Scaling Cocoa Agroforestry

A spatial approach to estimate the carbon sequestration potential of global cocoa agroforestry production

By

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Abstract

Cocoa production plays a significant role in global tree cover and biodiversity loss. Amid rising concerns over its role in environmental degradation, agroforestry has emerged as a potential solution to satisfy growing global demand for cocoa in a climate-smart and sustainable way. As a shade tolerant crop, there has been much discussion over the potential ecosystem service benefits that cocoa agroforestry can provide if adopted in degraded production areas. However, not much is known in the academic literature regarding the amount of cocoa agroforestry that currently exists globally. It is also unclear to what extent cocoa agroforestry can be scaled up to and what the potential scale of impact of such an endeavor would be in terms of carbon sequestration. This study aims to address these questions by developing a spatial model that uses georeferenced data on global cocoa production and percentage of tree cover in agricultural areas to estimate the presence and distribution of cocoa agroforestry globally. Using data from the MapSPAM project on the physical area of cocoa production, this study found that approximately 10-21% of global cocoa production areas were covered by cocoa agroforestry systems in 2010. By applying global average findings on cocoa agroforestry benefits from Niether et al. 2020 to global cocoa monoculture areas in 2010, this study found that scaling agroforestry would contribute to sequestering approximately 175 to 199 million tons of carbon. This study also found that scaled agroforestry adoption is likely to reduce cocoa production by about 1.2 to 1.3 million tons per year. Further research examining the carbon benefits and ecosystem services of agroforestry adoption at different regional levels is needed to improve estimates provided in this global assessment. Moreover, challenges in adopting agroforestry are likely to differ across the multiple cocoa producing regions. Further research is thus needed to highlight the environmental constraints and socio-economic bottlenecks that may limit the benefits of agroforestry adoption in each of these regions.

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1. Introduction

1.1 Agriculture and climate change

The agricultural sector currently faces an enormous challenge. How can it meet increasing production demands while reducing the wide-ranging environmental impacts caused by conventional agricultural practices? Conventional agriculture contributes significantly to climate change, biodiversity loss, and the degradation of terrestrial and aquatic ecosystems. Today, croplands and pastures are estimated to cover about 38% of Earth's terrestrial surface (12% and 26%, respectively) (Foley, et al., 2011). This is the largest allocation of land for use by one sector (Foley, et al., 2011). Deforestation to clear land for crop production and livestock raising currently accounts for 12% of global GHG emissions (Foley, et al., 2011; Hosonuma, et al., 2012; IPCC, 2014; Frank, et al., 2017). Although land-use for agricultural production has only expanded by 3% globally since 1985, this expansion has occurred mostly in the tropics (Foley, et al., 2011). One study found that about 80% of new croplands that emerged between 1980 and 2000 replaced tropical forest areas (Gibbs, et al., 2010). Considering that most global biodiversity hotspots occur in the tropics, slowing and eventually halting agricultural expansion into these areas will be critical in reducing the sector's environmental impacts.

1.2 Environmental impacts of cocoa production

A tropical commodity that is increasing in global demand is cocoa (IISD, 2019). Cocoa is a shade-tolerant crop that is native to humid tropical forest climates in Mesoamerica (Hütz-Adams, et al., 2016). Globally, it is an important agricultural commodity that is primarily grown by smallholder farmers in humid to semi-arid climates that extend from 25˚N to 25˚S along the equator (Asigbaase, et al., 2020). It provides a livelihood to about 40-50 million people worldwide (Hütz-Adams, et al., 2016; Asigbaase, et al., 2020). In 2019, about 5.6 million tons of cocoa beans were produced globally, a 30% increase from the 4.3 million tons produced in 2010 and 93% increase from the 2.9 million tons produced in 2000 (FAOSTAT, 2000, 2010, 2019; Wessel & Quist Wessel, 2015). The top five cocoa producing countries in 2019 were Côte d'Ivoire, Ghana, Indonesia, Nigeria, and Ecuador, accounting for approximately 39%, 15%, 14%, 6% and 5% of global production, respectively (FAOSTAT, 2000, 2010, 2019).

Cocoa cultivation plays a significant role in global tree cover loss (Wade, et al., 2010; Gockowski & Sonwa, 2011; Tondoh, et al., 2015; Wessel & Quist Wessel, 2015; Norris, et al., 2010). It is estimated that the global expansion of cocoa production from 1988 to 2008 replaced 2-3 million ha of forests (Gockowski & Sonwa, 2011; Kroeger, et al., 2017). Other studies have found that this expansion in the global production of cocoa over the past fifty years has cumulatively replaced approximately 14-15 million ha of forest cover (Clough, et al., 2011; Vaast & Somarriba, 2014). To illustrate, it has been found that 80% of the total deforestation seen in Ghana between 1990 and 2008 was driven by agricultural production (European Commision, 2013; Kroeger, et al., 2017). Cocoa production contributed the most to the agricultural expansion in this period, accounting for 27% of total deforestation (European Commision, 2013; Kroeger, et al., 2017).

Increases in deforestation linked to cocoa production is often attributed to declining production per hectare in existing cocoa plots (Tondoh, et al., 2015). This trend is associated with poor soil quality, increased incidences of pests and diseases, as well as poor management practices found in many of these cocoa production areas (Wessel & Quist Wessel, 2015). These challenges are enhanced by increasing temperatures and changing rainfall patterns caused by climate change that are projected to worsen in coming years (Asigbaase, et al., 2020).

1.3 Agroforestry

Amid these concerns, agroforestry practices have gained a lot of attention and momentum in the scientific literature and policy discourse as a climate-smart way to sustainably intensify cocoa production (Blaser, et al., 2018).

Agroforestry is a type of land management system that deliberately integrates woody perennials, such as trees and shrubs, in varying spatial arrangements and temporal sequences in agricultural production (IPCC, 2019a). It has been practiced at a small scale in a variety of agroecological regions including arid, tropical, temperate, boreal, and Mediterranean areas (Nair, 2012). In agroforestry, trees, crops, and animals are integrated to create mutually beneficial relationships, such as providing elements within the system with shade, nutrients, or water.

This land management practice encompasses many different species integration designs that differ in the amount of tree cover, tree density, plant diversity and nature of integration of these elements in the system. The integration of these elements can be done along spatial dimensions, temporal dimensions, or a combination of both (Ruiz-Agudelo, et al., 2019). Examples of tree integration on agricultural fields along a spatial dimension include intercropping with shade trees and other crops, silvopasture, alley cropping, live fences, hedge rows, wind breaks, riparian buffers, and woodlots (Elevitch, et al., 2018) . Examples of tree integration on agricultural fields along a temporal dimension include sequential cropping and diversified multi-strata systems (Elevitch, et al., 2018). Cocoa agroforestry practices generally include shade tree intercropping, alley cropping, live fences, riparian buffers, woodlots, and diversified multi-strata systems (Chavarría, 2021). Figure 1 below provides an example of what a multi-strata agroforestry system looks like. In a multi-strata cocoa agroforestry system, cocoa trees occupy the shrub/understory layer. Tree density and diversity is generally higher in these multi-strata systems than in systems with intercropped shade trees or alley cropping systems.

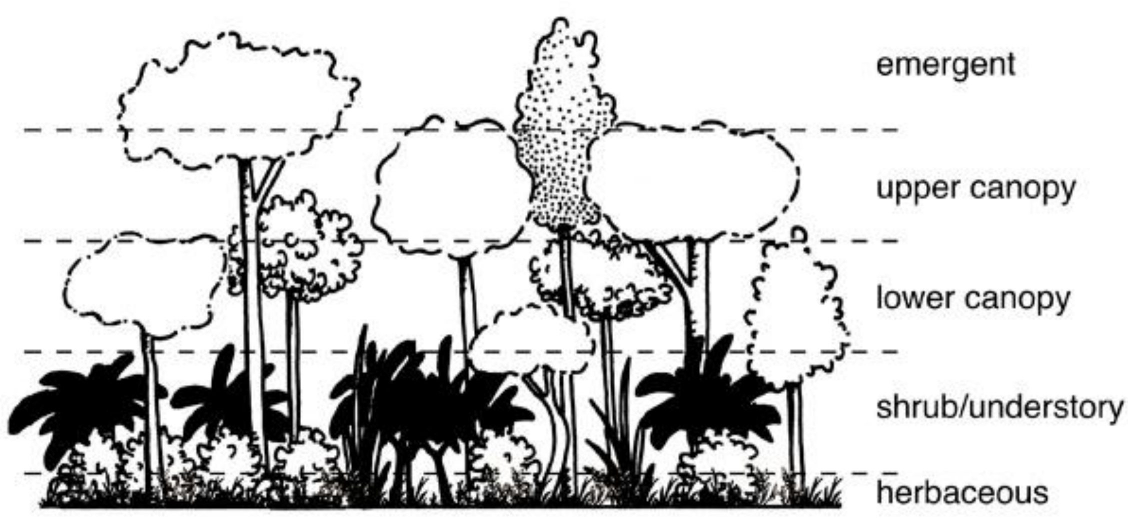

Figure 1: Structure of a multi-strata agroforest system (Elevitch, et al., 2018).

1.4 Benefits and trade-offs of agroforestry in the academic literature

Interest in agroforestry practices recently emerged from findings in the scientific literature regarding its capacity to buffer crops from increasing average temperatures and erratic rain patterns resulting from climate change (Lin, 2007; Jose, 2009; Tscharntke, et al., 2011). Other studies have found evidence that the application of these techniques in certain ecosystems improved soil quality and provided a mechanism that regulated the incidence of pests and diseases (Schroth, et al., 2000; Tscharntke, et al., 2011). Agroforests also contribute to climate change mitigation as it increases the presence of biomass and thus carbon sequestration potential of productive ecosystems (Schroth, et al., 2015; Zomer, et al., 2016). Moreover, by introducing a variety of species in their production system, such as in diversified multi-strata system designs, they can also provide support to preserving biodiversity (Clough, et al., 2009).

