Chapter 3
Cocoa in Monoculture and Dynamic Agroforestry

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Abstract The growing demand for cocoa beans and products worldwide has been met by expanding the area under cocoa production while productivity per hectare has stagnated at a low level of around 450 kg/ha per year in the last decade. Throughout the tropics cocoa has increasingly been cultivated in full-sun monocultures in order to maximize short-term productivity and profitability, which has been associated with soil erosion and degradation, biodiversity loss, as well as increased susceptibility to climate change impacts and pests and diseases. Dynamic agroforestry systems are an alternative production method which has long been practiced in Latin American countries such as Bolivia. Through mimicking natural forests, these systems offer multiple benefits such as soil fertility enhancement, reduction in pest and disease pressure, erosion control, and revenue diversification. In Côte d'Ivoire, where most cocoa is still produced in monocultures, dynamic agroforestry systems were recently introduced on a small scale.

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Here we use different research projects conducted in Bolivia and Côte d'Ivoire as case studies to review productivity, soil fertility as well as pests and diseases in dynamic agroforestry systems and monocultures, and outline factors influencing the adoption of dynamic agroforestry systems from the farmers' perspective. We found productivity under agroforestry systems to be either similar or higher compared to monocultures. We recorded 161 % higher total system yields in an on-station field trial and an on-farm study in Bolivia, and in an on-farm study in Côte d'Ivoire. Cocoa yields were 12–46 % higher in agroforestry systems compared to monocultures. In addition, cocoa in dynamic agroforestry systems exhibited significantly less incidences of witches' broom, *Moniliophthora perniciosa*, compared to monocultures in Bolivia.

Farmers in Bolivia and Côte d'Ivoire observed more soil-related problems and incidences of pests and diseases in monocultures than in agroforestry systems, and they showed high interest to learn dynamic agroforestry management practices. However, adoption was strongly limited to project areas where dynamic agroforestry plots had been installed with farmers' participation. This highlights the importance of local organizations such as Ecotop, Ecosaf, El Ceibo and Biopartenaire Ltd., who implement such interventions on the ground. However, we found that there is space for improvement in the way organizations interact with farmers, especially in Côte d'Ivoire. Interactive knowledge sharing methods such as farmer field schools may help to stimulate farmers' protagonism and give scientists and external consultants the role of facilitators who integrate different forms of knowledge and make them visible to different stakeholders. Such a social learning process requires transdisciplinary research for the development of decision support tools which facilitate the determination of both optimal planting densities and shade levels, as well as adequate combinations of trees and accompanying species in order to achieve effective regulation of pests and diseases while ensuring favourable growing conditions.

Keywords Cocoa • Bolivia • Côte d'Ivoire • Dynamic agroforestry systems • Pests and diseases • Resilience • Participatory on-farm research • Transdisciplinary research

3.1 Introduction

3.1.1 Cocoa: Origin, Productivity, and Different Production Systems

The world produced 4.5 million tonnes of cocoa (*Theobroma cacao*) beans in 2013. Two-thirds were produced in Africa, especially in West African countries such as Côte d'Ivoire, Ghana, Nigeria, and Cameroon. The Americas and Asia each produced about one-sixth. The world's biggest producer country by far is Côte d'Ivoire:

it produced some 1.5 million tonnes, or one-third of the world's production. However, many countries only produce a small amount: Bolivia, for instance, only produced some 5,000 tonnes or 0.3 % of Côte d'Ivoire's production in 2013 (FAOSTAT 2015).

Not only the scale of production but also the methods differ vastly between Côte d'Ivoire and Bolivia. Cocoa originates from the lower strata of the Amazonian forests, and was traditionally grown beneath shade tree canopies of primary or secondary forest (Purseglove 1968; Rice and Greenberg 2000; Wood and Lass 2001). Today, growing cocoa in full-sun monocultures is widespread throughout the tropics, despite numerous problems associated with these systems (Tscharntke et al. 2011). In Côte d'Ivoire, most farmers produce cocoa in monocultures, while in Bolivia, shaded agroforestry systems are common. Cocoa production in monocultures often focuses on the use of agrochemicals and improved genetic material specifically developed and optimized for these systems. By contrast, in agroforestry systems producers often aim at substituting external inputs by the use of systems-inherent resources, e.g. nutrient cycling through pruning of shade trees (Vaast and Somarriba 2014).

Growing worldwide demand for cocoa beans and products has been met by expanding the area under cocoa production by almost 3 % in the last decade (data 2003–2013). In the same period, productivity per ha declined by 0.6 %, stagnating at a low level of around 450 kg ha^{-1} per year (FAOSTAT 2015). Smallholders produce almost 90 % of the world's cocoa (ICCO 2012) but will be unable to meet the rise in demand without suitable technical and land-tenure-related innovations (Vaast and Somarriba 2014). Hence, pressure to intensify cocoa production is likely to increase in the near future, which may lead to more monocultures being installed in currently forested areas (Schroth and Harvey 2007). In the following, we review results from three studies on cocoa in agroforestry and monocultures in Bolivia and Cote D'Ivoire. We justify the choice of these two contrasting countries by the differences and similarities in the main features of cocoa production outlined in Table 3.1, as well as by the different parameters discussed in detail in the following two subchapters. In addition, Bolivia is interesting because of its long-term experience with dynamic agroforestry systems, and Cote D'Ivoire because of the significant challenges in monocultures as well as a new dynamic agroforestry systems movement initiated by South-South cooperation between the two countries.

3.1.2 Cocoa Production in Bolivia

Most of Bolivia's cocoa supply comes from the Alto Beni region in the eastern foothills of the Andes. Since colonization by Franciscan monks in the eighteenth century, a wide range of cocoa landraces were probably traditionally collected and cultivated along with introduced varieties. In the last decades, cocoa has been promoted as an alternative to the production of coca (*Erythroxylum* spp.) in Alto Beni and other parts of Bolivia, e.g. the Pilon Lajas Biosphere Reserve or the Chapare

Table 3.1 Comparison of main features of cocoa production in Bolivia and Côte d'Ivoire

Country	Total cocoa production in 2013 [t][a]	Total area cultivated with cocoa in 2013 [ha][a]	Productivity in 2013 [kg ha^{-1}][a]	No. of cocoa producing families[b, c]	Average size of cocoa farms [ha][b, c]	Main pests and diseases
Bolivia	4,950	8,856	559	8,420	12–15 (cocoa plots < 5), plus wild cocoa collection areas	Cocoa mirid (*Monalonion dissimulatum*), witches' broom (*Moniliophthora perniciosa*), black pod rot (*Phytophthora* spp.), frosty pod rot (*Moniliophthora roreri*)
Côte d'Ivoire	1,448,992	2,500,000	580	700,000	2–5	Cocoa mirids (*Sahlbergella singularis*, *Distantiella theobroma*) black pod rot (*Phytophthora* spp.), Cocoa Swollen Shoot Virus Disease (CSSVD)

Sources: [a]FAOSTAT (2015). Available: http://faostat.fao.org/
[b]Bazoberry and Salazar (2008)
[c]Smith Dumont et al. (2014), and own research

region. With markets for speciality cocoa developing, there is now an increase in the collection of cocoa from landraces in more remote areas of the Beni and Pando departments (PNUD 2008).

Cocoa productivity per hectare in Bolivia lies below 600 kg ha^{-1} per year (FAOSTAT 2015). In Alto Beni, the farmers' organization El Ceibo and local consultancy Ecotop have played a pioneering role in promoting the production of cocoa under certified organic agroforestry systems since the 1980s. Founded in 1977, El Ceibo was the first organization worldwide to market certified organic cocoa beans according to USDA and EU requirements. El Ceibo's foundation "Programme of Implementation of Agroecological and Forestry initiatives; PIAF-El Ceibo" (PIAF) provides extension and organizes the internal control system needed for organic certification, while El Ceibo carries out the processing and trade at the national and international levels. Today, agroforestry systems are among the common cocoa production systems in the region, and farmers associated with El Ceibo receive a 42 %

higher price for their cocoa than others in the region, partly due to organic and Fair Trade premiums (Jacobi et al. 2015).

