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Supporting and regulating ecosystem services in cacao agroforestry systems

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Abstract Cacao agroforestry systems (CAFS) can provide *supporting* services such as optimum light conditions for cacao growth, water and nutrient cycling and *regulating* services such as pest and disease control and climate regulation. This review considers recent literature on the manifestation of these services in CAFS around the world to provide an overview of scientific knowledge. Crown structures of associated trees can facilitate optimum light conditions for cacao growth, and provide water through vertical root segregation. Leaf litter fall and roots from associated species contribute to nutrient cycling. Both nitrogen-fixing and non-nitrogen-fixing species can provide nutrients to the cacao plant, though competition from certain species may limit phosphorus and potassium uptake. Pest and disease regulating services can arise through careful shade management to create a microclimate which reduces susceptibility of cacao to fungal diseases and sun-loving pests. All CAFS store carbon to varying degrees; those resembling original forest much more than simple two-species systems from which shade trees are removed after maturity of the cacao stand. CAFS also promotes biodiversity conservation depending on structure, management, and landscape arrangement, though not to the extent of natural forests. Research opportunities to increase provision of these services include optimal spatial arrangement for nutrient cycling and functional diversity as well as landscape connectivity for biodiversity conservation. Trade-offs between carbon storage, biodiversity, cacao yield and socio-economic resilience are presented, indicating that optimization of ecosystem services in CAFS requires consideration of interactions between all services, including socio-cultural and economic ones.

Keywords Biodiversity conservation · Carbon storage · Landscape connectivity · Nutrient cycling · Pest and disease control · Trade-offs

Introduction

Low global market prices and diminishing yields due to aging trees and rising pest and disease pressure are encouraging cacao farmers to encroach on new forest lands, often in or near biodiversity hotspots, to establish new plantations (Clough et al. 2009; Jagoret et al. 2011). Deforestation for—and intensification of—agricultural systems are among the most important causes of loss or degradation of biodiversity and related ecosystem services worldwide (Foley et al. 2005), and contribute to the agriculture sector's already high level of greenhouse gas emissions (Harvey et al. 2013).

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Cacao is one of the primary cash crops in multiple West African countries (Aikpokpodion 2010; Asare et al. 2014) as well as parts of Indonesia (Abou Rajab et al. 2016; Clough et al. 2009) and Latin America (Arévalo-Gardini et al. 2015; Cassano et al. 2009; Faria et al. 2007). There are 6–7 million cacao farmers worldwide, of which 80–90% run small farms: 2–4 ha in Asia and Africa and slightly larger in the Americas (World Cocoa Foundation 2014). Originating in the understoreys of Amazonia, cacao is susceptible to cultivation in *forest-like* conditions to a greater extent than many other cropping systems (Schroth and Harvey 2007). Cacao yield per ha differs among regions, countries, type of cacao and growing system in place, with average yields around 300–400 kg ha^{-1} in Africa, 500 kg ha^{-1} in Asia, and 500–600 kg ha^{-1} in the Americas (World Cocoa Foundation 2014).

Approximately 70% of cacao is grown with some level of shade (Gockowski and Sonwa 2011), which can optimize yield while minimising environmental degradation (Andres et al. 2016; Somarriba et al. 2013). Research suggests that cacao agroforestry systems (CAFS) where shade is not removed after cacao maturity can contribute to a landscape matrix conserving high levels of biodiversity through providing buffer and refuge zones for wildlife (Asare 2006; Perfecto and Vandermeer 2008; Saj et al. 2017). CAFS can also contribute to improved pest and disease resilience, notably by changing resource availability and the microclimate (Andres et al. 2016; Ten Hoopen and Krauss 2016).

In recent years the concept of ecosystem services has been used to refer to advantages for human society attainable from ecosystems. Agroforestry systems help to maintain key ecosystem services including soil fertility, erosion management, biodiversity conservation and carbon storage (De Clerck et al. 2011; Muschler 2016). When used as part of an integrated landscape they offer a strategy to simultaneously pursue climate change adaptation and mitigation, food security, and poverty alleviation goals (Bentley et al. 2004; Harvey et al. 2013; Schneider et al. 2016). The Millennium Ecosystem Assessment (MEA 2005) aims to provide a basis for the maintenance of ecosystem functioning to ensure a range of services for human wellbeing. Four types of ecosystem services are identified: supporting, regulating, provisioning and cultural. This review of ecosystem services in CAFS covers supporting and regulating services related to ecological functioning. These services provide the basic ecological minimum to enable provisioning and cultural services, which involve people and their interaction with the ecosystem (MEA 2005) (Fig. 1).

Despite a rising number of publications in recent years addressing the provision of ecosystem services in CAFS, there is currently no recent review specifically considering supporting *and* regulating ecosystem services in CAFS in all cacao producing regions. To date, publications either address only one service in one CAFS (e.g. Deheuvels et al. 2014; Saj et al. 2013), one service across multiple CAFS (e.g. Hartemink 2005; Schroth and Harvey 2007), multiple services in one or two specific CAFS (e.g. Andres et al. 2016; Deheuvels 2015), or several services in agroforestry not specific to cacao (e.g. Tscharntke et al. 2011; Muschler 2016). This review considers literature on supporting and regulating services corresponding to the cacao tree, plot and landscape scale in an attempt to provide an overview of current knowledge on the occurrence of these services in CAFS around the world. Key areas for research are identified, and trade-offs between provision of different ecosystem services, including cacao yield and socio-economic resilience, are discussed.

Materials and methods

Literature review

This review covers literature using keywords: cacao, cocoa, agroforestry, ecosystem services, nutrient cycling, pest and disease control, landscape connectivity, biodiversity conservation, carbon storage and trade-offs. These keywords were chosen as they pertain to key supporting and regulating services in CAFS. Articles were chosen based on: relevance to the review topic and sub-topics, date of publication [post-2000, with the exception of important sources Beer (1988), Beer et al. (1998), de Oliveira Leite and Valle (1990) and Evans (1998)] and containing original data. The search engines Web of Science^{TM} (v5.22, Thomson Reuters).and Google Scholar (https://scholar.google.com; Google Inc.) were predominantly used, along with Research Gate (www.researchgate.net, ResearchGate GmbH). The initial search was conducted between January and April 2016, and completed between March and April 2017. For