While many of the benefits of tree integration into agricultural fields seem intuitive, there is yet to be a consensus in the academic literature regarding their extent and universality (Blaser, et al., 2018). Benefits of agroforestry adoption vary according to the nature of integration of trees and socio-economic conditions present in certain cocoa producing regions (Nair, 2012). Considering the variety of ways in which trees can be integrated and managed to create a productive agroforestry system, the occurrence of shade can produce diverse interacting effects in relation to different variables such as water availability, nutrient availability, pest and disease regulation, and temperature in different ecosystems (Blaser, et al., 2018). As such, it is likely that the net effect of shade on crop production in certain climates vulnerable to extreme changes will not always be positive. Some studies have even contested climate adaptation benefits of agroforestry systems, finding that in certain ecosystems in West Africa, cocoa agroforestry is less resilient to extreme climates than full sun cocoa monocultures (Abdulai, et al., 2017).

Besides ecosystem benefits, many studies in the academic literature have found that cocoa agroforests exhibit lower yields than their monoculture counterparts (Niether, et al., 2020). Shade trees compete with agricultural crops for light, water, and nutrients (Sanchez, 1995). Too much shade in an agroforestry system can lead to lower production quantities because of this competition (Dickie, et al., 2014). A study by Blaser et al. in 2018 found that cocoa agroforestry systems in West Africa with low-to-intermediate shade experienced benefits such as reduced local temperatures and enhanced carbon sequestration with no compromise to production quantities. In their review of cocoa agroforestry case-studies, they found that agroforestry systems with up to 30% shade tree cover were unlikely to experience decreases in mean annual production levels (Blaser, et al., 2018). The probability of production losses increased as shade tree cover in cocoa plots increased beyond 30% tree cover (Blaser, et al., 2018).

In a case-study review performed by Ruiz-Agudelo et al. in 2019, agroforestry systems with a medium diversity of plant species produced greater yields than those systems with less diversity. Systems with a medium percentage of shade cover outperformed systems with high or low percentage of shade cover (Ruiz-Agudelo, et al., 2019). Those systems that had a higher percentage of shade cover tended to be those incorporating multi-strata designs. Yields in these systems were lower than in mono-strata systems because of plants competing for light and resources. Systems with little shade cover also saw reduced yields likely because of reduced water retention of exposed soils (Ruiz-Agudelo, et al., 2019).

Other studies identified in a literature review of agroforestry consider impacts of tree-crop integration on nutrient cycling (Reed, et al., 2017). Systems that had medium and high species diversity, as well as medium and high shade cover performed significantly better in terms of nutrient cycling and water regulation than systems with low species diversity and minimum shade cover (Reed, et al., 2017; Ruiz-Agudelo, et al., 2019).

Other studies found in the literature explored the trade-offs between the ecosystem benefits gained from adopting agroforestry services and income of agricultural producers (Frank, et al., 2017). This trade-off was primarily driven by a reduction in yields of primary crops observed in the case studies that compared yields from monoculture to yields from agroforestry systems. Findings in these studies were often limited by not considering the costs incurred by producers in purchasing inputs, such as fertilizers and pesticides. Other studies also found that agroforestry adoption did not always negatively impact producer livelihoods, as these producers were often able to compensate lost income from reduced yields of primary crops by selling alternative products integrated in the system (e.g., high-value timber, medicinal plants and subsistence crops, such as yams and banana) (Frank, et al., 2017; Reed, et al., 2017; Ruiz-Agudelo, et al., 2019).

2. Research Question

Despite the vast amount of case studies evaluating the ecosystem service benefits and trade-offs of agroforestry adoption in cocoa producing regions, a global assessment providing information about the location and distribution of existing cocoa agroforestry areas is missing from the scientific body of literature. Moreover, it is largely unknown to what scale agroforestry adoption is theoretically feasible. Given the potential ecosystem service benefits of agroforestry adoption in many cocoa producing regions, understanding how much area is available to expand this land management practice to could provide some indication on the potential scale of impact of such an expansion in terms of carbon benefit and annual cocoa production. Recognizing this knowledge gap thus led to the following research question:

What is the carbon sequestration potential of upscaling agroforestry for global cocoa production?

Using 2010 as a reference year, this study aims to address the research question by first developing a spatial model that approximates the global distribution of cocoa agroforestry farms. This model is then used to estimate the number of hectares of cocoa agroforestry and cocoa monoculture that existed globally that year. Without these baseline estimates, it is hard to visualize the scope of impact in terms of carbon benefits. When scaling carbon benefits, only areas with existing cocoa production are considered. As some studies on agroforestry have found adoption in certain areas to have compromised yields, this study also evaluates the potential trade-off of agroforestry adoption in terms of yield and production losses. A global assessment is made to evaluate the scale of this trade-off against the scale of potential carbon benefits. Such an evaluation could provide stakeholders in the cocoa sector with more clarity regarding the potential of agroforestry as a pathway towards more sustainable and climate-smart production.

Considering the consumer and regulatory pressures the cocoa sector faces to address the environmental impacts associated with its production, the aim of this study is to provide stakeholders in the sector with a rough estimate of the potential scale of impact of supporting agroforestry transition projects in their supply chains. Considering developments in the voluntary carbon market, having a sense of the order of magnitude of removal units available through cocoa production management options could encourage key stakeholders to mobilize resources and invest in solutions that facilitate and effectively scale the adoption of agroforestry practices by smallholder cocoa farmers.

3. Methods

This study seeks to address the main research question by employing a top-down analytical approach. A spatial analysis that is global in scope was developed to reach a rough approximation of areas in cocoa producing regions managed as an agroforestry system. The aim of the spatial model is to estimate the approximate location and distribution of agroforestry production areas in the main cocoa producing regions, the area covered by cocoa agroforestry in 2010, and the area covered by cocoa monoculture in 2010. The datasets used for the spatial analysis include:

- "The Spatial Production Allocation Model (SPAM)" developed by the International Food Policy Research Institute (IFPRI) – available at http://mapspam.info
- "Global Tree Cover and Biomass Carbon on Agricultural Land" published by Zomer, et al. in 2016

Percentage of tree cover is used as a proxy to identify agroforestry systems in agricultural production areas. For purposes of this study, agroforestry is defined as productive agricultural areas with at least 30% tree cover**.** A 30% minimum tree cover threshold was chosen to identify agroforestry systems because that is the threshold used by Rainforest Alliance to certify agroforestry and forest friendly cocoa (Rainforest Alliance, 2017). To observe the effect on changes to land allocation, another dataset was created that defines agroforestry as agricultural areas with at least 40% tree cover. The spatial model thus considers two separate agroforestry threshold conditions and compares their output for hectares of cocoa agroforestry systems and hectares of cocoa monocultures. In addition, this study assumes that the share of land area covered by cocoa agroforestry systems is proportional to the share of agroforestry present in an agriculturally productive region. For example, if 10% of a cocoa producing cell is covered by agroforestry, then it is assumed that 10% of the cocoa production area in that cell is cocoa agroforestry.

Once land areas covered by cocoa agroforestry and monoculture systems are quantified, estimates of the mean carbon benefit and cocoa yields are taken from Niether, et al. 2020. The referenced study conducted a meta-analysis comparing the provision of ecosystem services between cocoa agroforestry systems and coco monocultures. Estimates from this study (Table 1) are then used to quantify the potential impact of scaling cocoa agroforestry to global cocoa production areas present in 2010 on carbon sequestration and on cocoa production quantities.

	Cocoa Agroforestry		Cocoa monoculture		Factor
	mean	**SD**	**mean**	**SD**	
Total C in system ($t \cdot ha^{-1}$)	37	± 28.9	14.2	± 9.0	2.6
Cocoa yield ($t \cdot ha^{-1}$)	0.6	± 0.4	0.9	± 0.7	1.5

Table 1: Mean values, standard deviations, and factor difference for yields and total carbon sequestered by cocoa agroforestry and monoculture systems (Niether, et al., 2020).

Two scenarios are defined to evaluate the potential scale of impact on both carbon storage and cocoa production quantity.

- Scenario 1 is the "2010 Estimate" scenario - it considers the total carbon stored by cocoa production in 2010 given the results from the spatial analysis for cocoa agroforestry area and cocoa monoculture area. For cocoa production quantity, it considers the values reported by the SPAM dataset for cocoa production and yield in 2010.

- Scenario 2 is the "Scaled Agroforestry" scenario - it considers the total carbon stored by cocoa production if all areas identified as cocoa monoculture area in 2010 were converted to and allocated the benefits of cocoa agroforestry systems. For cocoa production quantity, it considers the global amount of cocoa production if all areas identified as cocoa monoculture in 2010 were converted to and allocated yields found in agroforestry systems.

To quantify carbon stored by cocoa production for Scenario 1, the mean total carbon stored in cocoa agroforestry systems (t/ha) is applied to the total area of cocoa agroforestry (ha) estimated by the by the model using data from 2010. Similarly, the mean total carbon stored in cocoa monoculture systems (t/ha) is applied to the total area of cocoa monoculture (ha) estimated by the model using data from 2010. The estimate for Scenario 1 is thus the sum of total carbon stored (t) by cocoa agroforestry areas and total carbon stored in monoculture areas in 2010. For Scenario 2, the mean total carbon stored in cocoa agroforestry systems (t/ha) is applied to the total area of cocoa production (ha), i.e. total cocoa agroforestry area and total cocoa monoculture area existing in 2010. The potential scale of impact of converting all cocoa monoculture areas to cocoa agroforestry systems is thus the difference in total carbon stored (t) by cocoa production between Scenario 1 and Scenario 2.

To estimate the scale of impact of such a transition on annual cocoa production quantity, the production layer from the SPAM dataset was used. For Scenario 1, values for production of dry cocoa beans from the SPAM were summed across all cocoa production cells to get a global estimate for total tons of cocoa produced in 2010. For Scenario 2, production values for each cocoa production cell were separated according to the share of agroforestry and monoculture present in that cell. Values for monoculture production of dry cocoa beans were then divided by the factor difference between mean results for cocoa yield found by Niether et al. 2020 (Table 1). Adjusted monoculture production values were then summed with corresponding production values for existing cocoa agroforestry systems for each cell. The potential scale of impact of scaling agroforestry on cocoa production quantity is the change in total production quantity between Scenario 1 and Scenario 2.