Cocoa in Bolivia is cultivated on the margins of the highly diverse sub-humid rainforests in the foothills of the Andes. Plots are usually clear-cut to install a cocoa plantation, and the shade trees are either planted or result from natural regeneration. Bolivian cocoa farmers use among many others the popular agroforestry shade trees *Gliricidia* spp., *Erythrina* spp., and *Inga* spp., which double up as hedgerows or fodder trees for livestock, or are used in the preparation of natural remedies. A study on tree diversity found 105 tree species from 38 families on cocoa agroforestry plantations in Alto Beni (Jacobi et al. 2014). The most frequent tree species were *Leucaena leucocephala*, an N-fixing species, *Amburana cearensis*, a high-value timber species, *Attalea phalerata*, a native palm tree of which all parts have a traditional use from construction materials to natural remedies, *Inga* spp., an N-fixing fruit tree, and *Swietenia macrophylla*, a high-value timber tree. Farmers mentioned the main advantages of agroforestry systems to be income from timber, better water balance and soil quality, and the positive effect of shade on cocoa trees and working conditions (Jacobi et al. 2014).

The worldwide trend of intensifying production through simplifying cocoa production systems (Vaast and Somarriba 2014; Tscharntke et al. 2011) is also observable in Bolivia. Today, 40–50 % of the cocoa plantations are monocultures (El Ceibo, personal communication). However, young cocoa trees are usually associated with bananas or plantains (*Musa* spp.) for temporal shade during the first years of the establishment of a cocoa plantation, but are later eliminated. The resulting full-sun systems are sometimes framed by fruit trees. Previous research indicated that Bolivian farmers who were not associated with a local farmers' organization, and who regarded cocoa as a short- to medium-term investment rather than a long-term livelihood strategy, cultivated cocoa in monocultures more often (Jacobi et al. 2013).

Climate change will affect Bolivia more serverely in the near future than it already does (World Bank 2009; Mc Dowell and Hess 2012; Seiler et al. 2013). A study on agroecosystem resilience of cocoa farms found that local farmers described the plantations of Alto Beni as highly susceptible to climate change and mentioned heat waves, droughts, floods, and disease outbreaks related to climatic variability as the main problems (Jacobi et al. 2013).

The main pests and diseases affecting cocoa production in Bolivia are the cocoa mirid (*Monalonion dissimulatum*), witches' broom (*Moniliophthora perniciosa*), and black pod rot (*Phytophthora palmivora*) (July 2008). Witches' broom has arguably been the biggest problem with reported yield losses of up to 100 % (Milz 2006). In recent years, the devastating fungal disease frosty pod rot (*Moniliophthora roreri*) appeared for the first time in Bolivia, severely affecting cocoa production in Alto Beni, also with yield losses of up to 100 % and many farming families abandoning cocoa production (El Ceibo, personal communication).

3.1.3 Cocoa Production in Côte d'Ivoire

Cocoa is the dominant crop in the economy of Côte d'Ivoire, accounting for 15 % of the country's GDP and representing 38 % of exports (Kouamé 2010; DBR 2014; CCC 2015). Small-scale farmers with an average farm size between 2 and 5 ha produce 95 % of Côte d'Ivoire's cocoa (Kouamé 2010), and the cocoa sector employs a total of more than four million of the country's 22 million inhabitants (Hatloy et al. 2012).

Historical large-scale expansion of cocoa production in Côte d'Ivoire started after World War I. At this time, cocoa was cultivated under primary forest trees, and later under naturally regrown forests (N'Goran 1998). Most cocoa farmers did not cut down the biggest forest trees, or at least not all of them. The undergrowth was cut and burnt, while some of the largest trees were maintained to form the upper canopy of cocoa agroforests. In the 1960s, the government started promoting intensive full-sun production systems in order to maximize short-term yields (Ruf and Schroth 2004; Asare 2005; Koko et al. 2013; N'Goran 1998). The programmes encouraged complete forest clearance (Ruf and Zadi 1998), advising farmers to remove native forest trees from their plots for a number of antagonistic reasons such as pest and disease relationships, allellopatic behaviour, or low shade quality because of their dense or low canopy (Smith Dumont et al. 2014; FIRCA 2008).

Cocoa production in Côte d'Ivoire expanded from East to West, with the Eastern and Central regions under traditional management with trees, while the Western region was planted more recently with monocultures or low shade systems (Asare 2005). During plantation establishment, temporal shade for young cocoa trees is usually provided by crops such as plantains (*Musa × paradisiaca*) or yams (*Dioscorea* spp.) which are later eliminated, leading gradually to a full-sun system (Petithuguenin 1998).

Even though much of Côte d'Ivoire's cocoa is grown in monocultures, input use and productivity remain low. Over a decade ago, Ruf (2001) already predicted an expected yield decrease in the near future. Today, low yields of 269–560 kg ha^{-1} per year which are further declining challenge Côte d'Ivoire's entire cocoa value chain, as most plantations are monoculture systems with low soil fertility and high pest and disease pressures (Ruf 2011; Tscharntke et al. 2011; Assiri et al. 2009; Gyau et al. 2014). According to Ruf and Zadi (1998), two to three generations of full-sun cocoa production caused considerably more environmental damage than shaded cocoa farming would have. Milz (2012) described the current challenges in cocoa production in Côte d'Ivoire as a function of full-sun production systems, pests and diseases, and a lack of management. In addition, farming families are challenged by increasing food insecurity due to yield declines of food crops such as yams, manioc, corn, peanuts which compete for land with cocoa and other perennial and annual cash crops (Smith Dumont et al. 2014).

Main pests and diseases affecting Ivorian cocoa are cocoa mirids (*Sahlbergella singularis*, *Distantiella theobroma*) and black pod rot (*Phytophthora* spp.), causing yield losses estimated at 15–30 % and 10–15 %, respectively (Petithuguenin 1998).

In addition, a disease eradicated at the end of the 1950s – Cocoa Swollen Shoot Virus Disease (CSSVD) – was rediscovered in 2003 in the Central-West region of Côte d'Ivoire (N'Guessan et al. 2013). CSSVD is now one of the major limitations to cocoa productivity in West Africa. In Ghana, for instance, a government eradication programme has cut down more than 200 million infected cocoa trees (Dzahini-Obiatey et al. 2010).

Although full-sun or low-shade smallholder production is dominant, shaded cocoa farms still exist in Côte d'Ivoire (Daniels 2006). The shade trees on Ivorian farms are either native, i.e. naturally regenerated and therefore randomly distributed, or planted. Farmers also use their trees for firewood such as *Cola nitida, Funtumia africana, Mangifera indica, Musanga cecropioides*; food in terms of fruits, leaves, flowers, palm wine among others e.g. *Persea americana, Citrus reticulate, Spondias mombin, Elaeis guineensis*; timber for local construction, e.g. *Funtumia africana, Cola cordifolia, Celtis mildbraedii*; and for the preparation of natural remedies, e.g. *Cola nitida, Alstonia congensis, Spathodea campanulata* (Smith Dumont et al. 2014; Gyau et al. 2014; Herzog 1994). Smith Dumont et al. (2014) showed that farmers favour the integration of trees in their production systems, as they believe that shade trees (i) protect the cocoa trees from heat stress during the dry season, (ii) enhance soil fertility, and (iii) control soil erosion.

In 2010 the Ivorian government started supporting the establishment of cocoa agroforestry through the reintroduction of shade trees (Gyau et al. 2014), which was reinforeced by launching a new law which transferred tree rights from the state to individual farmers or village collectives (MEF 2014). Research and development initiatives as well as various certification schemes have recently begun to encourage the planting of trees. They advise planting native trees to improve the provision of ecosystem services (TCC 2010; Matissek et al. 2012). The Ivorian national extension service (ANADER) has also started to promote agroforestry in cooperation with certification bodies. In both countries, total cocoa production increased between 1993 and 2013. In Côte d'Ivoire it increased by 79 %, from 800,000 tonnes to 1.5 million tonnes. In Bolivia it increased by 33 %, from 3,710 tonnes to 4,950 tonnes. However, this was achieved by expanding the area under production by +5 % in Côte d'Ivoire, and by +157 % in Bolivia, while productivity per hectare remained below 600 kg ha^{-1} per year in both countries (FAOSTAT 2015). Farmers in both countries mention erratic rainfall distribution as one of the main problems of cocoa production (Milz 2012; Jacobi et al. 2013). The use of agrochemicals is more common in Côte d'Ivoire than in Bolivia.