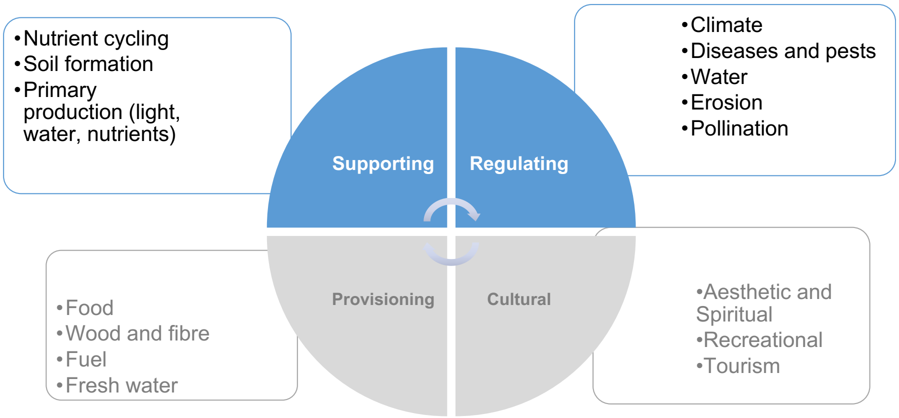

Fig. 1 Ecosystem services (modified from MEA 2005). *Note* this review focuses on *supporting* and *regulating* services only

information on individual services, the sub-topic was typed with "cacao"/"cocoa" and "agroforestry systems" in the same search, separated by a "+" sign or a "AND" according to the search engine. A concerted effort to include research conducted on CAFS in all major producing regions was made, with 102 articles forming the basis of the review: 24 from Africa, 33 from the Americas, 16 from Asia (all from Indonesia except 1 from India), and 13 reviews of a particular service over multiple regions. The other 15 works included in the review are the Millennium Ecosystem Services Report, the World Cacao Foundation on global yields, and 13 publications on a global scale, on topics of measurement and payment for ecosystem services, mathematical modelling in agroforestry systems, trade-offs and agroforestry or tropical agriculture, not specific to cacao. Figure 2 presents the number of published articles per region on each supporting and regulating service in CAFS discussed by this review of the 87 articles on CAFS. This includes 4 articles on coffee agroforestry systems—Lin (2007), Dechert et al. (2005), Beer (1988) and Beer et al. (1998)—the first makes specific reference to transferability of results to CAFS, and the remaining refer to both coffee and cacao agroforestry systems and indicate which results are applicable to CAFS. 7 studies fell into two categories (such as tree diversity and carbon storage), the remaining 80 studies were allocated to one category only.

Articles referring only to cacao monocultures, and those referring to agroforestry systems or tropical agriculture more generally were avoided but not excluded if they provided information applicable to CAFS not found on cacao—e.g. Buresh et al. (2004) and Van Noordwijk and Cadisch (2002) on nutrient cycling in vertical soil profiles and the studies on mathematical modelling of interactions in agroforestry systems. Provisioning and cultural services, such as farmer livelihoods, economic benefits (including comparison of yields between CAFS and cacao monocultures), and cultural connection to land, were deemed outside the main scope of this article, which aims to consider services related to ecological functioning. The relationship between these services and those covered by the review are considered to some extent in the discussion.

The categories of ecosystem services as used and described in the MEA (2005) provided an initial structure for the review, however strict adherence to MEA labels was avoided due to overlap between service types.

Types of CAFS

Shade management systems in CAFS range from complex systems resembling natural forests, to simple plantations using few associated species (Beer et al. 1998; Rice and Greenberg 2000). Significant differences in occurrence of regulating and supporting ecosystem services arise depending on the CAFS in place, and whether it is a simple two-species system, a semi-complex system, or a highly complex system resembling natural forest. Given inconsistencies in making these distinctions among the literature, uneven amounts of information about CAFS canopy structures and tree densities, and lack of concurrence across the

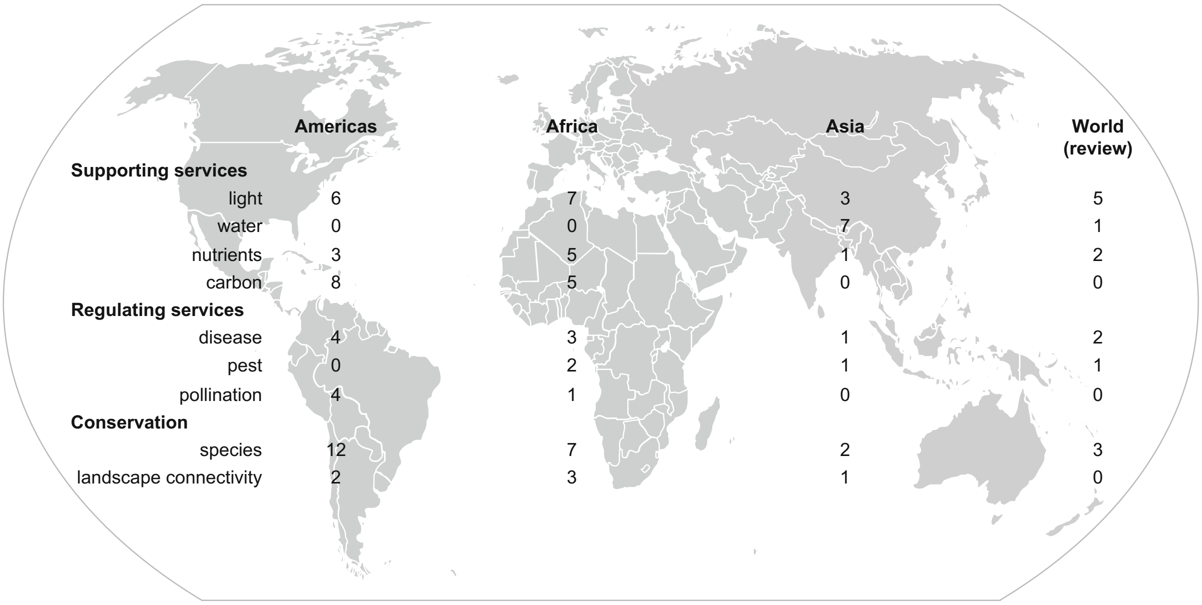

Fig. 2 Number of published scientific articles used in the review per geographical zone and topic studied

literature in what constitutes a *complex* CAFS, this review does not consistently distinguish between simple and complex CAFS as such, but does provide detail on CAFS type where possible.

Results

Primary production and nutrient cycling in CAFS

A summary of services provided by shade species in CAFS in the realm of light, water and nutrient availability for the cacao tree is presented in Table 1. Together, these services enable primary production of cacao, a supporting service that operates on the cacao tree and plot scale. These services are discussed in relative isolation here, but they are closely linked with pest and disease occurrence ("Pest and disease occurrence and pollination in CAFS" section).

Light/shade conditions for cacao production

Multiple studies have investigated impacts of shade for cacao growth with respect to optimum light incidence levels for photosynthesis by the cacao tree. The impact of upper canopy species on light infiltration is dependent on specific crown structures, which affect the dispersal of light, even in simple 2-species CAFS (Isaac et al. 2007). Light is most important for the growth of young cacao trees, and is less of a concern for older cacao trees (Tscharntke et al. 2011). Beer et al. (1998) cited optimum shading for cacao growth between 40 and 70%; a standard which is still maintained in the literature today. In Cameroon, highest yield corresponded to between 40 and 50% shade in semi-complex CAFS, 15–50 years old (Bisseleua et al. 2009). In Indonesia, yields, number of harvested fruits and number without pest infestation was highest at 30–40% shade cover in simple CAFS (Gras et al. 2016). Low shade cover, around 0–25%, saturates and stresses the cacao tree, and does not necessarily lead to higher cacao yield, particularly over the long term (20–25 years) (Abou Rajab et al. 2016). These optimum ranges indicate that well-managed CAFS a priori provide better conditions for cacao production than cacao monocultures or forests with heavy canopy (Tscharntke et al. 2011). However, optimum shading for cacao development must be considered along with impact of shade on pest and disease occurrence (see "Pest and disease occurrence and pollination in CAFS" section).