To complement the global spatial analysis, interviews were conducted with stakeholders involved in the cocoa supply chain. The following individuals were interviewed throughout the course of this study.

- Bo van Elzakker – Director of AgroEco at the Louis Bolk Institute, an independent advisory-research-development organization that is focused on developing and scaling organic product value chains in West Africa.
- Emma van de Ven – Strategy Lead for the Acorn Project at Rabobank, a project that seeks to support smallholder farmers transition to agroforestry production by leveraging ex-post carbon removal unit purchases.
- César de Mendes – Founder of Chocolates deMendes, a Brazilian artisanal chocolate brand that exclusively procures native Amazonian or agroforestry cocoa with the aim of contributing to the indigenous cultural preservation and environmental conservation of the Brazilian Amazon.
- Jean-Yves Chavarría Duriaux – Research and Development Consultant at the Cornell Lab of Ornithology, a research lab dedicated to advancing and supporting biodiversity conservation through research, education, and citizen science on birds.

- Jerry Toth – Co-founder and Director of Operations at the Third Millennium Alliance, a non-governmental conservation organization that supports smallholder farmers in Ecuador transition to agroforestry management by leveraging payments for ecosystem services and providing training in conservation farming.

Interviews were done to collect information and distill insights about the social, economic, and technical challenges that smallholder cocoa farmers face in Latin America and West Africa to adopt agroforestry practices.

A general overview of the approach used in the study is provided in Figure 2 below.

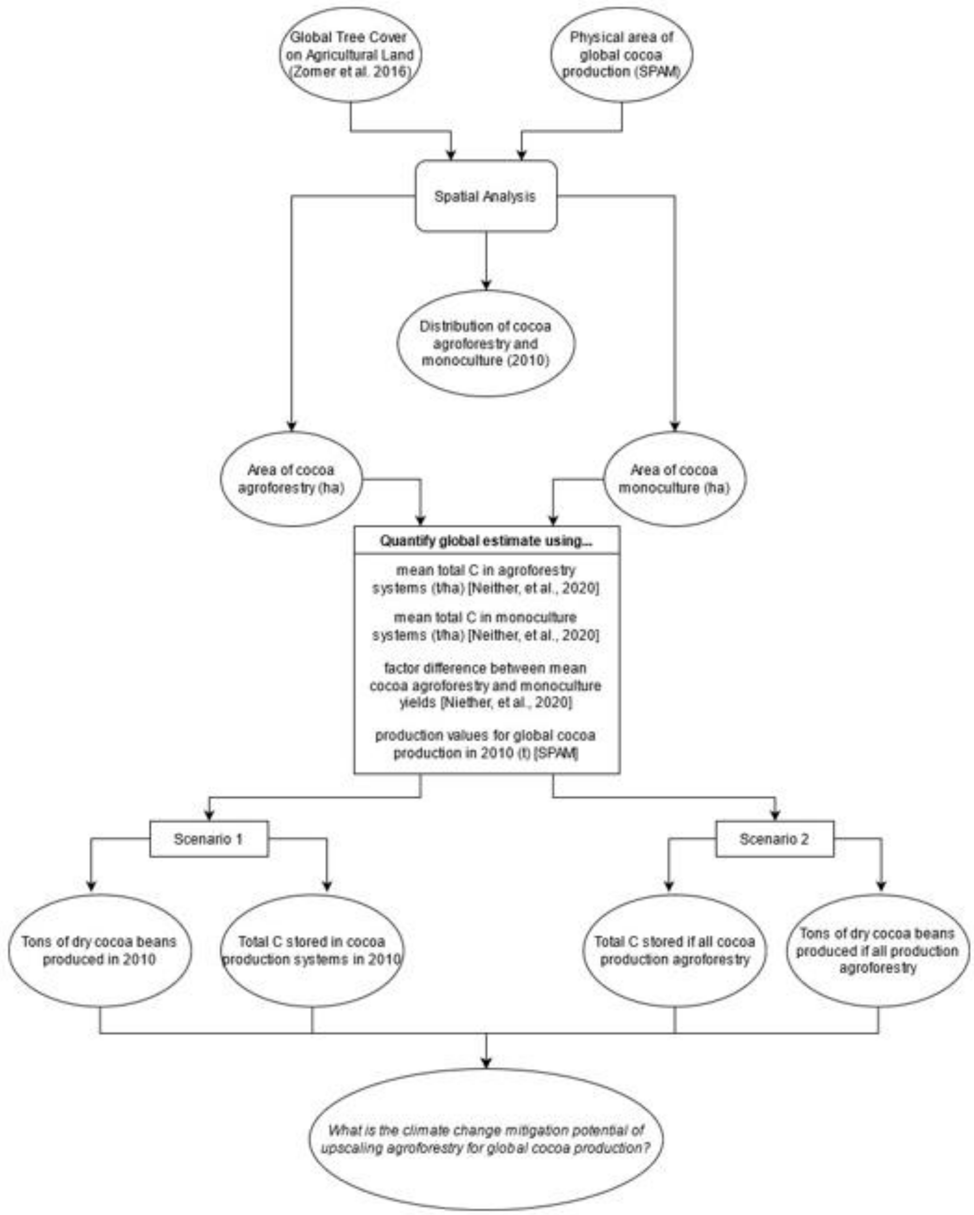

Figure 2: Overview of the Research Approach.

4. Results and discussion

4.1 The global distribution of cocoa agroforestry and monoculture production

The total amount of land cover used to cultivate cocoa in 2010 reached approximately 9.8 M hectares (You, et al., 2014). Results from the MapSPAM global dataset and the global spatial analysis of this study were broken down to consider variations in the allocation of land to cocoa production, cocoa agroforestry, and cocoa monoculture across the four main cocoa producing regions – West Africa, South America, Central America, and Southeast Asia.

In 2010, cocoa production areas in West Africa accounted for approximately 64% (6.2 M ha) of the global land area dedicated to cultivating cocoa (You, et al., 2014). Production regions in South America, Central America and Southeast Asia accounted for 13% (1.3 M ha), 3% (0.3 M ha) and 19% (1.9 M ha) of total global cocoa production area respectively (You, et al., 2014). The remaining 0.7% (0.1 M ha) of global cocoa production area is found in Central Africa (You, et al., 2014).

Using a minimum threshold of 30% tree cover as a proxy to identify agroforestry production areas, this study found that cocoa agroforestry occupied 2.1 million ha of land globally (Table 2). As such, cocoa agroforestry accounted for 21% of global cocoa production area in 2010 (Table 3). Although West Africa is the largest cocoa producing region in terms of both physical area and annual cocoa production, it is the region with the smallest share of cocoa agroforestry production relative to its total production area. This study found that only 15% (1 million ha) of cocoa production areas in West Africa were managed in agroforestry systems. The share of cocoa production areas that are managed in agroforestry systems in South America, Central America, and Southeast Asia account for 21% (0.3 million ha), 47% (0.1 million ha), and 39% (0.7 million ha) of total cocoa production areas in each of their regions, respectively.

Agroforestry threshold	Cocoa agroforestry area in 2010 (ha)	Cocoa monoculture area in 2010 (ha)	Total cocoa production area in 2010 (ha)
30% min. tree cover	2.1 million	7.7 million	9.8 million
40% min. tree cover	1.1 million	8.7 million	9.8 million

Table 2: Estimated global area of cocoa agroforestry systems and cocoa monocultures in 2010.

Agroforestry threshold	Cocoa agroforestry	Cocoa monoculture
	Share of total cocoa production area in 2010 (%)	
30% min. tree cover	21	79
40% min. tree cover	10	90

Table 3: Share of total cocoa production area occupied by cocoa agroforestry systems and cocoa monocultures in 2010.

When changing the minimum threshold for agroforestry to 40% tree cover, the total land area occupied by cocoa agroforestry globally dropped to 1.1 million hectares (Table 2). Under this assumption, cocoa agroforestry occupied only 10% of total cocoa production areas existing in 2010 globally (Table 3).

Changing this threshold condition had the most visible impact in West Africa. In West Africa, cocoa agroforestry production areas with at least 40% tree cover tend to appear as islands surrounded by areas with decreasing levels of tree cover (Figure 3). Most cocoa producing areas that have cocoa agroforestry systems present in South America, Central America and Southeast Asia tend to encompass more areas with at least 40% tree cover (Figure 4, Figure 5 and Figure 6, respectively). Moreover, cocoa agroforestry tends to be distributed more evenly throughout cocoa producing areas in these regions.