3.1.4 Agroforestry Systems: An Alternative?

In agroforestry systems, farmers can produce timber, fruits, fodder, firewood, construction material, ornamentals, and plants used in medicine and rituals along with cocoa and other marketable food crops (Cerda et al. 2014; Jagoret et al. 2014; Somarriba et al. 2014; Sonwa et al. 2014). These systems can therefore make an

Table 3.2 Benefits provided by cocoa agroforestry systems reported in the literature

Benefit	Study
Improved pollination	De Beenhouwer et al. (2013)
Long-term stable cocoa yields	Rice and Greenberg (2000); Obiri et al. (2007); Bisseleua et al. (2013)
Longer lifespan of cocoa plantations	Obiri et al. (2007); Ruf and Zadi (1998)
Control of pests and diseases, erosion control	Tscharntke et al. (2011); Smith Dumont et al. (2014); Bieng et al. (2013); Gidoin et al. (2014); Sperber et al. (2004); Lin (2011)
Biodiversity conservation and enhancement	Rice and Greenberg (2000); Clough et al. (2009b); Fonte and Six (2010); Sonwa et al. (2007)
Climate change mitigation through C sequestration	Schroth et al. (2013); Somarriba et al. (2013); Somarriba et al. (2014); Jacobi et al. (2014); Fonte et al. (2010b); Verchot et al. (2007); Saj et al. (2013); Clough et al. (2010)
Nutrient cycling	Buresh et al. (2004); Gama-Rodrigues (2011)
Soil fertility maintenance or enhancement	Fonte et al. (2010a); Isaac et al. (2007); Tscharntke et al. (2011); Mbow et al. (2014)
Watershed protection	Garrity (2004)
Reduction of deforestation	Asare (2006); Clough et al. (2011); Tscharntke et al. (2012)

important contribution to the livelihoods and food security of smallholders by decreasing their vulnerability towards changing external factors such as food price fluctuations on global markets or pest and disease outbreaks (Tscharntke et al. 2011; Duguma et al. 2001; Bentley et al. 2004; Cerda et al. 2014; Schroth et al. 2000; Bos et al. 2007; Rice and Greenberg 2000; Sonwa et al. 2007). In addition, agroforestry systems provide multiple benefits and contribute to a wide array of ecosystem services as outlined in Table 3.2.

While there is ample evidence for the high ecological and social potential of agroforestry systems (Clough et al. 2009a; Tscharntke et al. 2011; Jacobi et al. 2014), recent literature suggests that under current market conditions they are often not economically viable in the short term compared to monocultures (Vaast and Somarriba 2014). Consequently, the improvement of market conditions for agroforestry systems is a key factor for their implementation at a larger scale. Furthermore, it is necessary to understand the dynamics of economic benefits at farm level in agroforestry systems and monocultures (Schneider et al. under review).

3.1.5 Dynamic Agroforestry: Principles and Examples

"Dynamic", "successional" and "analog" agroforestry systems are cross-cutting concepts based on principles of plant density and diversity (Analog Forestry Network RIFA 2012; Schulz 2011; Milz 2012). Dynamic agroforestry systems are based on the understanding of the succession and structure of natural ecosystems. The main features of dynamic agroforestry systems are (i) high planting densities

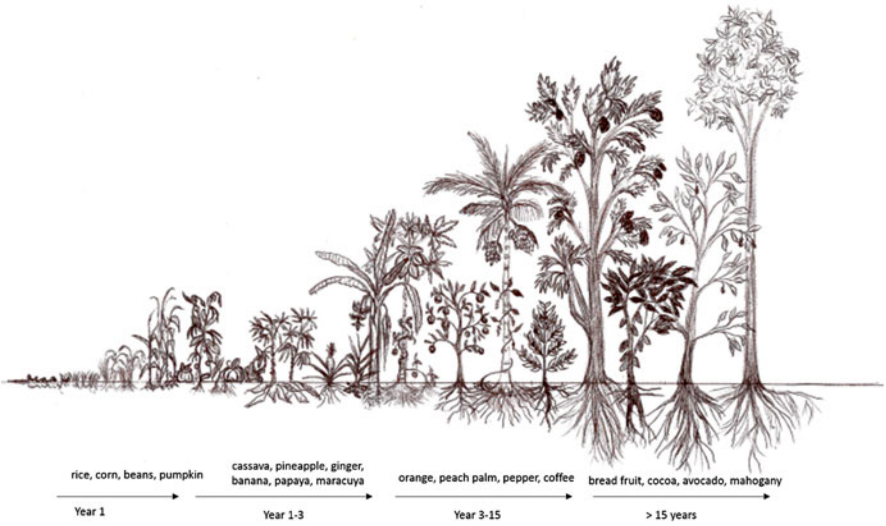

Fig. 3.1 Example of crops in a dynamic agroforestry system in the humid tropics of Bolivia. Note: In the majority of cases, all species are planted/sown at the same time, and also non-crop species are integrated e.g. to accumulate biomass (Source: figure based on own research)

and diversity, stratification, and a high energy flow usually without the use of external inputs; (ii) management practices such as different types of pruning interventions, e.g. rehabilitation, formative, maintenance pruning, selective weeding or grafting, and selection of healthy, productive planting material.

Like in natural species sucession, crops are grouped according to their lifespan into pioneer, secondary, and primary species. All the species are planted or sown at the same time, leading to a "crop succession" (Fig. 3.1) enriched by the regeneration of native plants (Götsch 1994). Pioneer species include rice, cassava, or pigeon peas. These are subsequently replaced until the system is characterized by secondary species such as pineapple, papaya, and banana, as well as slower growing secondary and primary tree species which simultaneously develop in their shade. The cocoa tree is a primary species with a potential life span of more than 100 years (Wood and Lass 2001). After about 10–15 years, the secondary species dominate the system, and are eventually replaced by the primary species. Plants which have completed their life cycle are either harvested or cut down, chopped up, and left to decompose in the plots to help maintain soil fertility.

The higher, emergent to canopy strata of the system may be occupied by rubber and timber trees, the middle, low canopy to understory strata by fruit trees including oil palm, and the lower, understory to forest floor strata, by cocoa trees. This stratification and the planting of tree species with complementary root systems aims at minimizing the competition for light, water, and nutrients, by assuring that different ecological niches are occupied (Götsch 1994). This way, synergies between the subsequent successional phases are enhanced, and each successional phase creates the necessary conditions for the plant species of the next successional phase.

In a dynamic agroforestry system, every plant is potentially useful. Ernst Götsch (1994) described for the Brazilian context how invasive pioneer plants can be highly beneficial for the system, as they may play a vital role in enhancing soil fertility. Götsch (1994) observed more vigorous plant growth and higher productivity when crops were introduced during an adequate successional phase of the overall system. The author further described how secondary species developed well under pioneer species, but not vice versa, and concluded that productivity depends on sucessional dynamics of the system which can be stimulated by pruning (Götsch 1994). Schulz et al. (1994) described that dynamic agroforestry farmers oberved a kind of allelopathic effect of maturing plants, reducing the growth of their neighbouring plants at the end of their life cycle, and a growth stimulating effect of young plants, increasing the vegetative growth of their neighbouring plants.

A major advantage of dynamic agroforestry systems is that the high crop diversity allows for harvests and income already during the first year of plantation establishment. This allows dynamic agroforestry farmers to avoid the "hunger gap" that occurs in cocoa monocultures, which only start to produce after 4–6 years. The continuous addition of organic material from pruning maintains soil fertility, and the complexity of the system may lead to a natural self-regulation of pests and diseases.