Water availability for cacao

Water use rates by cacao are largely influenced by local temperature, humidity and net radiation (Köhler

Table 1 Occurrence of light, water and nutrient supporting services in CAFS

	Services	Limitations	Determining factor/comments
Light	Optimum light incidence levels for cacao growth and yield can be attained through shade management (Bisseleua et al. 2009; Beer et al. 1998; Isaac et al. 2007)	Overshading leads to excessive vegetation growth and reduced yields (Beer et al. 1998), especially in young cacao (Schneider et al. 2016); shade impacts pest and disease occurrence—Table 2	Crown structure of canopy species (Isaac et al. 2007); shade management (Tscharntke et al. 2011)
Water	Water cycling (Schwendenmann et al. 2010); water use efficiencies (Carr and Lockwood 2011); minimisation of extremes in air and soil moisture and temperature (Lin 2007; Lin et al. 2008)	Water availability for cacao can be occasionally limited by shade species (Beer et al. 1998; Carr and Lockwood 2011)	Root attributes (density, spatial distribution) of canopy species (Schwendenmann et al. 2010) Lack of research on water requirements of cacao in field studies, on mature plants, in shade (Carr and Lockwood 2011)
Nutrients	K, P, Mg, Ca & N: Higher soil residence index (de Oliveira Leite and Valle 1990)	Nutrient through fall via rain is higher in unshaded plots (de Oliveira Leite and Valle 1990)	Canopy species in place (Isaac et al. 2007; Anim-Kwapong 2003; de Oliveira Leite and Valle 1990)
	N: Increased availability via leaf litter fall (Anim-Kwapong 2003); N-fixing species can assist N-availability for cacao (Beer et al. 1988);	N: None found	Age of soils (Aikpokpodion 2010); soil type (Araujo et al. 2013; Snoeck et al. 2010)
	P: No significant services added by CAFS.	P: Can be limited by some N-fixing species (Hartemink 2005)	
	K: Increased availability via leaf litter fall (Hartemink 2005; Isaac et al. 2007; Anim-Kwapong 2003)	K: Limited uptake by cacao when stored in some timber species' trunks (Isaac et al. 2007)	

et al. 2009; van Straaten et al. 2010). The cacao tree grows in periods after rain and is dormant during periods of no rain (Carr and Lockwood 2011). Cacao tree root systems consist of a thick tap root (can reach 1.5–2.0 m) and a mass of lateral roots occupying the first soil horizon (0.2–0.4 m) that spread outwards >5 m from the stem (Carr and Lockwood 2011); this represents the main channel for the movement of moisture and nutrients (Hartemink 2005). The real evapotranspiration rate has been calculated at 3–6 mm day^{-1} during wet seasons. The past 15 years have seen a rise in the number of publications on water stress/availability for cacao in shaded conditions. Despite an acknowledged possibility of competition between cacao and associated trees, multiple field observations and empirical studies underline that water use seems complementary between associated species and cacao trees, throughout a range of species and management intensities (Lin 2007; Lin et al. 2008; Schwendenmann et al. 2010). In a simple 2-species CAFS in Indonesia, an N-fixing (*Gliricidium spium*) canopy cover improved water uptake by the cacao tree on the plot scale (Köhler et al. 2009). In the same study region, complementary use of soil water resources through vertical segregation of roots between cacao and *Gliricidia* species was identified (Moser et al. 2010; Schwendenmann et al. 2010). These findings are important as hydraulic conductivity, the passage of water, has been identified as a better indicator of cacao stem growth than foliar traits and wood density in CAFS (Kotowska et al. 2015). Furthermore, the presence of shade species in both 2-species and multi-species coffee systems reduces fluctuations in air and soil moisture, and facilitates overall lower air and soil temperatures and higher humidity than monocultures, suggesting presence of shade species can protect crops from microclimate extremes and drought, findings which are considered likely to be transferable to CAFS under similar conditions (Lin 2007). Overall, along with research into drought-tolerant cacao cultivars, planting cacao under shade, with appropriate species and management, may constitute an adaptation strategy to increased drought conditions predicted for some producing regions

Table 2 Influence of shade on a selection of pests and diseases affecting cacao in CAFS

Pest or disease	Host/affected species	Increased/decreased occurrence under shade	Reference
Cacao swollen shoot virus (vector: many insects)	*Cola chlamydantha, cola gigantean, Sterculia tragacantha, Bombax buonopozense, Ceiba pentandra*	Increased when host species present	Schroth et al. (2000)
	Any species—forest structure	Decreased when forest structure unfavourable to ant vectors—such as in shaded cacao	Lass (1985) in Schroth et al. (2000) and ten Hoopen and Krauss (2016)
Monilia or Frosty pod rot (*Moniliophthora roreri)* (fungi; vector: wind)	Fungi principally vectored by wind; though *Moniolophthora perniciosa* often facilitates infection	Controversial. Increased under dense shade, decreased under moderate shade.	Evans (1998), Dahlquist et al. (2007) and Medeiros et al. (2010)
Witches' broom (*Moniolophthora perniciosa)* (fungi)	N/A	Decreased: microclimate under shade favours natural antagonists	Evans (1998)
		Mixed: Different microclimates along vertical stratification impact presence of disease and antagonists	Loguercio et al. (2009)
Black pod disease (*Phythophthora capsici*, *P. citrophthora*, *P. palmivora*) (fungi)	Rubber (*Hevea*), black pepper (*Piper nigrum*), coconut (*Cocos nucifera*) are hosts but limited cross-infection between species	Increased: simple shade as forest structure favours ant vectors Decreased: complex shade favours endophytes that are natural antagonists	Arnold et al. (2003) in Bos et al. (2007a) and ten Hoopen and Krauss (2016)
	C. nitida, P. guajava, T. scleroxylon, A. altilis, M. indica, C. petandra (hosts)		Smith Dumont et al. (2014)
		Decreased with increased cacao tree abundance	Gidoin et al. (2014)
South American leaf spot (*Mycena citricolor*) (fungi)	*Inga*, *Citrus* and *Mangifera* are alternative hosts and inoculum	Increased under excessive shade	Wellman (1961) in Beer et al. (1998)
Mirids (*Sahlbergella singularis, Distantiella theobroma*) (insect)	*Bombacaceae* (host)	Complex/decreased: mirids are often sun-loving, but not always. Occurrence of mirid pockets in regions of relative highest light intensity, decreased occurrence in homogenous shade	Mossu (1990) in Schroth et al. (2000) and Babin et al. (2010)
Mirids (*Sahlbergella singularis, Distantiella theobroma*) (insect)	*Cola* and other Sterculiaceae (host)		
	Citrus (host)	Increased	Smith Dumont et al. (2014)
Helopeltis theobromae (species of mirid insect)	*Cocos nucifera*	Decreased when *Cocos nucifera* planted instead of *Gliricidia sepium,* as ant antagonist increased	Way and Khoo (1991) in Schroth et al. (2000)
	Different species of hosts didn't affect mirid density, spatial arrangement of hosts did.	Decreased with low number randomly distributed forest trees	Gidoin et al. (2014)
Cacao pod borer *Conopomorpha cramerella* (insect)	Rambutan (*Nephelium lappaceum*); *Cola nitida*		Mossu (1990) in Schroth et al. (2000)
Shoot borer *Terastia meticolosalis* (insect)	*Erythrina*	Increased under *Erythrina* in W. Africa, not in Latin America	Schroth et al. (2000)
Cow pea, legume or black nut aphid (*Aphis craccivora)* (insect)	*Gliricidia sepium*	Increased	Soto and Madrigal (1988) in Schroth et al. (2000)