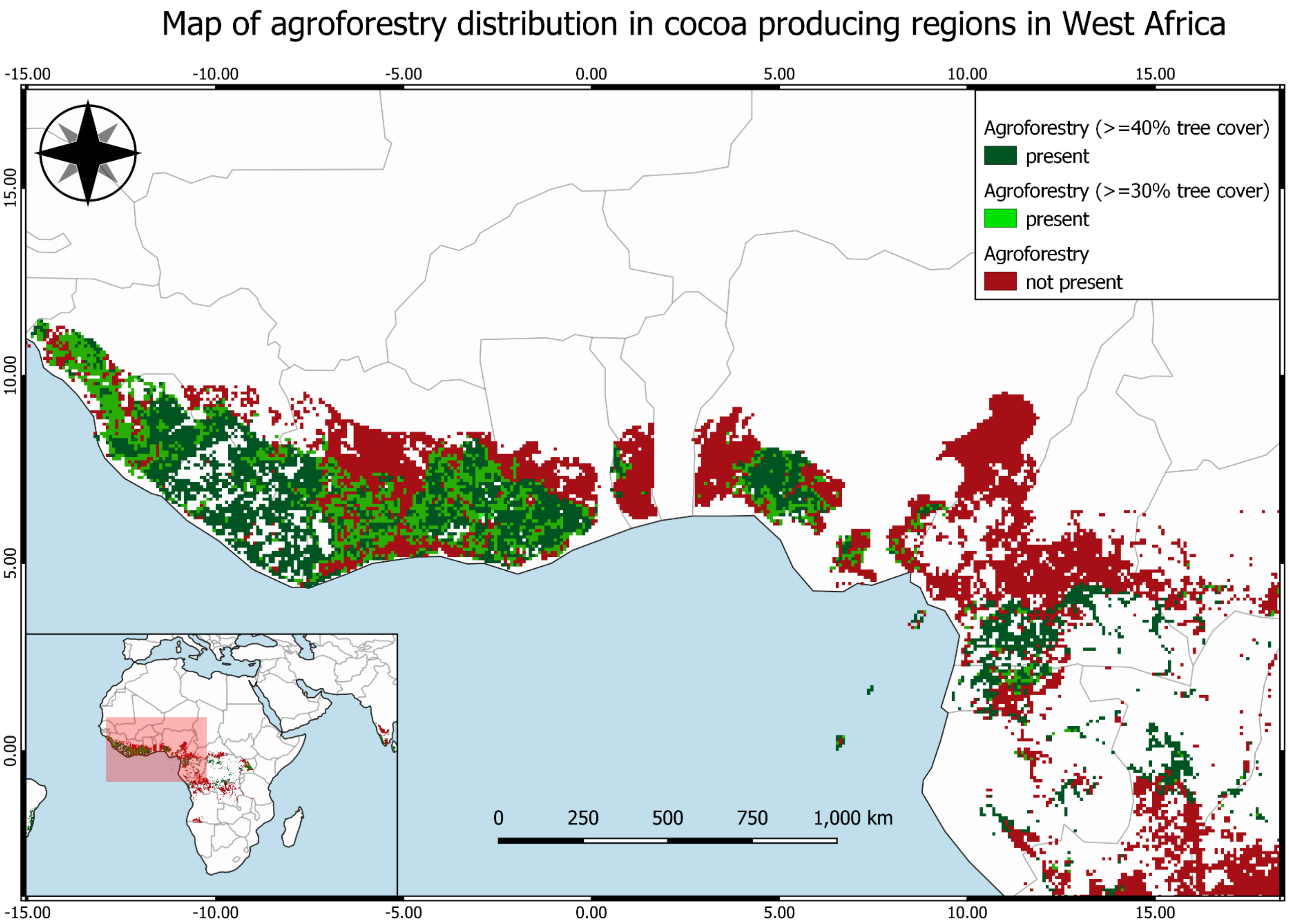

Figure 3: Map of agroforestry presence and distribution in cocoa producing regions in West Africa in 2010.

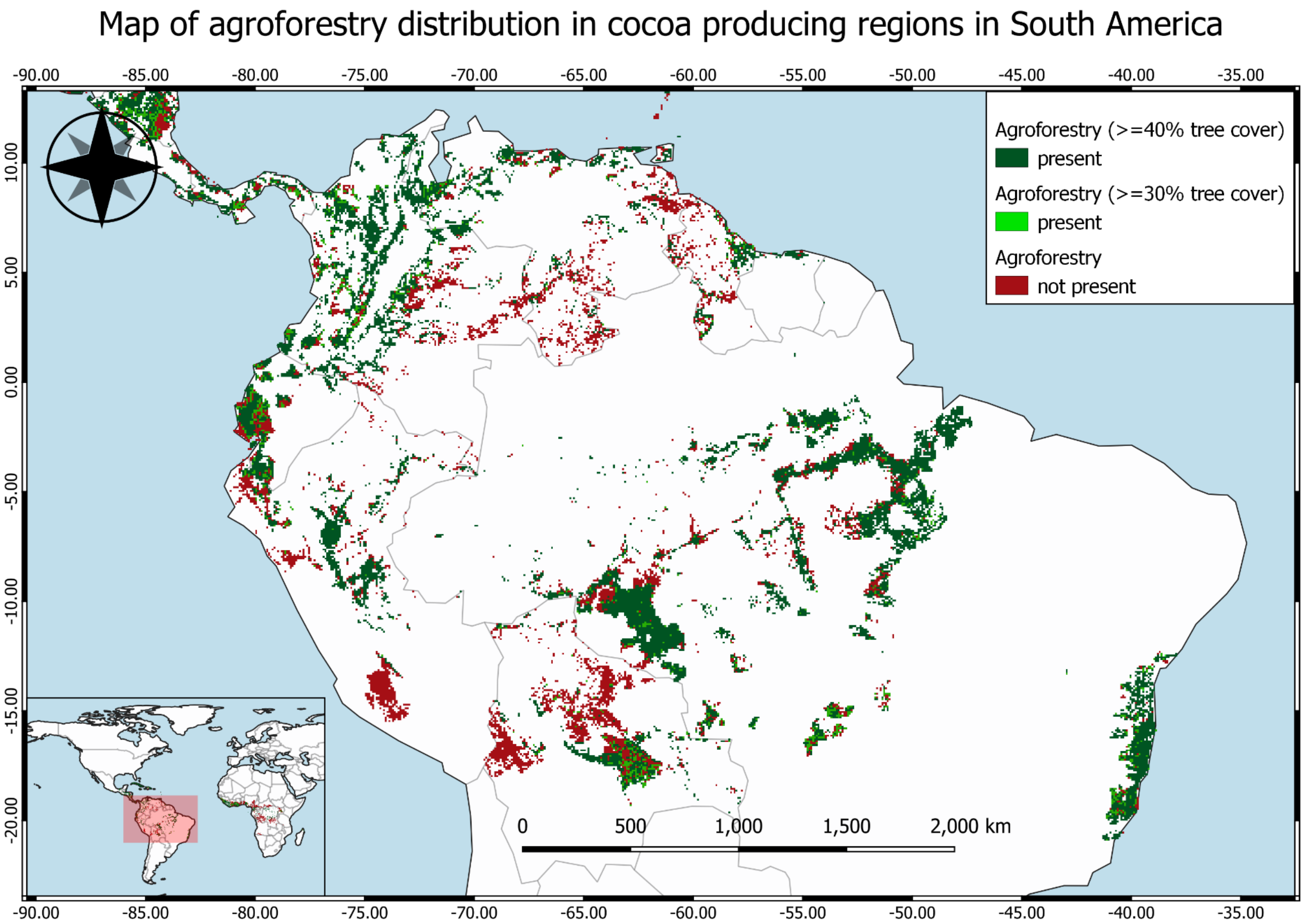

Figure 4: Map of agroforestry presence and distribution in cocoa producing regions in South America in 2010.

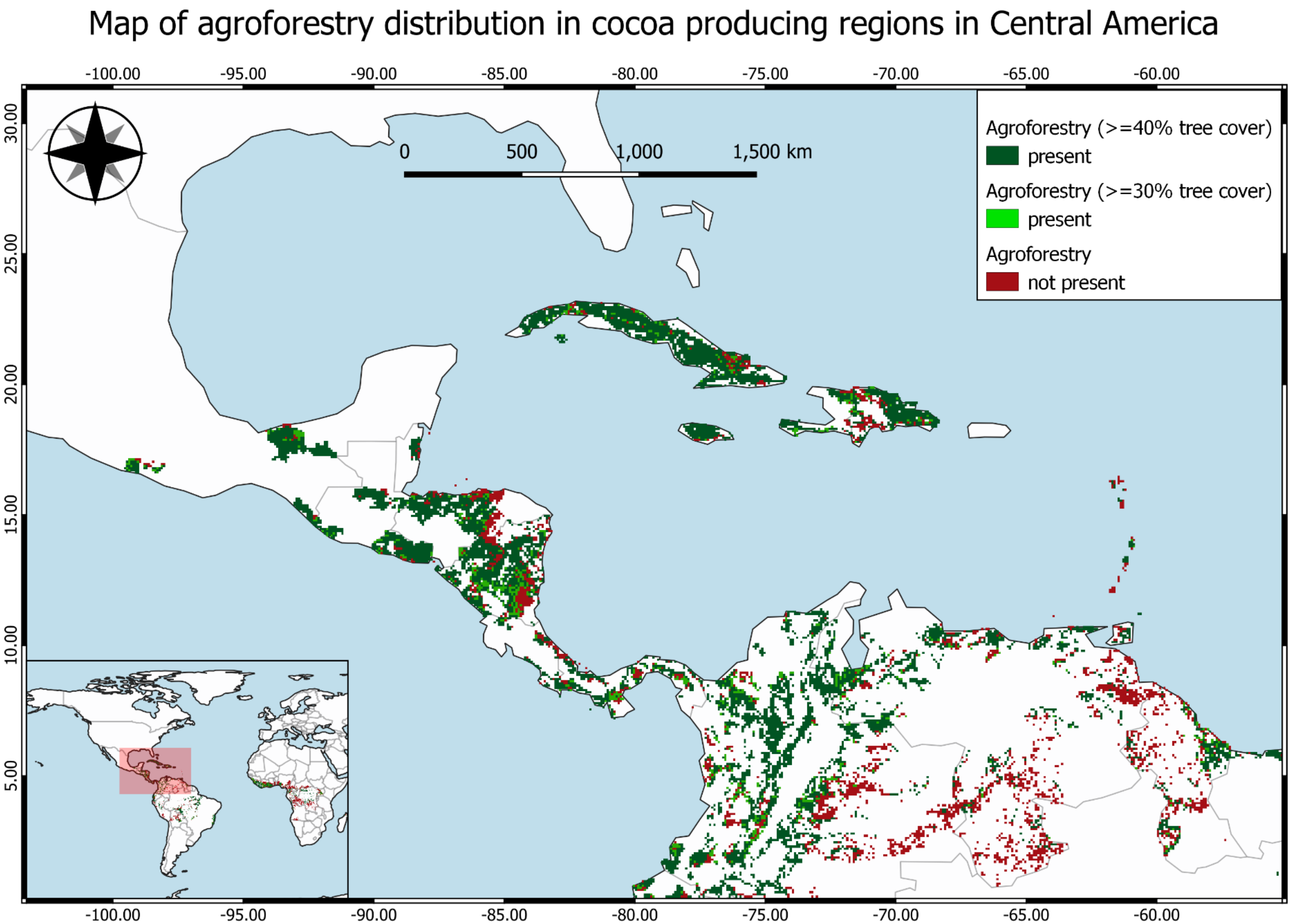

Figure 5: Map of agroforestry presence and distribution in cocoa producing regions in Central America in 2010.