The few empirical studies on dynamic agroforestry systems conducted to date compared dynamic agroforestry plots to monocultures in Bolivia, and showed higher productivity and soil fertility in dynamic agroforestry systems. Todt et al. (2010, 2009) found significantly higher nutrient concentrations, thicker Ah horizons, and higher organic matter content in dynamic agroforestry systems which were cultivated for more than 20 years. Milz (2010) studied the damage of fruit flies (*Anastrepha* spp. and *Ceratitis captitata)* in citrus trees. He found more than double the amount of aborted fruits due to fruit fly damage in monocultures than in dynamic agroforestry systems. Productivity per orange tree was significantly higher in dynamic agroforestry systems and the sugar content of the fruit was not significantly different beween the two systems (Milz 2010). Gruberg (2011) assessed pests, diseases, and productivity in dynamic agroforestry vs. low-diversity cocoa and citrus systems, and found less incidence of witches' broom and black pot rot, similar cocoa productivity, and a multitude of different products in dynamic agroforestry systems. Schulz (2011) and Vieira et al. (2009)) described how heavily degraded castor bean (*Ricinus communis*) monocultures were successfully restored with dynamic agroforestry systems in Bahia, Brazil. In one study, castor bean production increased by 90 %, and total productivity increased fourfold after the implementation of dynamic agroforestry systems (Schulz 2011).

In Bolivia, Ecotop has facilitated the establishment of 100–150 ha of dynamic agroforestry systems, mainly in the Alto Beni region, and the organization "Shared space of agroforestry systems" (Ecosaf) has established around 50 ha in semi-arid Interandean valleys. With the goal of supporting farmers to increase cocoa productivity, adapt to climatic constraints and pest pressure, and address the challenge of food security, Biopartenaire Ltd., a fully owned subsidiary of the Barry Callebaut Group, and Ecotop introduced the concept of dynamic agroforestry to Côte d'Ivoire in 2012 with financial support from the Sustainable Trade Initiative (IDH, http://www.idhsustainabletrade.com/) and Barry Callebaut. To date Biopartenaire Ltd. has trained more than 1,000 farmers.

3.2 Selected Case Studies

3.2.1 On-Station Comparison of Agroforestry versus Full-Sun Systems under Organic and Conventional Management in Bolivia

The studies published to date on the long-term agronomic and socio-economic effects of different cocoa production systems have mostly focused on existing cocoa production systems in farmers' fields throughout the tropics (Beer et al. 1998; Belsky and Siebert 2003; Aneani et al. 2011; Clough et al. 2011; Jagoret et al. 2011; Ruf 2011; Jacobi et al. 2013, 2014; Somarriba et al. 2013; Dawoe et al. 2014). Due to the limited data from controlled on-station trials, the Swiss-based Research Institute of Organic Agriculture (FiBL) has set up a long-term on-station experiment in Alto Beni, Bolivia. Alto Beni is a settlement region at the border of the departments of La Paz, Beni, and Cochabamba, in the north-eastern foothills of the Bolivian Andes (Jacobi et al. 2013). The region derives its name from the river Beni, which is part of the Amazon watershed, and lies between 350 and 1,500 m above sea level. Average annual rainfall is 1,440 mm. Temperatures range from 22.4 °C to 26.8 °C with a yearly average of 25.2 °C. The project is part of a larger programme called "Farming Systems Comparison in the Tropics" (www.systems-comparison.fibl.org), and conducts further on-station and on-farm trials in Kenya and India (Forster et al. 2013).

The five different cocoa production systems under comparison include two monocultures and two agroforestry systems, one under conventional and one under certified organic management, as well as a dynamic agroforestry with zero external input under certified organic management. The experiment is set up as a full-factorial, randomized complete block design with four replications, i.e. a pairwise comparison of agroforestry under conventional and under certified organic management, and monoculture under conventional and under certified organic management. The factors tested are: (i) crop diversity in monocultures vs. agroforestry; (ii) management practice, i.e. conventional vs. certified organic; and (iii) cultivar with 12 different cocoa cultivars/hybrids. The combination of the factors "crop diversity" and "management practice" make up the system effect. Figure 3.2 shows example plots of a conventional monoculture and a dynamic agroforestry system 4 years after cocoa tree planting in the long-term on-station field trial in Bolivia.

In this chapter, we present the first 3 years of cocoa harvest (2011–2013), as well as yields of non-cocoa crops, i.e. the by-crops between the start of the experiment 2009 and 2013. We hypothesize that in agroforestry systems, the yields of by-crops

Fig. 3.2 *Left panel*: young cocoa monoculture in Bolivia. *Right panel*: young dynamic cocoa agroforestry system after shade tree pruning in Bolivia. Pictures of both plots were taken 4 years after cocoa tree planting (Source: own research)

lead to higher total system yields as the sum of all marketable goods compared to monocultures. We assessed total system yields by adding up the yields of all the products harvested during the establishment phase from 2009 to 2013, expressed in kg dry matter per ha. These products included cocoa harvested in all systems from 2011 to 2013, plantain harvested in all systems from 2009 to 2011, banana harvested in conventional, certified organic, and dynamic agroforestry systems from 2012 to 2013, maize (*Zea mays*), rice (*Oryza sativa*), pigeon pea (*Cajanus cajan*), achiote (*Bixa orellana*), cassava (*Manihot esculenta*), hibiscus (*Hibiscus sabdariffa*), pineapple (*Ananas comosus*), tannia (*Xanthosoma sagittifolium*), ginger (*Zingiber officinale*), and turmeric (*Curcuma longa*) harvested in dynamic agroforestry systems from 2009 to 2013 (Schneider et al. under review).

Results showed significantly higher cocoa dry bean yields in the conventional monoculture (+153 %), and significantly lower yields in the dynamic agroforestry system (−70 %) compared to all the other systems in 2013, the third year of harvest. Yields in 2013 ranged between around 600 kg ha^{-1} per year in the conventional monoculture and 100 kg ha^{-1} per year in the dynamic agroforestry system. Furthermore, we recorded significantly higher total system yields in all three agroforestry systems compared to the two monocultures (by +161 % and +81 % in the two agroforestry systems and dynamic agroforestry, respectively). The main explanations of these results are the substantial amounts of bananas harvested in the agroforestry systems in 2012 and 2013, and the considerable amounts of fruits and tubers harvested between 2009 and 2013 in the dynamic agroforestry system. It has to be noted that banana trees were removed from the two monocultures at the end of 2011 in order to achieve the targeted full-sun system. Even though the monocultures had achieved both the highest cocoa dry bean yields and highest plantain yields between 2009 and 2011, total system yields of the monocultures could not reach the level of the three agroforestry systems (Schneider et al. under review). Looking at these results from the farmers' point of view, it is not only about producing more; it also matters how many different products you produce, in which quantity and, perhaps most importantly, if there is a market for the produce. As there is a lack of evidence about the economic viability of different cocoa production systems, we are currently assessing the systems in our trial in this respect.

3.2.2 On-Farm Comparison of Different Cocoa Production Systems in Bolivia

We assessed dynamic and simple agroforestry systems, as well as full-sun monocultures in Alto Beni by (i) sampling plots of a quarter hectare in size, on a total of 12 farms with four farms per system, (ii) counting the pods and assessing incidences of cocoa mirid, witches' broom, and black pod rot on the ten central cocoa trees of each plot, (iii) categorizing incidences of pests and diseases using the following index: 0 = no visible incidence, 1 = one incidence per tree or pod, 2 = two to ten incidences per tree, and 3 = more than ten incidences per tree, and (iv) comparing the means of each system using Wilcoxon and Kruskal-Wallis rank sum tests with the statistical software R, Version 3.1.2 (R_Core_Team 2014).