Table 2 continued

Pest or disease	Host/affected species	Increased/decreased occurrence under shade	Reference
Thrips (*Selenothrips rubrocinctus)* (insect)		Decreased: prefers high sun environment	Mossu (1990) in Schroth et al. (2000)
Leaf miner (*Leucoptera meyricki)* (insect)		Decreased: prefers high sun environment	Mossu (1990) in Schroth et al. (2000)
Rodents	Oil palms (*Elaeis guineensis*), *C. pentandra, T. sclerocylon*	Increased when host species present	Smith Dumont et al. (2014)

where rainfall is already critically low for cacao physiology (Moser et al. 2010; Schwendenmann et al. 2010).

Nutrient availability and cycling

CAFS are often described as low-input systems with no fertilization or where fertilization rates are low or inefficient (Snoeck et al. 2016). When CAFS are first established on cleared forest lands, nutrient availability initially relies upon the so called "forest rent"—i.e. using up the remaining soil nutrients from the forest, and the shade of remaining trees. After this initial period, nutrient availability in CAFS depends upon through-fall from rain (especially for potassium) or leaf litter fall from associated species (de Oliveira and Valle 1990) while another part relies on soil properties. Whether shade species in CAFS compete or facilitate nutrient availability and uptake by the cacao tree depends on the system in place and topoclimatic conditions.

For the cacao tree, N-fixing leguminous shade species such as *Gliricidia* or *Erythrina* are often used in simple CAFS and are generally thought to facilitate N transfer to trees, though empirical results do not consistently support this assumption (Tscharntke et al. 2011). Dechert et al. (2005) report enriched N in simple cacao and coffee AFS due to N-fixation from leguminous shade trees in Indonesia. Isaac et al. (2007) did not find the species *Albizia*, a known N-fixer, to increase soil N levels in simple CAFS at the plot scale, while Anim-Kwapong (2003) did. Complex CAFS such as those in Cameroon do not privilege N-fixing species and generally contain few N-fixers, preferring large deciduous trees for soil fertility (Saj et al. 2017).

Phosphorous (P) is known to be low and slow to accumulate in cacao production systems (Hartemink 2005). P in cacao and shade trees is often higher in non-leguminous systems, as leguminous species' rhizobium requires large amounts of P and thus limits P uptake by cacao and by other associated species (Hartemink 2005). Isaac et al. (2007) found cacao P uptake increased by 22–45% under all shade treatments (comparing different 2-species CAFS to monocultures), whereas P soil availability decreased under all shade treatments. These results suggest competition for P between cacao and shade trees, reinforced in the case of N-fixing shade species. This competition may result in a P deficiency for cacao trees since highly weathered tropical soils are known to be P deficient (Jadin and Snoeck 1984 in Snoeck et al. 2010).

Potassium (K) is the most readily available nutrient for cacao trees in CAFS, and the most responsive to having shade trees present (Isaac et al. 2007). Soil K levels depend on K levels in vegetation and annual leaf litter fall (Hartemink 2005). Isaac et al. (2007) found increased soil exchangeable K under *Newbouldia laevis*, while Beer (1988) found that some species such as *Cordia alliodora*, when not pruned, store K in tree stems. Concerning competition for N, Sujatha and Bhat (2013) observed a lack of competition where nutrients are provided via inputs such as organic compost, at least in the simple *Areca*-cacao systems studied. However, this treatment does not supply required K, which can have negative consequences for N use efficiency, and the overall conclusion of this study was that current application rates of organic fertilizers were insufficient to sustain yield and nutrient demands over the long term, particularly for K (Sujatha and Bhat 2013).

Other nutrients important for cacao growth include Calcium and Magnesium, which vary regionally depending on soil parent material (particularly Calcium) and soil type (i.e. high levels of Magnesium leaching in sandy soils in Nigeria) (Aikpokpodion 2010).

At a plot scale, leaf litter fall and fine root turnover are key components of nutrient cycling in CAFS (Hartemink 2005). The presence of shade trees contributes to heavy leaf litter inputs, which maintain high levels of soil organic material, even in simple CAFS (Anim-Kwapong 2003; Smiley and Kroschel 2008). These leaf litter inputs are important to replace nutrients taken up by the cacao tree, particularly during pod development phase under simple CAFS (Aikpokpodion 2010; Anim-Kwapong 2003—simple CAFS). Aikpokpodion (2010) found deficiencies in Mg and P in soils were reflected in cacao leaves (critical levels cited for soil Mg at 0.8 cmol kg^{-1}, for P at 10 mg kg^{-1}; simple CAFS). Snoeck et al. (2010) found higher density of vesicular arbuscular mycorrhizal (VAM) fungi spores in old CAFS (>25 years; 36 spores g^{-1} dry soil) compared to young CAFS (1–4 years; 16 spores g^{-1} dry soil), indicating better soil fertility in older CAFS. In this same study, lower C:N ratios were observed in the older cacao forest and secondary forest studied (around 13), reflecting normal rates of organic matter decomposition while the younger CAFS had a higher C:N ratio (around 16), indicating slower rates. This finding has also been observed by Dawoe et al. (2010). These temporal differences may be related to time taken (15–25 years) for recovery after the conversion process, where traditional conversion processes such as burning and selective clearing are used (Snoeck et al. 2010). Arévalo-Gardini et al. (2015) found higher soil pH, increased CEC, and exchangeable Mg over time in natural forests than CAFS.

On soil quality, Rousseau et al. (2012) identified indicators in CAFS in Costa Rica, in particular macrofauna groups, and conclude the range of CAFS types studied (simple to complex) are able to conserve soil and provide soil related ecosystem services. Zaia et al. (2012) also found good potential for CAFS to contribute to soil quality in *Cabruca*[1] systems in Brazil, where high capacity for storage of organic C, total N, organic P, microbial biomass N & C, and mineralizable N were observed.

Some authors discuss the capacity of associated species providing a ‘safety net’ for nutrient cycling, arguing that deeper roots of associated species such as *Citrus* spp (citrus)*,* *Psidium guajava* (guava*)* and *Mangifera indica* (mango), allow nutrients which have moved down through the soil profile outside of the effective root zone of cacao trees to be recycled (Buresh et al. 2004; Van Noordwijk and Cadisch 2002). This concept that deeper and more extensive tree roots will invariably be able to take up and cycle more nutrients from the soil compared to crops with shallower root systems has been affirmed in various forms of agroforestry (Nair 2008). However, its’ applicability may partly depend on depth of soil, a factor which is little studied in the literature. Finally, nutrient availability is highly influenced by water availability and competition for light between different components of CAFS, interactions which define the dynamics of biological activities within these systems. Research on these interactions tends to be based on developing mathematical models (e.g. WalNuLCAS model from Van Noordwijck et al. 2011; Hi-sAFE model from Talbot 2011) which may help overcome the lack of field data on this subject (Keesman et al. 2011).