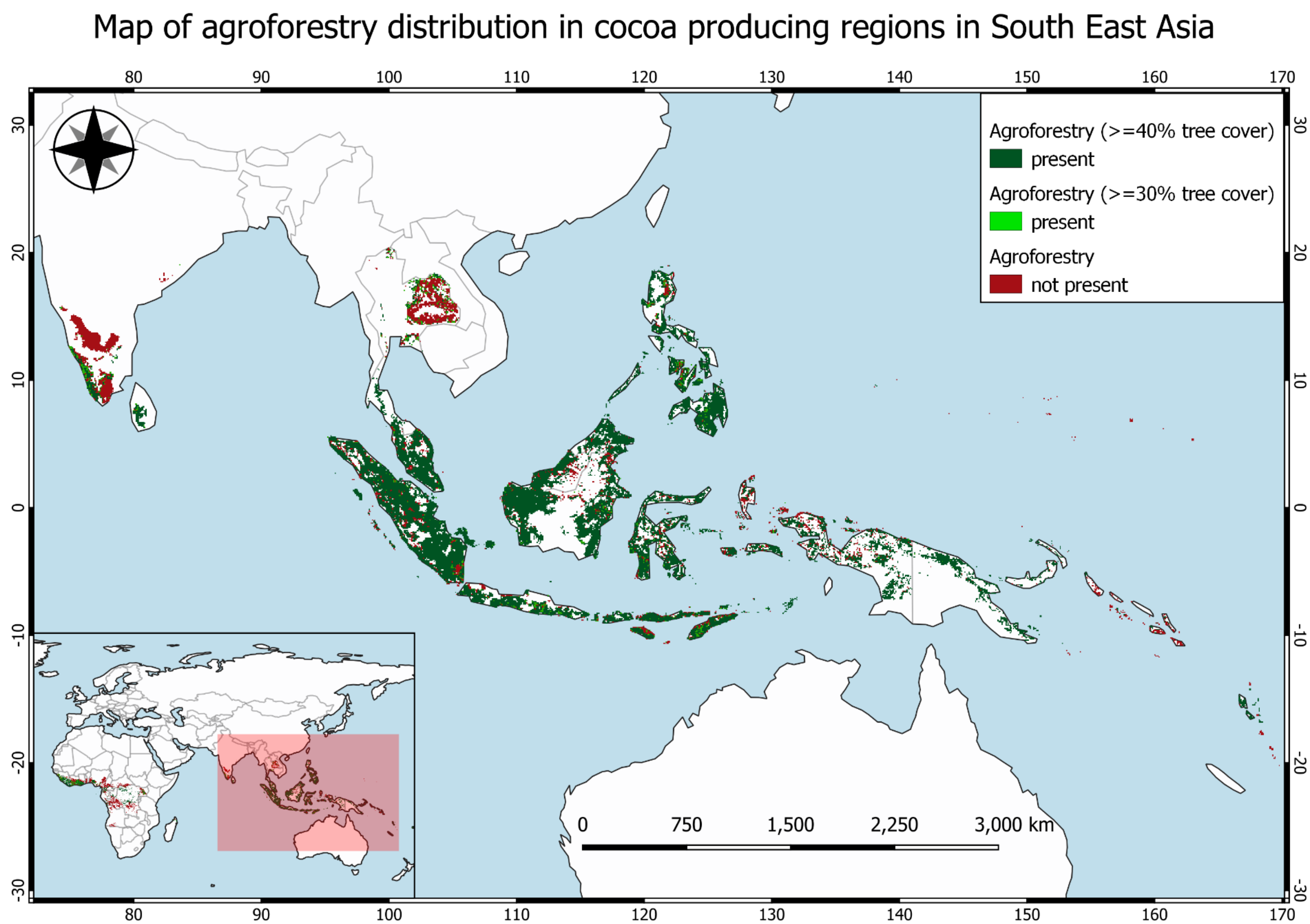

Figure 6: Map of agroforestry presence and distribution in cocoa producing regions in Southeast Asia in 2010.

When changing the minimum tree cover threshold to 40%, the amount of land occupied by cocoa agroforestry in West Africa fell by 73% from 1 million ha of land to 0.3 million ha of land. In other words, only 4% of total cocoa production areas in West Africa were managed in agroforestry systems in 2010 given a 40% minimum tree cover threshold compared to 15% given a 30% minimum tree cover threshold. For South America, changing this condition cut the amount of area identified as agroforestry by roughly 41% from 0.3 million ha to 0.2 million ha. Cocoa agroforestry area accounts for 13% of total cocoa production area in South America under the revised condition compared to 21% in the previous condition. In Central America, cocoa agroforestry areas identified by the spatial model dropped by 51% from 0.1 million ha to 0.06 million ha. Approximately 23% of total cocoa production area was thus identified as an agroforestry system in Central America given the new threshold compared to 47% previously. Changing the agroforestry threshold condition had the smallest effect on cocoa production areas identified as agroforestry in Southeast Asia. Areas occupied by agroforestry fell by 23% from 0.7 million ha to 0.6 million ha. As such, cocoa agroforestry accounted for 30% of total cocoa production area in Southeast Asia in 2010 compared to 39% under the 30% minimum tree cover condition.

The effect of tree cover percentage on the amount of area identified as cocoa agroforestry may have varied across these regions because of differences in local climate and ecosystems present in each of these regions. Cocoa production in South America, Central America and Southeast Asia tends to occur in areas that are more populated by humid tropical forest cover and vegetation compared to West Africa. Forest cover and vegetation in cocoa producing regions in West Africa tends to be drier and less dense (Miles, et al., 2006). The tropical dry forests found in West Africa are characterized by high seasonality in terms of rainfall patterns and on average tend to experience more months of drought compared to the tropical forests found in the cocoa producing regions of South America, Central America, and Southeast Asia (Mooney, et al., 1995). In Ghana, for example, cocoa production occupies wet to dry areas along a moisture-aridity gradient that goes from southwest (humid) to northeast (dry) (Coulter, et al., 2016). This gradient is visible in Figure 3 of this study, with cocoa agroforestry areas present in the southwestern regions of Ghana, while regions towards the northeast of the country tend to be entirely occupied by unshaded monocultures. Rainfall in cocoa production regions in Latin America, Central America and Southeast Asia range from 140 cm per year to 200 centimeters per year (Alvim & Zentmyer, 2019). Meanwhile, rainfall in southwestern regions of Ghana reach 180 centimeters per year, while northwestern regions see 110 centimeters per year (Coulter, et al., 2016). Similar rainfall patterns are found in the cocoa producing regions of Côte d'Ivoire and Nigeria (Coulter, et al., 2016). Recent trends indicate that cocoa production is increasingly reaching into areas with savanna vegetation (Coulter, et al., 2016). This can be seen in Figure 3, with cocoa production reaching into the northern shrublands of Côte d'Ivoire, Ghana, and Nigeria.

The differences in tree cover patterns between the cocoa producing regions in West Africa and the remaining cocoa producing regions may also offer an indication of differences in familiarity with agroforestry systems as well as differences in what are considered best practices by smallholder farmers managing cocoa in these regions. In Latin America and Southeast Asia, cocoa plantations are typically established under existing shade tree cover and over the years tend to be converted to non-shaded monocultures to grow production (Abou-Rajab, et al., 2016; Chavarría, 2021). As a species that is native to the tropical forests of the Amazon basin and Mesoamerica, cocoa is often found and consumed in local markets in Latin America as a fruit or ingredient in a variety of dishes and beverages (Mendes, 2021). Experts working to support cocoa farmers with agroforestry management find that smallholder producers in Latin America tend to be familiar with cocoa as a crop suited to shaded environments, stating that their grandparents and great grandparents often managed their lands for subsistence with cocoa as a shaded crop (Chavarría, 2021; Toth, 2021).

Contrastingly, cocoa was introduced in West Africa during the region's colonial occupation (Hütz-Adams, et al., 2016; Poelmans & Swinnen, 2019). Cocoa production was subsequently established in the region as an export industry to satisfy the demands of European and North American markets for chocolate (Poelmans & Swinnen, 2019). Although chocolate consumption in many African cities has increased over the last couple of decades, most processing facilities for chocolate, confectionary, and cosmetic products remain in Europe and the Americas (Confectionary News, 2017; IISD, 2019). Local consumption of cocoa products in West Africa is thus socio-economically restricted and virtually non-existent among smallholder cocoa farmers in West Africa (Confectionary News, 2017; Wessel & Quist Wessel, 2015). Considering the lack of local markets and appreciation for the cocoa fruit and beans, cocoa production in West Africa has maintained its value and legacy as an export-oriented commodity (Elzakker, 2021). Smallholder cocoa farmers tend to rely on the knowledge, resources and incentives passed onto them by government bodies to manage their cocoa farms in such a way that maximizes production for export (Elzakker, 2021). Managing farms as full sun monocultures is often advocated as the best practice by national cocoa bodies in Ghana (COCOBOD) and Côte d'Ivoire (Conseil du Café-Cacao) to maximize yields (Wessel & Quist Wessel, 2015; Elzakker, 2021). As such, many smallholder farmers establish their production areas by clearing primary or degraded forest and savanna land areas to plant and cultivate cocoa species as rapidly as possible (Wessel & Quist Wessel, 2015).