We obtained qualitative information on the farmers' rationales behind their respective production system, and identified the major constraints of cocoa farmers in three focus group discussions with about ten farmers each in different parts of the study area. Then, we conducted semi-structured interviews with the owners of the 12 sampling plots, and three additional monoculture cocoa farmers (Jacobi et al. 2013), from which we also obtained information on cocoa yields. Furthermore, we elaborated possible strategies to address the major constraints of cocoa production in a participatory workshop with 30 regional cocoa farmers, and assessed strategies and constraints of sustainable cocoa production through five interviews with local agricultural consultants. As frosty pod rot disease had spread considerably since we gathered our data (2010–2012), we conducted an additional interview on the impacts of this disease with an agricultural consultant of El Ceibo in February 2015 (referred to as: "El Ceibo, personal communication").

3.2.2.1 Cocoa Productivity and Incidences of Pests and Diseases in On-Farm Systems in Bolivia

According to cocoa farmers in Alto Beni, incidences of pests and diseases are more intense and frequent in monocultures than in agroforestry systems (Jacobi et al. 2013). However, with the appearance of frosty pod rot many producers appear to be cutting down shade trees in order to avoid high relative air humidity in their systems, which is believed to increase incidences of the disease (El Ceibo, personal communication). The effect of this adaptation strategy on incidences of frosty pod rot remains to be investigated. Table 3.3 shows the numbers of cocoa pods and the incidences of mirids, witches' broom, and black pod rot on cocoa trees in the different production systems assessed.

Table 3.3 Pod count and incidences of cocoa pests and diseases on 12 cocoa farms in Bolivia

	Pods >5 cm	SEM	Mirids	SEM	Witches' broom	SEM	Black pod rot	SEM
Mean dynamic agroforestry	12.8[a]	1.31	0.58[a]	0.17	0.50[a]	0.10	0.43[a]	0.12
Mean agroforestry	15.5[a]	2.53	0.40[a]	0.13	1.32[b]	0.14	0.30[a]	0.09
Mean monoculture	20.1[a]	3.43	1.00[b]	0.16	2.58[c]	0.10	0.65[a]	0.15

SEM standard error of the mean, agroforestry = "simple" agroforestry system, for a description see Jacobi et al. (2013). No significant difference for numbers sharing the same letter indicates results from Wilcoxon and Kruskal-Wallis rank sum tests

There were more pods >5 cm in monocultures, but the difference was not statistically significant due to a high variability of the data within the groups. The information on cocoa yield from interviews with cocoa farmers showed mean annual yields in dynamic agroforestry systems, simple agroforestry systems, and monocultures of 510, 423, and 350 kg dry beans per ha, respectively (Jacobi et al. 2013). These findings together with the data shown in Table 3.3 indicate that cocoa trees in monocultures developed more pods, but also showed more incidences of pests and diseases which led to a high loss of pods before harvest.

We found more mirids in monocultures than in the agroforestry systems. The difference was greatest for incidences of witches' broom, which increased significantly from dynamic agroforestry to simple agroforestry and from simple agroforestry to monocultures. The fact that witches' broom is among the main cocoa diseases in Alto Beni (Milz 2006) highlights the considerable implications of dynamic agroforestry from our results. As frosty pod rot has only recently begun to spread in Bolivia, no empirical data on its incidence in full-sun and agroforestry systems are available to our knowledge. However, two research studies from Costa Rica found less pressure from frosty pod rot under higher and more complex shade in terms of diversity and spatial distribution of trees in cocoa plantations (Bieng et al. 2013; Gidoin et al. 2014).

Pruning is a crucial management intervention influencing the regulation of pests and diseases in cocoa production systems (Franzen and Mulder 2007). Unfortunately, many cocoa farmers, lacking the equipment and workforce, face difficulties in pruning their cocoa trees. This is why, to regulate humidity in their systems, they often prefer to eliminate shade trees (El Ceibo, personal communication) rather than adequately space or prune them (Schroth et al. 2000). Another reported strategy is the use of different planting materials such as the CCN-51 variety from Ecuador, which is more tolerant to both full-sun conditions and frosty pod rot than other varieties in Alto Beni. Planting CCN-51 is an example of an adaptation strategy which could further favour the shift from agroforestry to monocultures in Alto Beni and other cocoa production areas.

3.2.2.2 Factors Influencing Adoption of Dynamic Agroforestry in Bolivia

The disadvantages of cocoa agroforestry systems in Bolivia are the lack of necessary labour, equipment, technical support, and capacity building to maintain the systems. Elderly farmers face additional difficulties in pruning their shade trees, which is why many cocoa farmers only prune their systems when cocoa prices are high or expected to increase (El Ceibo, personal communication). This is a common strategy for coping with cocoa price volatility (Tscharntke et al. 2011), but works best in agroforestry systems, as monocultures without management face greater ecological pressure (Vaast and Somarriba 2014).

The advantages and disadvantages of dynamic agroforestry systems mentioned by cocoa farmers during our workshops are listed in Table 3.5. All of them said shade trees are crucial to reducing both ecological and economic risks, and to adapting to climate change (Jacobi et al. 2013). Adaptation strategies mentioned were (i) increasing soil organic matter, (ii) incorporating more trees into the land use systems, and (iii) increasing plant diversity for both diversified production and enhanced regulation of pests and diseases. Despite this, only four of the participants managed a dynamic agroforestry system, while about half of them had simple agroforestry systems with few shade tree species.

Those cocoa producers who managed a dynamic agroforestry system indicated that they strongly relate to the plants in their systems. They expressed a high interest in the ecological context and showed a high knowledge of plant species, both domesticated and wild, and their uses. They had all been in contact with an organization or project working on dynamic agroforestry systems, and observed ecological processes and interactions on their farms. In addition, all dynamic agroforestry farmers said that neighbours were taking up at least some dynamic agroforestry management practices such as increased planting densities or diversification. However, managing a dynamic agroforestry system requires a high level of specialized knowledge, as well as the ability and equipment to prune trees. Adoption of dynamic agroforestry involves more than knowledge transfer: social learning and transdisciplinary approaches are important pathways for successful adoption. Capacity building, knowledge exchange networks, and continuous technical support may therefore be important means of enhancing the adoption of dynamic agroforestry systems in Bolivia.

Incentives for dynamic agroforestry systems could be created through projects and extension services, i.e. by a more constant presence of local organizations and projects. Following the examples of Ecotop and Ecosaf in Bolivia, such technical support could help to uphold year-round production of a variety of products and thus lead to a lower dependency on cocoa. Dynamic agroforestry is also a promising way of restoring degraded soils (Milz 2010; Todt 2010) and is suitable for production systems on steep slopes. Dynamic agroforestry farms may therefore be eligible for payments for ecosystem services (PES). However, incentives from PES remain difficult to access and/or unviable for cocoa producers in Alto Beni (Jacobi et al. 2014).

3.2.3 On-Farm Comparison of Different Cocoa Production Systems in Côte d'Ivoire

Our study was located between the departments of Yamoussoukro and Bouaflé, in the forest-savannah transition zone of the Central and Central-West regions of Côte d'Ivoire. This region was part of the main area of cocoa production until about three decades ago, when it became unsuitable for cocoa due to outbreaks of pests and diseases, as well as a prolonged period of drought in the 1980s. The area is a mosaic of mesophilic, semi-deciduous forest and Guinean savannah environments (MEDD 2011). The average annual rainfall is 1000–1200 mm, and the temperature ranges from 14 °C to 39 °C. Farmers are mainly engaged in subsistence agriculture cultivating mainly yams, cassava, plantain, rice, and maize, and production of cash crops such as cocoa and coffee. Both Yamoussoukro and Bouaflé are characterized by low-yielding full-sun systems and high pressure of CSSVD, a disease that requires eradication of affected plants and subsequent replanting.

Biopartenaire Ltd. and Ecotop installed their first dynamic agroforestry trial plots in farmers' mature, low-yielding monocultures (Type 1) by pruning cocoa trees and diversifying plantations at the start of 2013. We studied yields of cocoa and by-crops in these dynamic agroforestry vs. monoculture plots, and, through interviews, assessed the reasons motivating the involved farmers to adopt dynamic agroforestry (Franzel et al. 2001). In addition, we looked at not yet productive plantations which were replanted on sites infected with CSSVD (Type 2). In these, there was no cocoa to harvest yet, so we used interviews to assess cocoa yield levels prior to replanting as well as current by-crop yields (Beerli 2014).