Carbon storage

In general, carbon (C) in CAFS depends upon associated tree species and density and is greater in CAFS than cacao monocultures (Bisseleua et al. 2009; Magne et al. 2014; Norgrove and Hauser 2013; Saj et al. 2017; Schroth et al. 2015). The extent of C in a CAFS at both the plot and landscape scale depends on a number of specific biological, climatic, soil and management factors (Nair 2008; Magne et al. 2014) as well as the number of large trees present (Schroth et al. 2015, 2016). Diversified CAFS holds more C than simple 2-species systems in all cacao producing regions (Jacobi et al. 2014; Schroth et al. 2015, 2016; Somarriba et al. 2013). At the plot scale, Abou Rajab et al. (2016) found a fivefold increase in above and below-ground C stock with increasing tree diversity and above-ground biomass in a comparison of cacao monoculture, cacao/*Gliricidium*, and cacao/several species (from 11 to 57 Mg ha^{-1}). Most carbon in CAFS is found in the soil and in above-ground biomass, rather than in the cacao trees themselves (Norgrove and Hauser 2013; Saj et al. 2013; Somarriba et al. 2013). In Cameroon, average C in complex CAFS was reported at 70 t C ha^{-1}, with cacao tree contribution only 2–12% of total C (Saj

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[1] *Cabruca* is the name for CAFS in Brazil, which are a traditional system of planting cacao under thinned out native forests (Sambuichi et al. 2012).

et al. 2013). Saj et al. (2013, 2017) also reported that some CAFS—aged more than 60 years old and/or very dense (over 100 associated trees ha^{-1})—could exhibit equivalent C storage than local (disturbed) forests. Therefore, aboveground C is linked to associated stand composition and density (Jacobi et al. 2014; Magne et al. 2014; Somarriba et al. 2013). On belowground C, Araujo et al. (2013) found high variations (from 719 to 2090 Mg ha^{-1}) in soil C between *Cabruca* systems with 50 or more trees ha^{-1}, 21–49 trees ha^{-1} and 20 or less trees ha^{-1} with highest C content in ultisols and oxisols. The same study found comparable soil organic C (SOC), the component responsible for C sequestration, among cacao/*Hevea*, cacao/*Erythrina* and *Cabruca* systems. Similarly, Gama-Rodrigues et al. (2010) found comparable SOC between CAFS and natural forest in Brazil (mean 302 Mg ha^{-1}). However, Leuschner et al. (2013) found much higher SOC in forest (134 Mg C ha^{-1}) than simple CAFS (78 Mg C ha^{-1}) in Indonesia (*Glyricidia* and a few *Cocos nucifera),* and that depths below 1 m contain more than 40% of SOC, which are not always included in SOC studies. Overall, results suggest diverse CAFS not highly modified from natural forest can be an important source of C and holds great potential for climate mitigation, but not young and simple CAFS.

Pest and disease occurrence and pollination in CAFS

CAFS can provide pest and disease regulating services, notably on the plot scale but also on a landscape scale. Their capacity to do so depends on their management and local pest and disease pressure (Schroth et al. 2000; Tscharntke et al. 2011), as well as vegetation composition and spatial structure (Babin et al. 2010; Gidoin et al. 2014). Table 2, while not exhaustive, lists the well-established impacts of shade on diseases and pests in CAFS. The *enemies* or *insurance* hypothesis claims that organisms are less likely to reach pest proportions in more complex predator assemblages (Rice and Greenberg 2000), as a high level of species richness contributes to increased overall resilience to pest and disease outbreaks (Bisseleua et al. 2009).

Babin et al. (2010) found mirids prefer areas of relatively higher light intensity within complex CAFS, yet warn that while a CAFS with homogenous light distribution may reduce overall mirid populations, excessive shade is conducive to black pod rot (*Phytophthora megakarya* in this case) and thus a light balance unfavourable to both mirids and black pod rot is needed. Gidoin et al. (2014) studied the impact of vegetation composition and spatial structure on mirid abundance and black pod prevalence on complex CAFS (>10 associated species) in Cameroon. Contrary to expectations, they found decreased black pod prevalence in sites with increased abundance of cacao trees. Hypotheses proposed include a particularly low year of pest and disease occurrence that year, host species composition, and spatial structure of both cacao and shade trees creating a favourable microclimate at the plot scale. Gidoin et al. (2014) also observed decreased density of mirids in plots with a low number of randomly distributed forest trees, as opposed to aggregated plots. Finally, physiological stresses such as those incurred by pest and disease are often cited to be lower in CAFS than monocultures due to increased availability of plant nutrients on more fertile soils (Schroth et al. 2000).

Disease protection

Fungal diseases are a major cause of damage to cacao in all cultivation systems, estimated to cause 40% of annual cacao production losses (ten Hoopen et al. 2012). Principal diseases include black pod disease (*Phytophthora* sp*),* witches broom (*Moniliophthera pernicosa*), frosty pod rot (also called monilia; *Moniliophthora roteri*), cacao swollen shoot virus and vascular streak dieback (*Ceratobasidium theobromae*) (Medeiros et al. 2010; ten Hoopen and Krauss 2016). In some cases, the microclimate of a CAFS can encourage populations of a pathogen's natural antagonists or minimise fluctuations of air humidity that initiate fungus sporulation and favour autoinfection (Evans 1998; Medeiros et al. 2010). For example, black pod disease is known to proliferate on cacao under simple shade cover, yet has been found to be significantly reduced under a more diverse layer of shade (Arnold et al. 2003 in Bos et al. 2007a). This effect is likely due to the high diversity of cacao endophytes present under high shade levels, which are important antagonists of this disease (ten Hoopen and Kraus 2016). Loguercio et al. (2009) discovered appearance of different microclimates along a vertical gradient in simple CAFS in Brazil, that affected sporulation of biocontrol agent (*Trichoderma stromaticum*) and subsequent antagonism to *Moniliophthera perniciosa*. Hence it appears that many areas remain to be explored in order to better understand and manage the effects associated tree species have on fungal communities' development in CAFS.