Despite differences in the extent of cultural familiarity with cocoa and agroforestry management among smallholder farmers in Latin America and West Africa, cocoa production remains mostly dedicated to supplying a globally traded commodity (Ven, 2021). Most smallholder farmers dependent on cocoa production for a livelihood, regardless of region, must contend with incredibly volatile market prices that often limit their ability to make long-term investments in sustainable land management practices such as agroforestry (Elzakker, 2021). The socio-economic conditions that constrain farmers' capacities to make economic decisions that are likely to benefit them in the long-term are a significant barrier to agroforestry adoption (Hütz-Adams, et al., 2016). Constrained by the need to make short-term gains in an especially volatile market, smallholder cocoa farmers are more likely to continue to manage their cocoa plots as partially shaded or unshaded cocoa monocultures and encroach on primary forest areas with the hope of making short-term gains in yield and reducing their input costs (Hütz-Adams, et al., 2016; Elzakker, 2021).

As shown in Figure 7, Figure 8, Figure 9, and Figure 10, most of the cocoa production areas that had a presence of cocoa agroforestry in their corresponding regions (Figure 3, Figure 4, Figure 5, and Figure 6) contain less than 1% of cocoa agroforestry. These maps provide a clearer indication of the amount of work necessary to scale cocoa agroforestry in each region. In West Africa (Figure 7), cocoa producing areas with the greatest share of cocoa agroforestry occur in regions where cocoa production has had a longer historical presence. This pattern suggests that cocoa agroforestry in West Africa tends to be adopted on older cocoa production plots as a strategy to maintain sufficient production or subsistence in areas with potentially declining cocoa yields. Cocoa agroforestry areas tend to occur more in the southwestern Ashanti region of Ghana, the eastern region of Côte d'Ivoire, as well as in central pockets of Nigeria and Cameroon. These regions occur in areas that have more humid forests. As such, it is likely that the climate conditions present in those regions make agroforestry presence more favorable. In

South America (Figure 8), the northwestern region of Salvador in Brazil sees the greatest share of cocoa agroforestry area. This region was the largest export-oriented producing region for cocoa until the 1930's when production in West Africa took over (Poelmans & Swinnen, 2019). Although it currently remains the largest cocoa producing region in Brazil, cocoa production was decimated in the region by the outbreak of witches' broom in the 1980s (Poelmans & Swinnen, 2019). Many producers in the region either employed industrial measures to eradicate the disease or shifted and expanded their production further north to the Amazonian state of Pará (Mendes, 2021). A few producers adopted more holistic measures, such as diversified agroforestry management, to make up for losses in cocoa production by selling high value timber and other tree crops valuable in local markets (Mendes, 2021). The higher concentration of agroforestry found by the spatial model in the region of Salvador thus suggests that cocoa agroforestry farms in the region are likely to be remnants of old farms that may have survived due to adopted agroforestry management practices. In Central America (Figure 9), the Dominican Republic appears to have the greatest share of cocoa agroforestry area. Finally, in Southeast Asia (Figure 10) it appears that the island of Sulawesi in Indonesia contains the greatest share of cocoa agroforestry area. The amount of land found to be covered by cocoa agroforestry in Southeast Asia is around 30-39% of total cocoa production area in the region. Although cocoa production has grown tremendously in Indonesia since the 1960's, it is possible that areas identified as cocoa agroforestry in the region could be confounded with the presence of other forest product monocultures, such as oil palm, that are grown intensively in the region (Poelmans & Swinnen, 2019). As such, further research and examination of land cover using remote-sensing data for the region is needed to evaluate to what extent cocoa agroforestry areas identified in this model overlap with the production of other forest commodities.

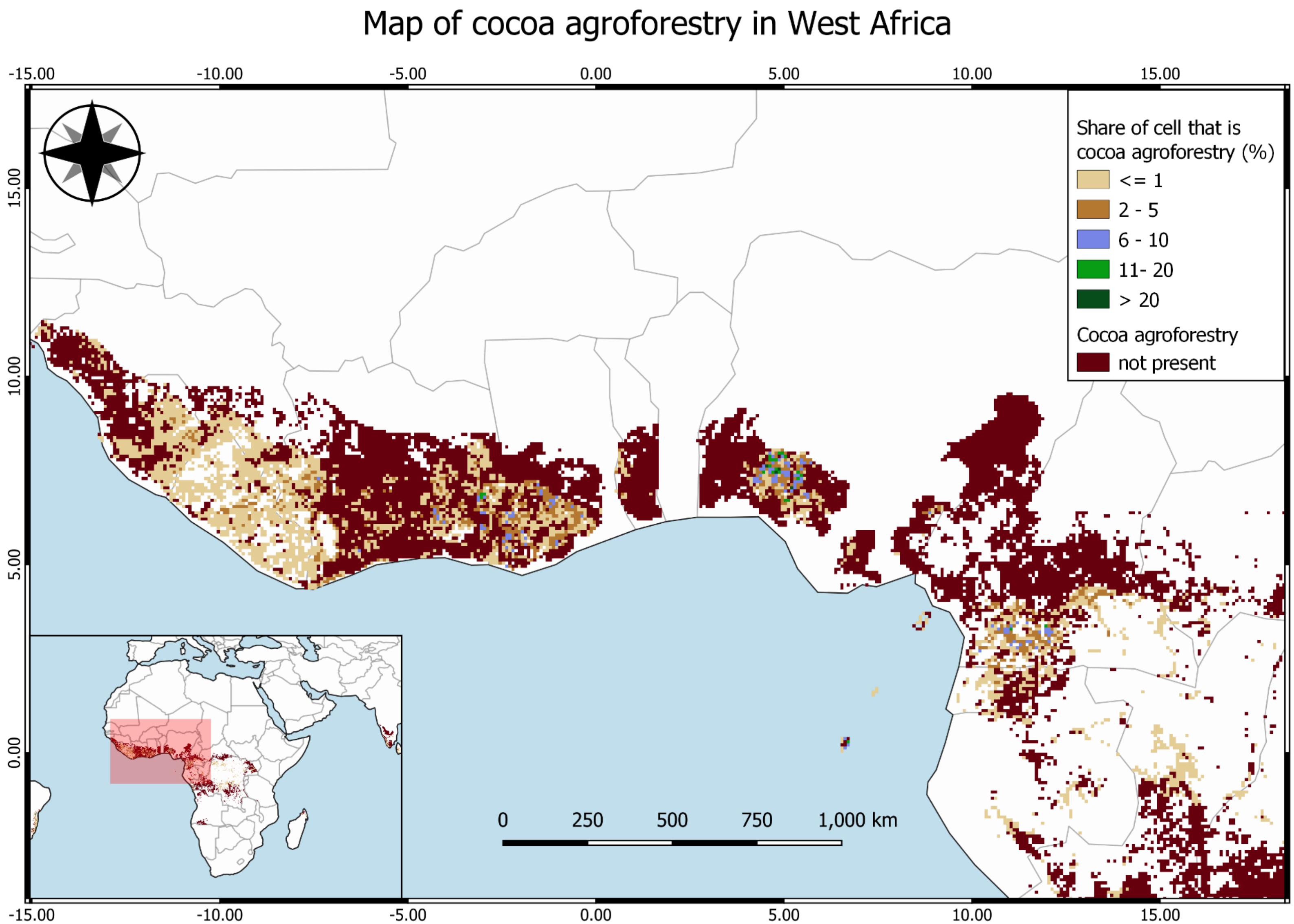

Figure 7: Map of the share of cocoa agroforestry in cocoa producing regions in West Africa in 2010.

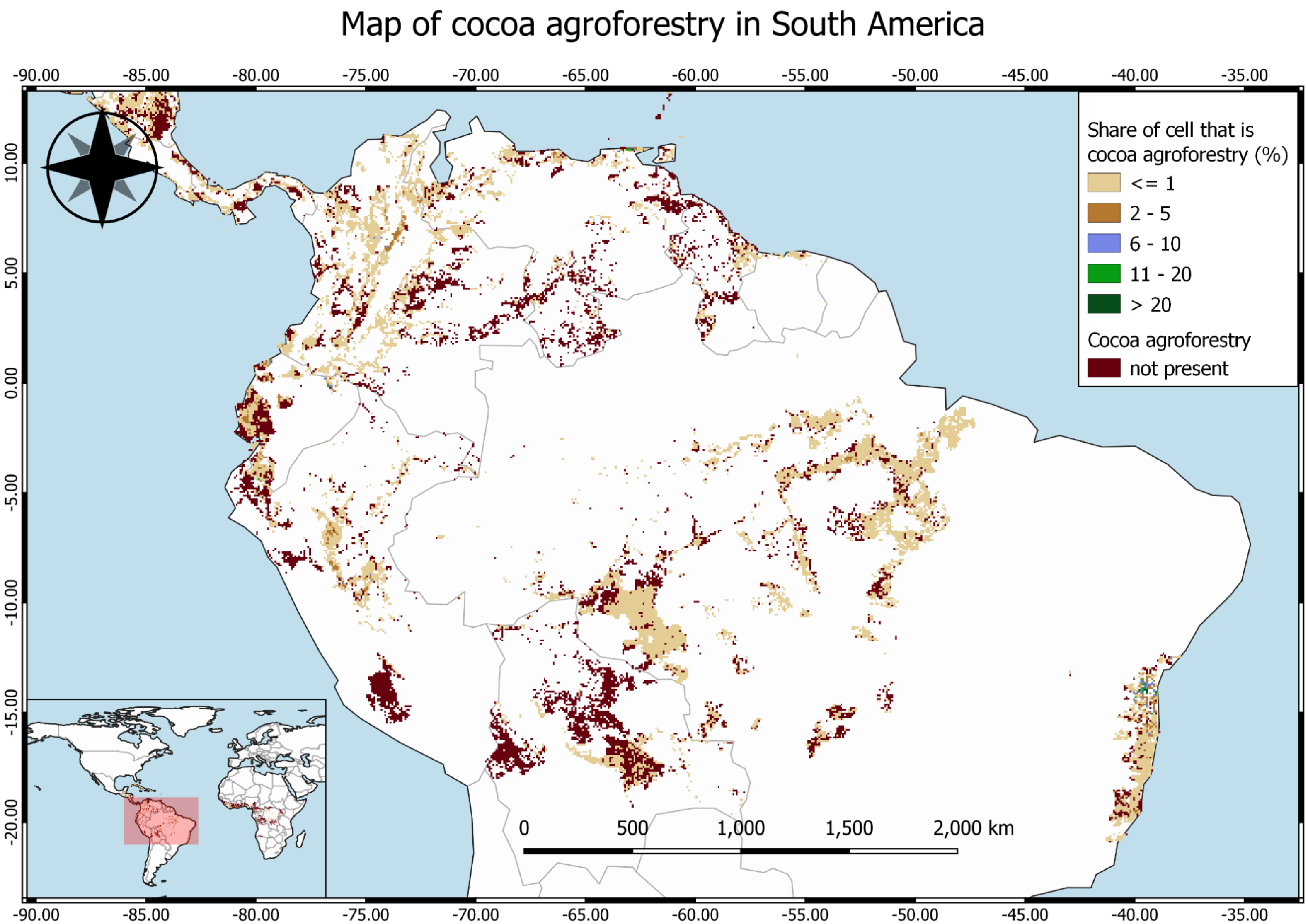

Figure 8: Map of the share of cocoa agroforestry in cocoa producing regions in South America in 2010.