For cocoa yield, we recorded fresh and dry bean weights. Type 1 plantations were split into two study categories, in-depth and trend: (i) for the in-depth study, we did precise yield measurements on 40 plantations; (ii) for the trend study, we obtained less precise information on a further 550 plantations with the help of agroforestry experts who assisted farmers in measuring the yields themselves. Besides cocoa yield, we investigated short-term profitability with net return = marketed yield * current market price, and biophysical performance by measuring the yield of by-crops. We evaluated the profitability of Type 2 plantations by comparing annual yield losses of CSSV-infected monocultures with the installation costs of dynamic agroforestry systems per area. In addition, we documented incidences of pests and diseases, and obtained additional socio-economic information e.g. on the educational level of farmers, installation, maintenance, labour, costs for external inputs through interviews in the in-depth study (n = 43).

Factors influencing adoption of either dynamic agroforestry or monocultures were investigated through farmer interviews. These included (i) initial motivation to try dynamic agroforestry, (ii) comprehension of the dynamic agroforestry approach, (iii) observations made when comparing dynamic agroforestry with monoculture plots, and (iv) objectives regarding the implementation of dynamic agroforestry systems. We also consulted the dynamic agroforestry experts on their experiences with

Table 3.4 On-farm study on adoption potential of dynamic agroforestry in Côte d'Ivoire (Beerli 2014)

	In-depth study (n = 40)	Trend study (n = 550)
Measurement period	October 2013 to January 2014 (fortnightly)	October 2013 to January 2014 (fortnightly)
Systems	Dynamic agroforestry vs. monoculture (adjacent plots)	Dynamic agroforestry vs. monoculture (adjacent plots)
Plot size	144 m^2 (10 central cocoa trees harvested per plot)	approximately 100 m^2 (all cocoa trees of the plot harvested)
Yield parameters recorded	Pods: number, weight, incidences of pests and diseases Fresh beans: weight Dried beans: weight	Pods: number
Further parameters recorded for plot characterization	Tree density: productive and unproductive cocoa trees Farmer information/estimates: plantation age, varieties, management practices, preceding crop, yield level in 2012, estimation of cocoa quality, soil quality, pests and diseases	Tree density: productive cocoa trees Farmer information/estimates: plantation age, varieties, management practices (frequency of weeding, application of pesticides, fertilizer, pruning)

adoption in the area, and we assessed the willingness to replace a plantation infected with CSSVD by a dynamic agroforestry system using the opportunity cost model. Table 3.4 gives an overview of the study.

3.2.3.1 Cocoa Productivity and Incidences of Pests and Diseases in On-Farm Systems in Côte d'Ivoire

When interpreting our results, we have to consider that our study took place within the first year after pruning and diversification measures to rehabilitate old cocoa stands. We therefore focus in the following on some elements explaining successful implementation of dynamic agroforestry at plot scale, and outline only a preliminary assessment of factors influencing dynamic agroforestry adoption.

Mature, formerly low-yielding monocultures (Type 1 plantations) in the trend study showed significantly higher pod counts and cocoa dry bean yields on dynamic agroforestry trial plots compared to the adjacent control monocultures: 12,747 compared to 11,965 pods ha^{-1} (+7 %), and 478 compared to 426 kg ha^{-1} per year (+12 %), respectively. The in-depth study indicated higher dry bean weight per pod and lower incidences of pests and diseases in dynamic agroforestry trial plots (Beerli 2014).

These positive effects can be mainly attributed to rehabilitation pruning, the principal management practice of dynamic agroforestry systems. It led to higher light inception which induced flowering and reduced losses of young pods, results that confirm the findings of Petithuguenin (1998). With a reduced cocoa canopy and planting density, the relative air humidity in the systems decreased, in turn creating less favourable conditions for pests and diseases as described by Smith Dumont et al. (2014).

As there is little evidence on the effects of pruning, we compared our results with on-farm surveys which looked at the effects of planting density and shade on cocoa yield; Deheuvels et al. (2012) found highest yields for agroforestry systems with low planting densities which were pruned twice a year, and reported a similar range of tree yields of 0.1–1.0 kg per tree and year as compared to 0.3 kg per tree and year in our study.

3.2.3.2 Preliminary Assessment of Factors Influencing Adoption of Dynamic Agroforestry Systems in Côte D'Ivoire

Short-term profitability of dynamic agroforestry systems in the in-depth study was lower than of monocultures in Type 1 plantations, mainly because of the initial investment to install the systems. Consequently, the net return from cocoa in dynamic agroforestry systems was lower compared to monocultures (−17.2 %), due to higher labour costs (+29.8 %). However, we could not include the by-crops as the farmers did not achieve considerable yields. It is important to mention that the installation of a dynamic agroforestry system is a mid- to long-term investment, and thus needs to be analysed accordingly. The dynamic agroforestry plots investigated in our study had only little time to show their effect, as our study took place only about 8 months after pruning and diversification of low-yielding cocoa monocultures. Production costs are expected to decrease in the near future for two reasons: better labour efficiency as farmers gain experience with an increasing area under dynamic agroforestry, and lower costs associated with pesticides (Clay 2004). In the trend study, net returns from cocoa were higher in dynamic agroforestry systems compared to the monocultures (+10.6 %).

The advantages and disadvantages of dynamic agroforestry mentioned by participants during our workshops are listed in Table 3.5. The results from the interviews were comparable for both plantation types: the higher the degree of perceived problems within their own plantation, the more willing the participants were to install a dynamic agroforestry trial plot, which confirms the findings of existing studies (D'Souza et al. 1993; Sood and Mitchell 2006). We found that farmers who estimated the benefit of dynamic agroforestry systems to be higher than the declining revenue might opt for replacement, since opportunity costs for replacement are lower. The main constraints mentioned for Type 1 plantations were drought and low productivity, while CSSVD was additionally mentioned for Type 2 plantations which confirms reports of farmers being more interested in agroforestry in areas where cocoa is devastated by diseases such as CSSVD (Gyau et al. 2014).

While the experts were able to explain the dynamic agroforestry system approach clearly, most dynamic agroforestry participants found it difficult to explain the principles of dynamic agroforestry in their own words. The advantages and

Table 3.5 Perceptions of and motivations for dynamic agroforestry of (a) dynamic agroforestry farmers/participants and (b) local experts in Bolivia and Côte d'Ivoire

Country		Bolivia[a]	Côte d'Ivoire[b]
Dynamic agroforestry farmers	Pro	Personal relationship to plants To conserve biodiversity and resources, and water quality and availability To host wildlife To produce healthy food Access to know-how: natural succession, plant sociology, year-round production Contact and exchange with research projects and organizations, as well as other dynamic agroforestry farmers	Effect of pruning is perceived to be positive Alternative to CSSVD plantations Access to know-how: natural succession, plant sociology
	Contra	Difficulties in pruning the trees High humidity can favour fungal diseases Market access with a diversity of produce is difficult	Too much work to manage by-crops Time consuming/labour intensive
Local experts	Pro	Soil restoration capacity Enhancement and revival of traditional ecological knowledge Healthier diet Biodiversity conservation, corridor function for fauna Resilient agroecological landscapes Connection to local, regional, and international markets with high quality products	Self-sufficiency Access to know-how Promotes discussion about traditional production methods Long-term positive effects on entire plantation (soil fertility, climate change adaptation, food resilience, etc.)
	Contra	Knowledge intensive Plants and seeds difficult to obtain	Lack of seeds Failure of by-crop Difficulties in sharing dynamic agroforestry knowledge with participants Unfamiliar by-crops are not popular and thus neglected by participants

[a]Dynamic agroforestry systems between 5 and 20 years old
[b]After 8 months of diversification of monocultures using a dynamic agroforestry design, cocoa trees were between 4 and 33 years old

management practices they mentioned were the same their dynamic agroforestry expert had told them, as well as those which were most visible in the short term, such as pruning. However, the majority of the participants were not able to link the applied methods to their long-term effects, indicating that there is a knowledge gap between dynamic agroforestry experts and farmers; this leads to an insufficient implementation of the principles of dynamic agroforestry, and indicates the need for more participatory, transdisciplinary research and social learning processes. Participants expressed their overall satisfaction with their observations, as they felt that cocoa productivity was increasing. Most farmers expressed their motivation to increase their area under dynamic agroforestry, but they felt they could not do it by themselves due to constraints such as labour costs and lack of knowledge, mentioned above. This statement corresponded to the feedback given by the dynamic agroforestry experts, who said that participants did not sufficiently manage the dynamic agroforestry trial plots. Pruning seemed to be the only popular management practice for the dynamic agroforestry systems, with most participants neglecting the by-crops, maybe because these are food crops traditionally cultivated by women. Participants attributed the failure of by-crops to drought and excessive shade. Overall, the acceptance of the implemented dynamic agroforestry extension programme was promising. These initiatives should be promoted, especially in regions affected by CSSVD.

