate and water
- Soil fertility
- Productivity and economic performance
- System design and setting objectives
- Establishment and management of young dynamic agroforestry systems

Together, these modules combine scientific evidence from the SysCom trial with didactical and practical experience of the ECOTOP foundation.

The training materials are freely available for download at: https://systems-comparison.fibl.org/resources/results-bolivia/training-materials.html

The elaboration and testing of the training curriculum were supported by the Leopold Bachmann Foundation.



Figure 15. A range of videos on the experiences of SysCom, its partners and other actors in Alto Beni, Bolivia, complements the training materials. All videos can be found on the Sara Ana YouTube channel: *https://www.youtube.com/@CentroSaraAnaBolivia*

Building communities of practice

The skills required to manage diversified agroforestry systems are rarely acquired through extension messages alone. They emerge through long-term learning processes that combine observation, experimentation, peer exchange and technical support. Networks that serve as a community of practice enable farmers, technicians, researchers, cooperatives, and private-sector actors to exchange experiences, adapt recommendations to local conditions, and collectively respond to new challenges.

Recognising these challenges, SysCom and its partners developed a comprehensive training curriculum that combines scientific evidence from the long-term experiment with practical experience from farmers, extension agents and agroforestry practitioners. Through demonstration plots, participatory learning approaches, peer-to-peer exchange, and repeated training activities, the programme aims to strengthen farmers' capacities for observation, analysis, and adaptive, informed decision-making.

Ultimately, the transition towards diversified cacao systems should be viewed not only as a technical process but also as a social learning process. As climatic and economic uncertainties continue to increase, strengthening knowledge networks, support services and communities of practice may become just as important as improving the cropping systems themselves.

3.7 Research priorities for the coming decades

Despite nearly two decades of research, the SysCom trial has also highlighted important knowledge gaps and new research questions. Many of the challenges facing cacao cropping, particularly those related to climate change, system diversification and scaling agroecological innovations, remain only partially understood. Addressing these questions will be essential for developing cropping systems that remain productive, resilient and attractive for future generations of farmers.

Understanding how diversified systems function

A first priority concerns the ecological processes that underpin the performance of diversified cacao systems. While SysCom has demonstrated the importance of canopy structure, biomass production and species composition, important uncertainties remain regarding the mechanisms through which associated species influence productivity, nutrient cycling, water use and resilience. In particular, belowground processes remain poorly understood. Future research should further investigate root interactions, nutrient acquisition strategies, hydraulic redistribution, and the ways in which different species combinations influence competition and complementarity for resources. A better understanding of these processes would improve the design and management of agroforestry systems and help farmers identify combinations of species that maximise synergies while limiting resource competition.

Fine-tuning agroforestry systems for greater efficiency and resilience

The results from SysCom have shown that the costs and benefits of agroforestry systems depend not only on cocoa yields but also on species selection, market conditions, labour requirements, and the temporal distribution of costs and revenues. The evolution of the trial has further illustrated that agroforestry systems require continuous adaptation to changing environmental and socioeconomic conditions. Future research should focus on identifying agroforestry configurations that maximise complementarities among system components while maintaining manageable labour demands and economic viability. Particular attention should be given to species combinations that improve the distribution of workloads and income throughout the year, enhance resilience to climatic and market shocks, and increase resource-use efficiency. Combining long-term experimental data with on-farm assessments and participatory approaches will be essential to develop agroforestry strategies that are both scientifically sound and adapted to farmers' realities.

Adapting cacao systems to climate change

Climate change represents one of the greatest uncertainties for the future of cacao production. SysCom has shown that agroforestry can substantially reduce heat exposure and atmospheric water demand, but important questions remain regarding the limits of these buffering effects under future climatic conditions. Identifying critical thresholds for temperature, water availability and atmospheric demand, as well as understanding how different cacao genotypes and associated tree species respond to increasing climatic stress, should therefore become a

major research priority. Future work should also investigate whether agroforestry alone will be sufficient to maintain cacao production in increasingly challenging environments or whether more profound transformations of cropping systems may ultimately be required.

Supporting agroecological transitions at scale

The long-term adoption of diversified systems depends on much more than their agronomic performance. Future research should therefore place greater emphasis on the social, economic and institutional dimensions of agroecological transitions. Understanding labour requirements, market opportunities, farmer decision-making processes, value-chain development and policy incentives will be essential for scaling diversified systems beyond experimental sites. Equally important is understanding how knowledge is generated, shared and applied by farmers, cooperatives, extension services and private-sector actors. Today, improving the conditions that enable innovation is as important as improving the cropping systems themselves.

Maintaining long-term observation platforms

One of the most important lessons from SysCom is the value of long-term experimentation. Many key findings, including shifts in productivity, changes in soil functioning, the emergence of new production constraints and the effects of climatic variability, only became visible after many years of observation. Short-term studies would have captured only a fraction of these dynamics. Long-term research and monitoring platforms therefore remain indispensable for understanding how agroecosystems evolve through time and for generating the evidence needed to support adaptation in an increasingly uncertain future.

Conclusion

After nearly two decades of research, SysCom Bolivia provides one of the most comprehensive long-term assessments of cacao cropping systems available in the humid tropics. The results challenge several widespread assumptions about cocoa production while providing practical insights for the development of more resilient farming systems.

A central finding of SysCom is that the long-term performance of cacao systems depends not only on whether they are managed as monocultures or agroforestry systems, nor solely on whether they follow organic or conventional practices. These characteristics matter, but their effects are strongly influenced by how systems are designed and managed. Across the different studies, productivity, economic performance, environmental outcomes and resilience consistently emerged from interactions among planting material, canopy structure, species composition, biomass dynamics and management decisions rather than from any single intervention.

The results further demonstrate that productivity, livelihoods and environmental sustainability are not necessarily opposing objectives. While diversified agroforestry systems generally produced lower cocoa yields than monocultures, they simultaneously generated additional food, marketable products, biodiversity, carbon storage, climate-buffering functions and ecosystem services. Consequently, evaluating cropping systems through cocoa yields alone provides only a partial understanding of their overall performance and contribution to rural livelihoods.

SysCom also highlights the importance of diversification as a strategy for increasing flexibility and reducing vulnerability. By combining species with complementary productive, ecological and economic functions, diversified systems distribute risks across products, ecological processes and time horizons. However, diversification is not a universal solution. Its benefits depend strongly on system design, species selection, canopy management, access to knowledge and farmers' capacity to continuously adapt management to changing conditions.

Ultimately, the central lesson of SysCom is that resilient cacao farms are not built around a single crop, technology, certification scheme or management practice. They are built around well-designed cropping systems capable of balancing productivity, livelihoods, environmental stewardship and adaptation over the long term. The future of cocoa production may therefore depend less on choosing between cropping models and more on improving our ability to design, manage and continuously adapt agroecosystems to changing environmental, economic and social conditions.

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