Pest control

The relationship between CAFS and pests is complex and highly variable. Associated trees can encourage ant populations known to protect cacao trees from pests such as the cacao bug *Helopeltis theobromae* (Schroth et al. 2000). Associated trees can also create an environment not favoured by the many herbivorous pest species preferring full sun environments (Babin et al. 2010). In their exclusion experiment in Indonesian CAFS of varying degrees of shade cover, Gras et al. (2016) found exclusion of ants strongly reduced cacao yields due to the subsequent rise in herbivore numbers in all but highly shaded CAFS (from 600 to 300 kg ha^{-1} year^{-1} at 15% canopy cover). Unexpectedly, exclusion of birds reduced yield (400 to 250 kg ha^{-1} year^{-1}) at 60% and increased yield (from 500 to 830 kg ha^{-1} year^{-1}) below 30% canopy cover (Gras et al. 2016). In CAFS in Brazil, bird exclusion gave rise to increased leaf damage and bat exclusion resulted in greater arthropod and plant-sucking insect relative abundance (Cassano et al. 2016). Furthermore, exclusion of these species, likely to arise to some extent with system intensification, impacted arthropod pest populations while shade variation did not; suggesting landscape-effects are more important than effects at the plot scale for pest control in this instance (Cassano et al. 2016). Sun-loving pest species for cacao include thrips (*Selenothrips rubrocinctus*), mirids (*Sahlbergella, Distantiella*) and the leaf miner (*Leucoptera meyricki*) as well as diseases that follow mirid attack (tracheomycose, *Calonectria, Colletotrichum*) and tend to be reduced under the shade environment of CAFS (Babin et al. 2010; Mossu et al. 1990 and Willey 1975 in Schroth et al. 2000). The impact of certain pests on cacao has also been found to be reduced in CAFS due to physical protection from mammal and bird pests provided by shade trees, even in relatively simple CAFS (Gras et al. 2016; Schroth and Harvey 2007). As for diseases, certain shade species can act as alternative hosts of pests, such as the Malvacae family and *Cola* spp which are known hosts for mirids (Babin et al. 2010). Hence it appears that, as for diseases, many areas remain to be explored in order to better understand—and then cope with—the effects of associated trees species on pest communities' development in CAFS.

Pollination

Rather little is known about pollination services in cacao (Chumacero de Schawe et al. 2016), despite all cacao varieties being dependent on insect pollination for pod development (Klein et al. 2008). Like many tropical plants, despite producing many flowers, only a few are pollinated—in cacao, less than 10% of flowers are pollinated and less than 5% of flowers reach pod development phase (Córdoba et al. 2013; Orozco-Aguilar and Sampson 2017). Cacao flowers are very small, and pollination by midges, particularly of the Ceratopogonidae family, are considered a key determinant of cacao yield (Córdoba et al. 2013; Gras et al. 2016; Groeneveld et al. 2010). However, on wild and planted cacao trees in Bolivia, use of glue to trap 631 visitors to 2237 cacao flowers identified a variety of visitors to cacao plants, suggested that Hymenoptera and small Diptera other than Ceratopogonidae may be important pollinating species in that region (Chumacero de Schawe et al. 2016). Overall shade cover is thought to be more important to pollinator abundance and assemblages in CAFS than shade tree species diversity (Córdoba et al. 2013), though both are important. Abundance of pollinating midges increases with density of cacao trees, leaf litter cover and decomposing fruit present on the ground (0.17–19.51 pollinators m^2, mean 4.6) (Córdoba et al. 2013). Multiple studies report strong influences on overall cacao pollinator abundance are shade, level of management intensity, use of inputs, and presence of other species (Orozco-Aguilar and Sampson 2017). Manual pollination may be an option to improve cacao yields in some regions such as Central America, but optimum pollination levels are difficult to determine given interactions with other factors influencing the loading capacity of the cacao tree such as nutrients, water and light (Orozco-Aguilar and Sampson 2013).

Conservation

CAFS are located in some of the world's biodiversity hotspots and when of complex composition can contribute significantly to biodiversity conservation (Bisseleua et al. 2009; Clough et al. 2009). Compared to other agricultural land uses replacing intact tropical rainforests, traditional CAFS with complex and structurally detailed canopies represent one of the least damaging to original forest biodiversity and one of the most biodiverse agroforestry types, with high capacity to conserve wildlife (Muschler 2016; Schroth and Harvey 2007; Vebrova et al. 2013). However, CAFS cannot represent a substitute for natural forest (Haro-Carrión et al. 2009; Jadán et al. 2015; Saj et al. 2017).

Individual species: diversity, abundance and habitat

The provision of habitat by CAFS on a plot scale is highly taxa and system dependent (Asare et al. 2014; Cassano et al. 2009; Deheuvels et al. 2014; Faria et al. 2007). The CAFS in place influences species' community composition and population density, abundance and richness (Table 3). While some CAFS can provide habitat for biodiversity, in most CAFS high amounts of thinning occurs, resulting in a substantial reduction in plant species diversity (Shannon index, species richness) compared to natural rainforest (Abada Mbolo et al. 2016; Sambuichi et al. 2012). In Cameroon, when compared to near-by forests, the reduction in tree density was found to range from 95% to ca. 70% and that of tree species richness to range from 80% to ca. 30% according to the complexity of the CAFS (Saj et al. 2017). Also in Cameroon, Abada Mbolo et al. (2016) observed a range of CAFS retain an average of 46% of near-by forest tree species. Sonwa et al. (2007) observed a reduction in the number of tree species in complex CAFS compared to primary forests in southern Cameroon (27.5%) and South-Western Cameroon (62.1%), respectively. This reduction is even more profound when natural forests are converted to cacao plantations (species richness 42 ± 13.4 compared to 19.2 ± 4.7 in 20 year old cacao stands in Côte d'Ivoire) (Tondoh et al. 2015). Ngo Bieng et al. (2013) studied a range of CAFS and found higher forest tree diversity in CAFS with clustered spatial structure (average richness 6.17 ± 0.79) compared to random or regular structures (4.00 ± 0.53; 4.47 ± 0.53 respectively), as the range of local environments in this structure favours existence of various functional types. However, in Central Cameroon where associated tree species are maintained in the long-term, conservation of tree species with a recognized conservation value has proven stable where their occurrence depends on CAFS complexity (Jagoret et al. 2014; Saj et al. 2017). Furthermore, Vebrova et al. (2013) remark a difference in taxonomic composition of CAFS (most common tree families) compared with primary and secondary forests. This is likely due to selection of planted species with uses for local communities (fruit, timber & fuel wood), which may influence whether the CAFS can support original flora and fauna. These changes in taxonomic composition are likely to be translated in terms of functional ecology. For example, Saj et al. (2017) showed that the distribution of some functional groups (e.g. leaf life span strategy, succession guilds) change when forests are converted into CAFS. Distributions of functional groups in this study were significantly altered by densities of associated trees in CAFS, with pioneer and deciduous species being regularly favoured by farmers even in the more complex systems. Haro-Carrión et al. (2009) observed complex CAFS can conserve vascular epiphyte biodiversity but are not a substitute for natural forest (average number epiphytes 101 in complex CAFS, 138 in forests. 50 × 50 m plots). Finally, altered forest structure and dynamics results in reduced availability of food resources (fruits, flowers and leaves of native tree and liana species) and a highly fractured canopy that impedes mobility of many arboreal species (Rolim and Chiarello 2004), such as sloth species (Vaughan et al. 2007).