3.3 Discussion

3.3.1 General Trends of Productivity, Soil Fertility and Pests and Diseases in Different Cocoa Production Systems

Tscharntke et al. (2011)) asked: which strategy is more viable for small-scale farmers, risk-averse long-term strategies such as agroforestry systems or short-term yield gains? Vaast and Somarriba (2014) found that full-sun monocultures are not a suitable strategy for small-scale farmers' risk management, and said that to foster agroforestry systems, innovative practices have to be developed, particularly with respect to shade regulation. This includes initiating selection programmes for cocoa genotypes in the context of agroforestry management, as well as appropriate practices of spacing and pruning trees at critical times in the production cycle. Furthermore, adequate combinations of different trees, e.g. with complementary leaf phenology, and local species have to be worked out with the objective of enhancing functional biodiversity.

Our results from Bolivia and Cote d'Ivoire confirm previous findings that farmers prefer to maintain shade trees in their cocoa systems in order to limit their vulnerability against outbreaks of pests and diseases as well as climate change impacts such as drought and heat stress (Johns 1999; Smith Dumont et al. 2014; Vaast and Somarriba 2014). However, sound recommendations for good agricultural practices in cocoa production systems which work in the farmers' context are scarce, especially when it comes to organic production (Schneider et al. under review). For example, little research has been done on mulching in cocoa. Mulching could contribute to the control of fungal diseases near the soil surface through leachates, as suggested for *Gliricidia sepium* biomass (Inostrosa and Fournier 1982).

However, besides good agronomic practice the most crucial factor in implementing agroforestry systems on a larger scale is arguably the improvement of market conditions. Bolivia is a model case study of how a socio-economic context has facilitated the successful implementation of cocoa agroforestry systems on about half the cocoa growing area. In order to improve the sustainability of worldwide cocoa production, the lessons we learnt from Bolivia may serve as an example for other cocoa growing areas which produce more substantial volumes such as West Africa or Southeast Asia.

Vaast and Somarriba (2014) reported on two recent studies (Gockowski et al. 2013; Asare et al. 2014) which assumed 20 % higher cocoa productivity in full-sun monocultures compared to well-managed agroforestry systems. But the underlying evidence for this assumption is not very strong, as only few studies, all of which were conducted 20–30 years ago, actually document the beneficial effect of removing shade to achieve higher yield (Vaast and Somarriba 2014). In addition, the influence of both cocoa varieties and the composition of shade tree species were not thoroughly addressed in these studies. Full-sun systems can achieve high yields in the short term (Vaast and Somarriba 2014). However, we have seen the prediction that cocoa production will decline within less than 20 years (Beer 1987) become true (Ruf and Zadi 1998). Monocultures thus have to be completely renewed much sooner than shaded systems. They also require the continuous input of agrochemicals and constant management to attain their maximum yield potential. By contrast, higher agro- and wild biodiversity in agroforestry systems is not necessarily negatively correlated with cocoa yield (Clough et al. 2011; Tscharntke et al. 2011; Steffan-Dewenter et al. 2007; Schroth et al. 2014), and shade trees were also associated with a longer lifespan of cocoa production systems (Obiri et al. 2007; Ruf and Schroth 2004; Ruf and Zadi 1998).

Looking beyond the yield of a single commodity such as cocoa, several studies have shown that diversified cropping systems are more productive per area than monocultures (Jaggi et al. 2004; Bellow et al. 2008; Rosset 1999; Tscharntke et al. 2012; Pokorny et al. 2013). These results indicate the significant contributions of agroforestry systems to local food security and risk distribution in smallholder contexts. However, studies on the optimization of total system yields, i.e. total land productivity, and tree-crop interactions in diversified systems are scarce (Bellow et al. 2008). Farmers often have detailed knowledge on their cultivation systems and related processes (Altieri 2004), which is crucial to take into account when trying to understand complex tree-crop interactions and designing projects to support agroforestry systems.

If no external inputs are added, soil fertility declines rapidly in full-sun systems, although it may decline even with the constant addition of mineral fertilizers. This is one of the major reasons for decreasing cocoa productivity worldwide (Vaast and

Somarriba 2014). Leguminous shade trees, for instance, can counteract this decline by continuous inputs of nutrients and organic matter to the soil through litter fall. The nutrients they fix in their vegetative materials can replace around 150 kg urea per ha and year (Tscharntke et al. 2011). This would also help prevent a lack of metabolic energy in the soil caused by the continuous energy and nutrient flux in the form of firewood and charcoal from rural to urban areas (Milz 2012). In addition, the decomposition of litter happens faster under shaded conditions, resulting in higher natural nitrogen and phosphorous levels in the soil and indicating that shaded systems are more sustainable than full-sun systems (Ofori-Frimpong et al. 2007)

Contrary to soil fertility, the findings of different studies on the effects of shade trees on incidences of pests and diseases in cocoa production systems are complex and ambiguous (Beer et al. 1998; Staver et al. 2001; Bedimo et al. 2012). Several authors mention regulatory effects of shade trees on pests (Tscharntke et al. 2011; Rice and Greenberg 2000; Schroth et al. 2000; Clough et al. 2009a, 2010; Daniels 2006; Campbell 1984). For example, they may decrease pest populations directly (Beer et al. 1998; Lin 2007; Jaramillo et al. 2009; Thorlakson and Neufeldt 2012), or indirectly by favouring natural pest antagonists (Opoku et al. 2002). However, some researchers suggested that the cooler microclimate in shaded systems coupled with high humidity and insufficient aeration may increase the incidences of fungal diseases (Schroth et al. 2000; Dakwa 1976), while others found that frosty pod rot was negatively correlated with shade and diversification (Bieng et al. 2013; Gidoin et al. 2014). Furthermore, some shade tree species may act as hosts of pests and diseases such as CSSVD (Ploetz 2007). Physiological stress of cocoa trees is reduced under agroforestry (Beer et al. 1998), which may enhance plant health and its defence against stressors. Ecological conditions such as altitude and slope exposure can also either favour or suppress pests and diseases depending on their effect on microclimatic conditions, i.e. relative air humidity and temperature. In summary, it is often difficult to identify adequate shade levels and tree species compositions that minimize damage from pests and diseases while ensuring favourable growing conditions for cocoa trees. This especially applies because the needed shade levels of the cocoa trees and the periods with the highest likelihood of pests and diseases vary over time. Therefore, research is still needed to assess the suitability of different tree species and optimal planting densities (Koko et al. 2013), and their effects on pests and diseases, as these can vary for different species (Franzen and Mulder 2007).

3.3.2 Resilient Adaptation of Different Cocoa Production Systems to Factors of Global Change

Vaast and Somarriba (2014) have pointed out the threats to ecosystem services of intensification of cocoa systems worldwide. They concluded that removing shade trees reduces the ability of cocoa farmers to adapt to factors of global change such as demographic pressure, food insecurity, cocoa price volatility, and climate change impacts. While the role of agroforestry systems as a mitigation and adaptation strategy for climate change impacts has been widely discussed, our research from Bolivia adds the component of socio-economic implications of shade trees in cocoa production systems (Jacobi et al. 2013, 2015). For example, farmers like to work in the shade rather than in the scorching sun, and they value the diversification of their production and the knowledge they have about their production system.