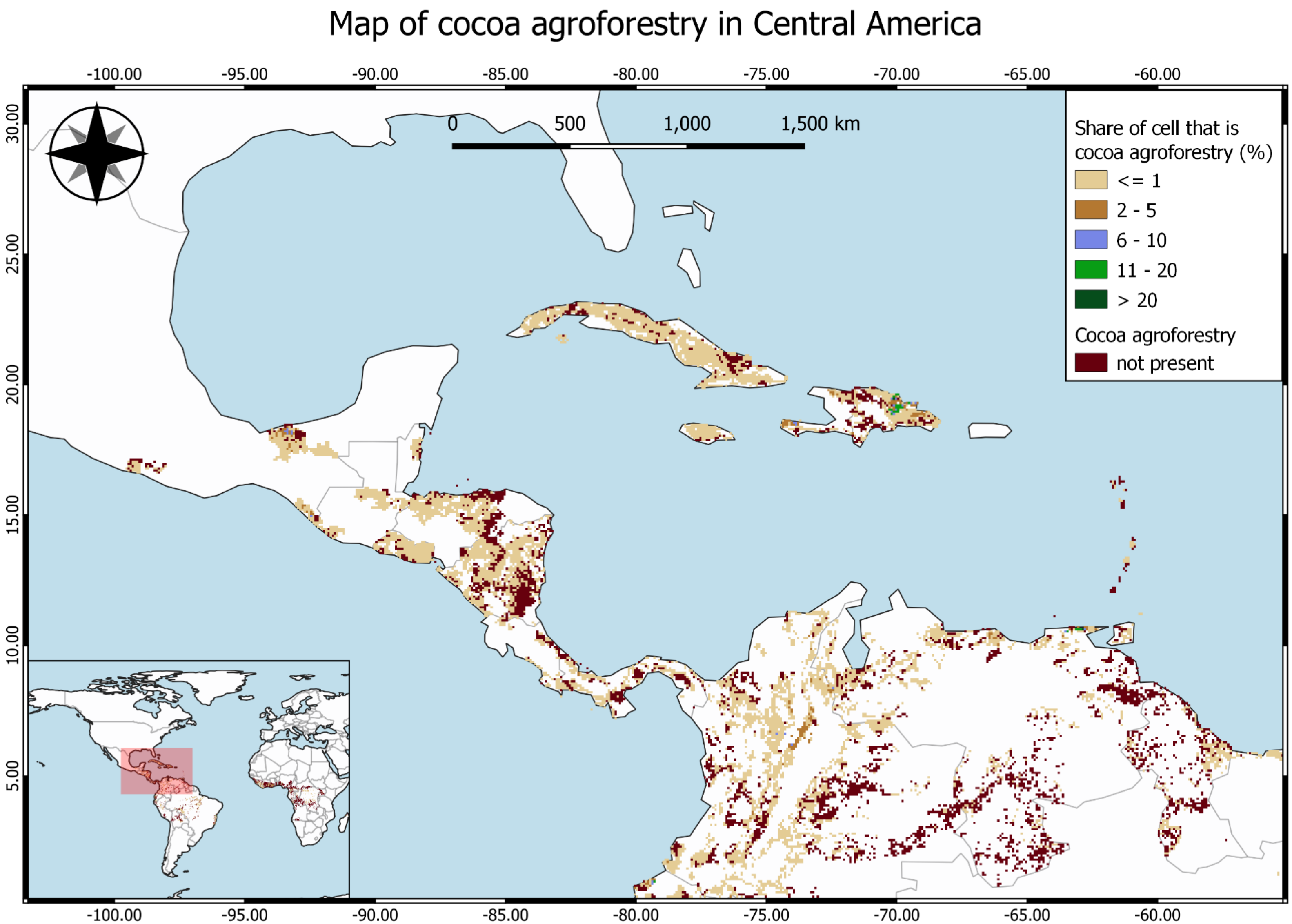

Figure 9: Map of the share of cocoa agroforestry in cocoa producing regions in Central America in 2010.

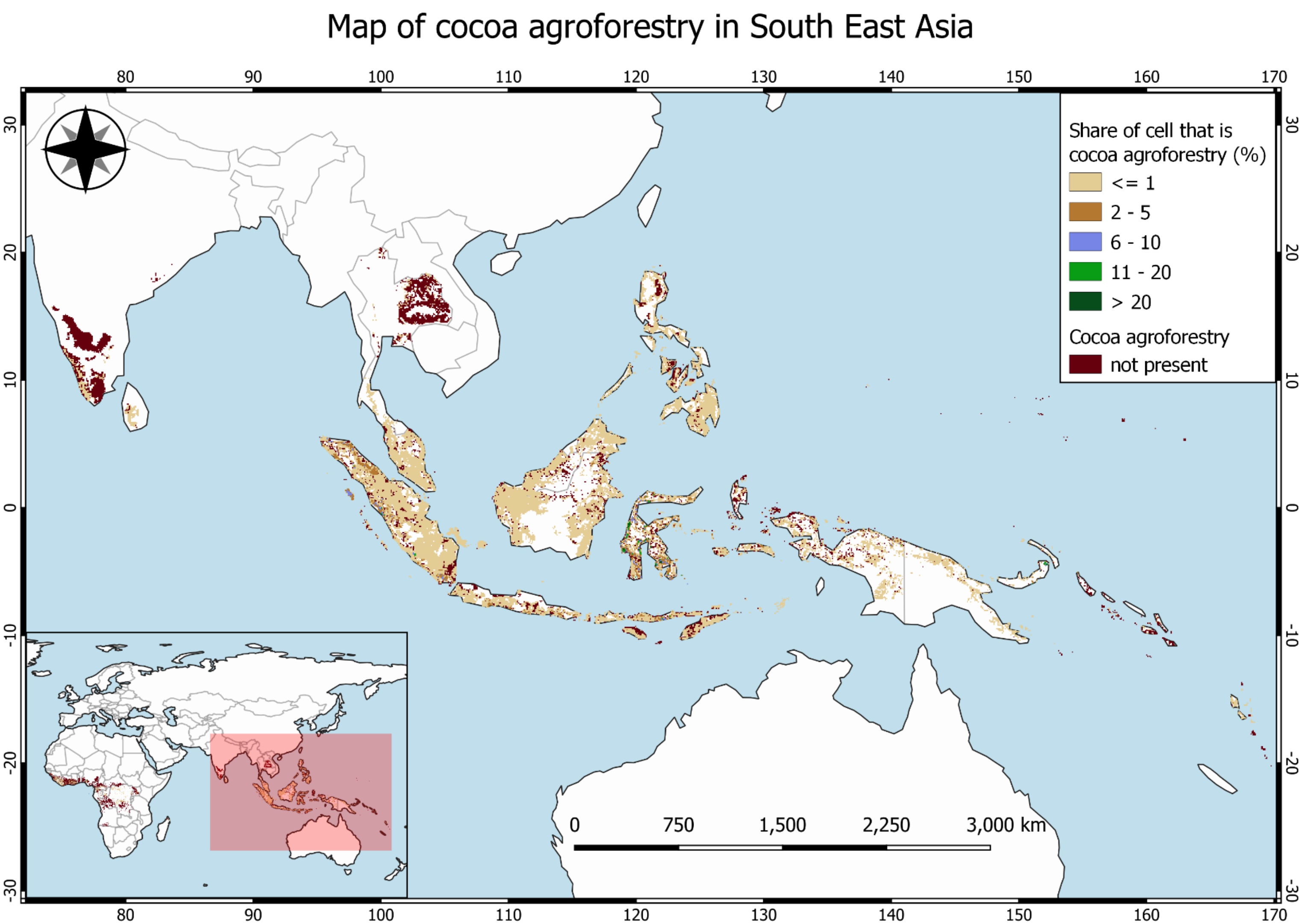

Figure 10: Map of the share of cocoa agroforestry in cocoa producing areas in Southeast Asia in 2010.

Scaling a transition to cocoa agroforestry will require providing smallholder cocoa farmers with higher incomes or access to finance that give them a way to manage the risks and losses involved in transitioning their production areas to agroforestry systems (Toth, 2021; Ven, 2021). Higher incomes could be provided to farmers by purchasing sustainably cultivated cocoa at a premium or offering them payments for ecosystem services such as avoided deforestation (e.g. REDD+), carbon sequestration or biodiversity conservation (Chavarría, 2021). Markets that offer cocoa farmers premiums for sustainably managed and specialty cocoa varieties have emerged in the last decade (IISD, 2019). However, such markets tend to occur at a niche level and there is a lack of knowledge regarding the extent to which average consumers are willing to pay for climate-smart and conservation friendly products in the future (Chavarría, 2021). Suspicion of green washing are likely to discourage consumer belief about the feasibility of conservation and climate-friendly claims (Ven, 2021). Moreover, offering higher prices in a value chain that leaves cocoa farmers hanging at the end is unlikely to adjust structural socio-economic barriers meaningfully (Elzakker, 2021). As such, stakeholder networks, infrastructures and comprehensive standards are necessary to promote value adding activities in cocoa producing nations, including the provision of ecosystem services (Chavarría, 2021). Such developments are also necessary to monitor and verify sustainability efforts and reported claims within short-feedback loops (Ven, 2021).