Landscape connectivity

As CAFS does not represent a substitute for natural forest in terms of conservation for many species (Haro-Carrión et al. 2009; Jadán et al. 2015; Saj et al. 2017), the contribution of CAFS to biodiversity conservation should also be considered on a landscape scale. Sambuichi et al. (2012) surveyed diversity of non-cacao trees in *Cabruca* systems in Brazil and concluded that complex CAFS have high diversity for an agricultural system (Shannon index ranging from 2.21 to 3.52) yet are poor substitutes for native forests concerning tree species richness (CAFS maintains on average 13.6% of natural forest species richness). Vebrova et al.'s (2013) comparison of CAFS to primary and secondary forest also concluded that CAFS are not a substitute for natural forests regarding taxonomic composition, tree community and spatial

Table 3 A selection of impacts of CAFS on biodiversity, comparing different levels of CAFS complexity and forests

System compared	Country	Species measured	Finding	Reference
CAFS versus forest (with different levels of perturbations)	Brazil	Birds, bats, frogs, ferns, and lizards	Species abundance lower in *Cabrucas*, patchiness and landscape forest cover important influence	Faria et al. (2007)
		Literature review: vertebrate fauna, invertebrate fauna and flora	Spatial configuration of different vegetation types (canopy composition and density) impacts habitat quality	Cassano et al. (2009)
	Cameroon	Tree species diversity	Reduction of 27.5% (south Cameroon) and 62.1% (southwest Cameroon) in no. tree species in CAFS compared to primary forests	Sonwa et al. (2007)
	Costa-Rica	Terrestrial vegetation, non-cacao epiphytes, soil macro-invertebrates, leaf-litter macro-invertebrates (species composition)	Significant differences	Deheuvels et al. (2014)
	Dominican Republic[a]	Birds and lizards (population densities)	Similar	Deheuvels (2015)
	Indonesia	Ants (species richness)	Similar	Bos et al. (2007b)
		Ants (community composition)	Significantly different	
		Beetles (species richness and abundance)	Similar	
	Peru	Tree composition, community characteristics, spatial structure	CAFS resembles secondary forest in species composition (richness and diversity), both much lower than primary forest	Vebrova et al. (2013)
Different types or tree densities of/in CAFS versus forest (with different levels of perturbations)	Brazil	Soil and litter fauna	Significant differences; acidity, nutrition and palatability key factors	Moço et al. (2010)
	Cameroon	Tree species richness, diversity and functional groups	Reduction from 95% to ca. 70% in tree densities, and from 80 to 30% in tree species richness, alteration of succession guilds and leaf life span strategies shares	Saj et al. (2017)
	Costa-Rica	Number of species (general)	Heavier shade and denser canopies have more species in common with native forest	Deheuvels et al. (2014)
CAFS versus forest versus monoculture	Ecuador	Species richness & beta-diversity of forest trees, C stocks, cacao & timber production	Negative correlation between cacao productivity and species richness, beta-diversity and total C	Jadán et al. (2015)
Different types of CAFS ans/or monoculture	Cameroon	Ants (species richness)	Higher in floristically and structurally diverse systems	Bisseleua et al. (2009)
	Costa-Rica	Forest trees	Higher species richness in CAFS with clustered spatial structure	Ngo Bieng et al. (2013)

Table 3 continued

System compared	Country	Species measured	Finding	Reference
		Birds and bats (species communities)	More diverse in simple CAFS than cacao monocultures	Harvey and Gonzalez (2007) in Schroth and Harvey (2007)
		Mammals and beetles (species richness)	Higher in simple CAFS than cacao monocultures	Harvey et al. (2005)

[a] Mostly CAFS with 3 major associated species: *Cocos nucifera*, *Erythrina poeppigiana* and *Roystonea hispaniolana*

structure (first order Jackknife estimated tree species richness 108.8 in primary forest, 45.4 in CAFS and 23.2 in secondary forest). Faria et al. (2007) also found community assembly of birds, bats, lizards, frogs and ferns of *Cabruca* forests was richer when greater landscape forest cover was maintained. Multiple authors suggest CAFS with diverse tree species can be seen as a buffer habitat promoting overall landscape heterogeneity, ecological corridors, buffer zones around protected areas or primary forests, and habitat, particularly when large forest trees are preserved (Cassano et al. 2009; Faria et al. 2007; Haro-Carrión et al. 2009; Sambuichi et al. 2012; Vebrova et al. 2013). Furthermore, Gras et al. (2016) found increased cacao yields with proximity to forests across Indonesian CAFS of different shading structures. Asare et al. (2014) identified important considerations to account for when establishing CAFS as ecological corridors in Ghana: extent of land use intensification, population density, resources available to wildlife, conservation laws and policy instruments, and local traditions and culture. Overall, there is much less research on the role of CAFS in landscape connectivity than in biodiversity conservation, though the role the play in both of these services is likely equally important.

Discussion

This review has presented knowledge on the provision of important supporting and regulating ecosystem services at multiple scales in CAFS around the world. Drawing clear conclusions from CAFS literature was difficult when not all articles provided detailed spatial or structural information on the CAFS, or at least not in comparable ways, and tended to lack description of the differences between CAFS covered by the review.

Research areas for optimizing supporting and regulating services in CAFS

A greater focus on the density of cacao planting, its management and renewal as well as on associated species introduction/preservation and management is needed in research on supporting and regulating services at the plot scale (e.g. Jagoret et al. 2017). Research on water cycling is required and needs to focus on the role of shade trees and influence of soil depth. While there is detailed knowledge on pest and disease occurrence in CAFS, more detailed knowledge on spatial arrangement, tree densities or species to use would help design CAFS to minimise pest and disease pressures. More detail on pollination ecology in all CAFS types would help to identify how to increase pollinator abundance and subsequent yields (Córdoba et al. 2013; Orozco-Aguilar and Sampson 2017). Canopy exclusion and manual pollination experiments may be useful in this area (Gras et al. 2016; Córdoba et al. 2013). On biodiversity conservation in CAFS, research should focus on the role of CAFS in landscape connectivity (Torquebiau et al. 2013) and be specific about CAFS type. Biodiversity assessments of CAFS should include comparisons with natural forests so that biodiversity value is not overestimated (Bos et al. 2007b), and be long term.

Overall, the high complexity and diversity of CAFS encountered all around the world suggests that research could be tackled in more original ways than have been occurring until present. Modelling interactions between different supporting and regulating services is one option which may help understanding of field results (see "Nutrient availability and cycling" section), another is the Pareto frontier approach: mapping the various relationships in an ecosystem along a curve to identify optimization points between trade-offs and synergies (Rapidel et al. 2015). Functional ecology and nutrient stoichiometry are other areas for future research in CAFS which appear less frequently in the literature but hold potential to improve understanding of CAFS. Finally, Fig. 2 shows that greater interest has been given to supporting and regulating services in the Americas and in Africa than in Asia, though Asia is the only region which has researched water use in CAFS (among studies considered by this review). Diversifying the research field with respect to research topics and growing regions, and greater exchange of results between regions would help identify where results are regional-specific or transversal, and would thus assist a greater understanding of CAFS around the world.

Provisioning and cultural ecosystem services

Regional differences regarding ecosystem services will become more pronounced when provisioning and cultural services are taken into account, given their dependence on culture, economies and governments that operate on a local and/or regional scale. Provisioning services in CAFS other than cacao yield come from other species providing food, fuel, timber and fibre (Bentley et al. 2004; Bisseleua et al. 2009; Deheuvels 2015; Magne et al. 2014; Schneider et al. 2016). Among these services, provision of food for household consumption appears to be the most important service provided, more so than provision of food or other products for the market (e.g. *Musa* (banana), *Mangifera* (mango) or *Persea* (avocado) (Bisseleua et al. 2009), though in Latin America timber production is an important secondary source of income in simple CAFS with >10% shade (Jadán et al. 2015). Key cultural services include attachment of cacao producers to their land, potential tourism related to intact forests that CAFS can help protect, and also consumer interest in eco-friendly cacao production (Bentley et al. 2004; Jadán et al. 2015). Farmers' knowledge, beliefs, and socioeconomic situation are central to decision making at the farm level (Andres et al. 2016; Asare et al. 2014; Dahlquist et al. 2007). Access to markets, certification schemes, the need to provide food for the family, and the value (both economic and social) of fruit, medicinal and timber species that can be grown with cacao are all important influences on provisioning and cultural services and consequently management decisions in all CAFS types (Andres et al. 2016; Asare et al. 2014; Bentley et al. 2004; Bisseleua et al. 2009; Jadán et al. 2015; Magne et al. 2014; Schroth et al. 2016).