Agricultural intensification and climate change are predicted to create synergies which increase the vulnerability of agricultural production (Lin et al. 2008). Cocoa trees are particularly susceptible to climate change impacts (Anim-Kwapong and Frimpong 2006; Laederach et al. 2013), especially to drought (Tscharntke et al. 2011). Diversification is necessary for the adaptability of agroecological systems to climate change impacts (Henry et al. 2009; Steffan-Dewenter et al. 2007; Lin et al. 2008; Tscharntke et al. 2011; Altieri and Nicholls 2013), besides other environmental benefits (Soto-Pinto et al. 2010). In sum, at a time when cocoa production systems need to be more resilient than ever, intensification in terms of the removal of shade has reduced their ecological resilience.

There are more climate change related studies on coffee (*Coffea* spp.) than on cocoa, but as coffee is also a typical perennial cash crop for smallholder families in the humid tropics which is grown under similar agroecological conditions, the results from these studies may also have implications for cocoa. Philpott et al. (2008) found that more diversified coffee sytems suffered less damage from hurricane Stan in Chiapas, Mexico. Shade trees protected the coffee plants from drought, as they reduced evapotranspiration and increased the infiltration capacity of the soil (Lin 2007). Nicholls et al. (2013) described how diversified farms in Cuba lost about 50 % of their production after hurricane Ike in 2008, compared to the 90–100 % lost by monoculture farms.

3.3.3 Next Steps: The Need for Transdisciplinarity in Future Cocoa Research

Designing agroecosystems similar to natural ecosystems may be the only way to sustainably cultivate cocoa (Milz 2012). Ideally, the objective should be to optimize systems for productivity, biodiversity, and food security in the long term, rather than short-term maximization of yield. However, the main constraints for large-scale adoption of approaches such as dynamic agroforestry systems are that they are knowledge and labour intensive. Not only do interested farmers have to understand the underlying principles of these approaches, they also need technical support, as well as help in establishing farmer-to-farmer knowledge and exchange networks, and fair prices for their produce. Organizations such as Ecotop, Ecosaf, El Ceibo, and Biopartenaire Ltd. are thus pivotal for initiating these processes on the ground in order to stimulate bottom-up learning approaches. While this might resolve the knowledge constraints, labour intensity remains a challenge. Smallholders optimize opportunity costs and invest labour into different activities accordingly. Hence the problem is again on the market side, i.e. producers are paid low prices for their cocoa, which underpins yet again the need to improve market conditions for produce from agroforestry systems.

One of the key factors future cocoa research needs to address is the optimal design of sustainable production systems. The above-mentioned social learning process must aim at the transdisciplinary development of decision support tools for determining optimal shade levels and adequate compositions of tree species under various scenarios, with the aim of minimizing damage from pests and diseases while ensuring favourable growing conditions. This is a complicated task, however, as both ecological conditions such as effects of shade trees on incidences of pests and diseases, and socio-economic factors such as age of farmers, or share of on-farm/off-farm income, impact the success of farmers on the ground and thus the adoption of agroforestry.

As agroecosystems are complex, the above challenges need to be tackled with complexity, i.e. diversity. This refers not only to diversity in production, but also to the ways knowledge is produced and shared, both between people and institutions. We as researchers need to reflect this diversity, complexity, and the processes involved in research by (i) integrating social and natural sciences in the design of our projects, and (ii) taking into account different forms of knowledge while regarding phenomena from a perspective that goes beyond specific disciplines and is based on broad participation (Hirsch-Hadorn et al. 2006). The majority of researchers have come to know that their knowledge is complementary rather than superior to that of farmers and other stakeholders. Researchers need to actively pursue the path of transdisciplinary and participatory action research which allows for the conservation and application of local knowledge, while enabling knowledge co-production and mutual learning among farmers, researchers, and other stakeholders such as consumers and policymakers. As Vaast and Somarriba (2014, p. 953) pointed out: "*The selection of tree species and combinations is likely to be most effective where farmers participate, so that their goals and aspirations are taken into account and their local agroforestry knowledge is incorporated into the design and management of the system.*" Such an integrative approach is also more likely to help identify and implement strategies to adapt to multiple stressors; adaptation to climate change impacts, for example, means much more than identifying and planting resistant crops (Pohl et al. 2010).

Bolivia, with its traditional as well as introduced forms of cocoa production, provides an example for transdisciplinary research and co-production of knowledge. Moreover, the cocoa cooperatives have established market chains for both collected and cultivated cocoa under the guiding vision of sustainable agriculture. The unique socio-economic setting of long-standing, well established cocoa cooperatives that engage in organic cocoa production in Alto Beni makes this region particularly suitable to study current and future economic, ecological, and social problems related to cocoa production.

Our research will be complemented by a new project in Ghana entitled "Transdisciplinary systems research to develop a holistic approach to reduce the spread and impact of cocoa swollen shoot virus disease in Ghana (TransdisCSSVD)". In this project, we aims at (i) quantitatively consolidating 75 years of research about the most promising CSSVD control options (meta-analysis), (ii) identifying the main constraints for adoption of available CSSVD control options (farmers' perspective) and (iii) filling an important knowledge gap about the contribution of cocoa production systems' diversification to reducing the spread of CSSVD (e.g. agroforestry; landscapes fragmentation with hedgerows, etc.). Planned dissemination activities include transdisciplinary workshops with policy makers to determine feasible ways of adapting the existing CSSVD prevention and control program. Furthermore, farmer field days and exchange workshops may stimulate implementation of results on the ground. IN addition, the CGIAR Research Program on Integrated Systems for the Humid Tropics launched a new innovation platform in Ghana earlier this year with the aim of facilitating sustainable intensification of cocoa production. These examples underline that researchers are taking steps towards transdisciplinary and participatory action research, making research more solution-oriented and relevant for the livelihoods of cocoa producers throughout the tropics.

Certification standards hold a certain potential to influence the future design of cocoa production systems. While there is the need to better assess the long-term effects of implementing good practices, including agroforestry, developed by eco-certification schemes across a wide range of ecological and socio-economical contexts (ICCO 2014), certification bodies also need to be open to continuous adaptation of their standards according to research results derived from projects with farmer involvement. Our experiences from Bolivia indicate that organic certification alone may not lead to a diversification of cocoa production systems or the implementation of dynamic agroforestry systems (Jacobi et al. 2013). We think that organic and other certification schemes should emphasize the need to diversify in order to foster the resilience of cocoa production systems to factors of global change. In addition, policymakers should address the costs associated with certification schemes, as these may present a major constraint for farmers wishing to obtain certification, and build incentives for organic and agroforestry produce also on the consumer side.

Sood and Mitchell (2006) found the attitude of farmers towards agroforestry systems to be the most important factor of adoption, which highlights the importance of extension programmes for knowledge sharing between agroforestry experts and farmers. Our experiences suggest that especially in areas where farmers face big challenges in their own plantations, the willingness to adopt agroforestry or dynamic agroforestry is high. However, as the perceptions of farmers about different production systems change according to their underlying motivation of engaging in them, such as expected income or knowledge gain on management practices in agroforestry systems, the way experts interact with farmers and their organizations, e.g. on the principles of system approaches such as agroforestry or dynamic agroforestry, needs to be improved. This was the case especially in Côte d'Ivoire, where we observed that this basic principle is not adequately applied. We advocate for interactive knowledge sharing methods such as farmer field schools, which stimulate farmers' protagonism and give scientists the role of mediators who integrate different forms of knowledge and make them visible to different stakeholders (Pohl et al. 2010). Much can be learnt from the Latin American agroecological movement, such as the "farmer-to-farmer" (campesino a campesino) movement and its learning approaches in which researchers and external consultants are facilitators rather than instructors (Holt-Giménez 2006).

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