Trade-offs

Trade-offs between provision of supporting and regulating services and provisioning and cultural ecosystem services such as yield, profitability, and cultural values often arise, as well as trade-offs within these service groups, and occur over a range of temporal and spatial scales. Examples of within service group trade-offs include those between climate mitigation and adaptation strategies in tropical agricultural systems (Harvey et al. 2013) and between optimum shading conditions for cacao growth and pest and disease control. Considering trade-offs helps to design CAFS which maximise yields and ecosystem service provision (Rapidel et al. 2015). However, the diversity of systems and management practices in place makes identification of clear trade-offs difficult (Magne et al. 2014). Conceptualizing agricultural systems at a landscape level is important in the evaluation of trade-offs (Cassano et al. 2009; Faria et al. 2007; Torquebiau et al. 2013).

Regarding conservation trade-offs, Wade et al. (2010) found aboveground C storage was 84% of forests in traditional CAFS (>25% shade) and 25% of forests in intensive cacao systems (<25% shade) (155, 131 and 39 Mg C ha^{-1} for forests, traditional and intensive CAFS) in Ghana, yet yield significantly increased in intensive cacao farms (321 kg ha^{-1} year^{-1};) compared to traditional farms (63 kg ha^{-1} year^{-1}). Magne et al. (2014) found intensive cacao systems with fertilizer inputs in Cameroon gave higher yields (967 kg ha^{-1} with fertilizer, 513 kg ha^{-1} without fertilizer) than traditional CAFS with low or no fertilizer treatment (346 kg ha^{-1}), yet the later had greater carbon storage. Also in Cameroon, Saj et al. (2013) found that mean basal area of cacao trees (a proxy often used to indicate cacao yield) related negatively to the Holdridge complexity index (used to assess forest structure diversity and species composition), yet C content in CAFS live trees related positively to the same index. In Ecuador, Jadán et al. (2015) also found yield and profitability 1.5 times greater in intensive cacao systems (<10% shade) than in CAFS (>10% shade), but C storage was 4–6 times greater, and beta-diversity and tree species richness higher, in CAFS than in intensive cacao sites.

To manage conservation trade-offs, Wade et al. (2010) compare *land sparing*, in which some land is devoted to intensive production and the rest restored or retained as forest; with *wild-life friendly*, a low yield approach favouring ecosystem services over the whole land area. In Ghana, a *land sparing* scenario with 38% of land under intensive cacao farming and 72% retained or restored as forest was identified as the optimum scenario to maintain reasonable cacao yields, C storage and biodiversity (Wade et al. 2010). However, an important point to consider described as the *boom and bust* cycle of cacao development is that intensive cacao systems are often associated with significant reductions in yield over time due to aging cacao trees, pest & disease encroachment, and soil degradation, and this often leads farmers to encroach on nearby forests to establish new plantations (Clough et al. 2009).

Regarding socio-cultural goals such as resilience to markets, growing cacao with other primary cash crops is a good way to maintain high overall yields and maintain some resilience to price fluctuations (Schneider et al. 2016; Sujatha and Bhat 2013). Sujatha and Bhat (2013) found *Areca*-cacao systems in India produced higher yield per unit area than *Areca* only systems, an important finding for areas such as India where space is limited by population demands for urbanization and industrialization (Sujatha and Bhat 2013). In Bolivia, a long term field trial found overall higher yields in CAFS than in cacao monocultures, despite higher light availability in the latter encouraging young plant growth (Schneider et al. 2016). In these cases, choice of tree species providing commercially viable products can boost income and increase resilience to shocks from global cacao price fluctuations, while maintaining the ecosystem services provided by CAFS (Jadán et al. 2015; Magne et al. 2014; Schneider et al. 2016). Also on socio-economic resilience, a comparison of organic and conventional monocultures and CAFS found much greater yield gaps between organic and conventional monocultures than between organic and conventional CAFS (Schneider et al. 2016), suggesting dependence on agrochemical inputs may be reduced and reasonable yields maintained in CAFS. This is important as many CAFS farmers do not use, or do not have reliable access to synthetic fertilizers (Jadán et al. 2015; Schneider et al. 2016).

To avoid negative effects of trade-offs, landscape planning considering environmental, social and economic goals of agricultural systems is key (Harvey et al. 2013). In some countries, the alleged incompatibility between agronomic, economic and ecological objectives in CAFS has encouraged the emergence of payment mechanisms for ecosystem services in order to encourage adoption of less intensive systems (Rapidel et al. 2011). Payments for C storage may help to offset losses in yield, but the significantly higher net profitability of cacao than C does not support this as an adequate replacement alone (Jadán et al. 2015; Magne et al. 2014). Another payment scheme option is one for biodiversity conservation such as those in coffee, which offers potential but has unconfirmed and highly variable success rates (Clough et al. 2009). Overall, there is a need for greater research into economic and socio-cultural valuation of trade-offs with ecological functions across a range of CAFS types, as overcoming these is a major challenge for the industry (Jadán et al. 2015; Magne et al. 2014; Vaast and Somarriba 2014).

Conclusion

This review has provided an overview of recent literature on supporting and regulating ecosystem services in CAFS around the world. Overall, the literature points to an ability for the wide range of CAFS types to support water and nutrient availability and cycling as well as pest and disease control, depending on the management strategy and species in place. Competition for nutrients and increased pest and disease occurrence can occur depending on tree species chosen. Regarding conservation, CAFS in general do not represent a substitute to natural forest for most species. However, on a landscape scale, complex CAFS can contribute to biodiversity conservation, particularly through landscape connectivity and use of local tree species, as well as to climate mitigation through C storage in soils, and biomass in large trees. Key knowledge gaps involve differences in supporting and regulating service provision between CAFS typologies, optimal spatial arrangement of cacao trees to minimize pest and disease occurrence while maintaining other ecosystem functions, and pollination services. However, much knowledge on these services is available today which can contribute to discussions about trade-offs with yield and other provisioning and cultural services to improve CAFS design. Current knowledge on trade-offs suggests that higher economic profitability of cacao monocultures in the early years of establishment may be outweighed by CAFS when long-term yields and quality indicators are considered, as well as contribution of non-cacao products to farmer resilience, and C-storage and conservation to ecosystem integrity. Overall it appears that provision of ecosystem services and associated trade-offs in CAFS are highly complex and demand consideration at all spatial and temporal scales in order to define optimal systems that improve livelihoods without degrading the important ecosystems in which they are found.

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