Leveraging the carbon market to purchase units of carbon sequestered by trees introduced in cocoa management systems is another way stakeholders in the cocoa supply chain are seeking to achieve a scalable transition to agroforestry (Ven, 2021). Purchases of offsets in carbon markets are booming (McDonnell, 2021). However, there are enormous challenges with leveraging such a market and ensuring that purchases are credible and translate to effective carbon removing activities on the ground. Beyond challenges with effectiveness, accounting, monitoring, certification, and standardization in the voluntary carbon market, there are structural barriers involved in the capacity to engage smallholder cocoa farmers at scale (Ven, 2021). One of the biggest barriers is the lack of land tenure or secure title ownership among smallholder farmers (Elzakker, 2021). Without secure land ownership, farmers have little incentive to make long-term land management investments. Indeed, most smallholder cocoa farmers in West Africa have been found to be migrants (Wessel & Quist Wessel, 2015). Permission to grow cocoa in certain land areas in Ghana and Côte d'Ivoire is often granted by local chiefs on a customary basis (Elzakker, 2021). Furthermore, it has been found that many land areas with customary ownership by chiefs often conflict with statutory laws regarding title (Wessel & Quist Wessel, 2015). Insecure and contested land titles also act as a barrier for intermediaries leveraging finance from carbon markets (Toth, 2021). These actors will either find it too risky to invest or be legally constrained to be able to provide smallholder farmers access to finance without title ownership or guarantees (Ven, 2021). As such, resolving or finding ways to overcome discrepancies between customary and statutory laws concerning land rights will be fundamental in the endeavor to scale agroforestry.

4.2 The carbon sequestration impact of globally scaling cocoa agroforestry

When allocating the global average carbon sequestration benefits of cocoa agroforestry systems and cocoa monocultures found by Niether et al. 2020 (Table 1) to the cocoa agroforestry and monoculture distribution identified by the spatial model with the 30% threshold, global cocoa production stored roughly 187 million tons of carbon in 2010. Using this threshold, approximately 78% of global cocoa production area in 2010 was managed as a monoculture. This amounts to 7.7 million hectares of land globally. Assuming those monoculture areas could be converted to cocoa agroforestry systems, approximately 175 million tons of additional carbon could be stored in cocoa production. In other words, scaling cocoa agroforestry to cocoa production areas globally could increase carbon storage in these agriculturally productive areas by 93%.

Using the 40% minimum tree cover threshold found that 8.7 million hectares of land were covered by cocoa monocultures globally in 2010. Under this assumed distribution of management, global cocoa production stored approximately 163 million tons of carbon. Converting these productive areas to agroforestry systems and allocating the corresponding carbon benefit estimated for cocoa agroforestry systems globally could increase carbon storage in cocoa production areas by 121%. In other words, approximately 199 M tons of additional carbon could be stored in cocoa production systems if all areas identified as monoculture in 2010 were converted to and allocated the benefits of agroforestry systems found in Niether, et al. 2020. An overview of the estimates for total carbon stored in cocoa agroforestry systems and cocoa monocultures for each Scenario ("2010 Estimate" and "All Agroforestry") are provided in Table 4, Table 5, and Table 6 below.

Agroforestry threshold	Total C stored by cocoa agroforestry in 2010 (t)	Total C stored by cocoa monoculture in 2010 (t)	Total C stored by cocoa production in Scenario 1 (t)
30% min. tree cover	78 million	109 million	187 million
40% min. tree cover	39 million	124 million	163 million

Table 4: Estimated total carbon stored by cocoa agroforestry systems and cocoa monocultures in 2010 (Scenario 1).

Agroforestry threshold	Total C stored by cocoa agroforestry in 2010 (t)	Total C stored by converted monoculture areas (t)	Total C stored by cocoa production in Scenario 2 (t)
30% min. tree cover	78 million	284 million	361 million
40% min. tree cover	39 million	322 million	361 million

Table 5: Estimated total carbon stored by cocoa production if agroforestry upscaled to cocoa monoculture areas exiting in 2010 (Scenario 2).

Agroforestry threshold	Total C stored by cocoa production in Scenario 1 (t)	Total C stored by cocoa production in Scenario 2 (t)	Change in total C stored (t)
30% min. tree cover	187 million	361 million	(+) 175 million
40% min. tree cover	163 million	361 million	(+) 199 million

Table 6: Estimated change in total carbon stored by cocoa production if agroforestry upscaled.

There is a high degree of uncertainty in the global averages used to estimate the gains in carbon storage from scaling agroforestry to global cocoa monoculture areas in 2010. This uncertainty is likely driven by the wide ranges in environmental conditions and management interventions reported in the case studies used in the meta-analysis, as well as the sample size (Niether, et al., 2020). Only 52 case studies comparing cocoa agroforestry systems and cocoa monocultures were considered. Given the scale of cocoa production and the breadth of areas it covers, this is a small sample to base a global assessment on. Out of the 52 case studies, 20 were in Ghana, 13 in Bolivia, 8 in Indonesia, 3 in Ecuador, 2 in each Cameroon and Malaysia, and 1 in each Côte d'Ivoire, Peru, Panama and Costa Rica.

Niether et al. calculated carbon storage in cocoa agroforestry systems and monocultures using average estimates of diameter at breast height (DBH) for cocoa and shade tree species reported by the studies (Niether, et al., 2020). These diameters were then plugged into separate allometric equations – one for cocoa trees and one for shade trees, regardless of species variety. Species variety is one of the factors that can influence the extent of carbon sequestration in cocoa agroforestry systems beyond tree cover.

About half of the studies conducted in West Africa and Southeast Asia considered systems with only one shade tree species, whereas most of the case studies conducted in Latin America considered cocoa agroforestry systems with at least 9 different shade tree species, and in several cases with up to 42 different shade tree species. The variation in the number of shade tree species used in cocoa agroforestry designs provides further indication about the differences in familiarity with agroforestry across regions. While shaded cocoa monoculture systems are more often found in literature searches on agroforestry in West Africa, searches on agroforestry in Latin America are more likely to include case studies of systems integrating more plant diversity in their designs.

Considering the variation in the way agroforestry practices are managed in different regions, the carbon benefit of adopting agroforestry for cocoa production is likely to be overestimated, especially given the finding that most cocoa monoculture areas theoretically available for conversion to agroforestry are in West Africa (approximately 5.3 million to 6.0 million ha), where establishing more diversified agroforestry systems is likely to be more challenging (Elzakker, 2021).

Besides the amount of tree cover and tree species variety, factors in agroforestry design that influence carbon sequestration include cocoa planting distance, shade tree planting distance, tree density, age of trees on a plot, tree purpose, tree maintenance (e.g. pruning, thinning or harvesting), tree species compatibility, competition with annual crops, fertilization, use of chemicals and use of cover crops (Niether, et al., 2020). Climate conditions that influence carbon sequestration include annual mean temperatures, annual precipitation, seasonal variation, humidity, soil type, soil texture and soil pH (Niether, et al., 2020).

The studies considered in the meta-analysis ranged widely across all these factors except for mean temperatures (Niether, et al. 2020). This variation thus affects the robustness of mean estimates used in this study, especially for areas where more regionally specific factors such as soil type may limit the potential gain in benefits from agroforestry adoption. Due to time constraints, this assessment did not evaluate regional factors that could limit carbon sequestration in certain regions. As such, further research to identify these is recommended.

Improving the robustness of estimates for carbon sequestration requires further research that compares carbon sequestration across more similar agroforestry designs in regions that have relatively similar soil types, seasonal variations, precipitation, and humidity levels. Conducting case studies with comparable system designs across different regions could also provide insights on which climate and environmental factors are more important for carbon sequestration in certain regions compared to others where such factors are not limiting. Moreover, this model overestimates the carbon sequestration potential of scaling agroforestry by not accounting for the potential presence of tree cover on agricultural areas below the tree cover threshold conditions. This is especially the case for the estimate using the 40% tree cover threshold to identify agroforestry. Further research and models incorporating gradual variations in tree density, sequestration estimates for specific species and their effects on carbon sequestration would also refine these carbon benefit estimates.

4.3 The impact of globally scaling cocoa agroforestry on production quantities and yields

According to data from SPAM on annual cocoa production (Table 7), approximately 4.4 million tons of cocoa were produced globally in 2010. West Africa produced approximately 64% (2.8 million tons) of global cocoa beans grown in 2010 (You, et al., 2014). Production regions in South America, Central America and Southeast Asia accounted for 12% (0.5 million tons), 3% (0.1 million tons) and 20% (0.9 million tons) of total global cocoa production quantities, respectively (You, et al., 2014).

You, et al. 2014 (SPAM)	**Cocoa production in 2010 [Scenario 1]**				
	Global	**West Africa**	**South America**	**Central America**	**Southeast Asia**
Production (Mt)	4.4	2.8	0.5	0.1	0.9
Share of global production (%)	*100%*	*64%*	*12%*	*3%*	*20%*

Table 7: Total amount of cocoa produced globally and in each of the four cocoa producing regions in 2010 (You, et al. 2014).

The average global yield for cocoa production in 2010 was 0.51 tons per hectare. As shown in Table 8, West Africa was the region with the lowest average yield, producing approximately 0.43 tons per hectare. South America was the region with the highest average yield, producing about 0.58 tons of cocoa per hectare. Southeast Asia followed closely behind with an average yield of 0.57 tons per hectare, while Central America averaged at around 0.55 tons per hectare. It is likely that environmental and climate factors such as soil quality and annual rainfall influence the difference seen in yields between West Africa and other producing regions. As previously mentioned, cocoa producing areas in South America, Central America and Southeast Asia tend to occur in more humid and dense tropical areas, while production in West Africa is increasingly encroaching on drier lands that likely experience more extreme seasonal variations in rainfall and less nutrient rich soils. Indeed, most cocoa producing areas in West Africa saw yields of approximately 0.24 tons per hectare, while most areas in South America saw yields of approximately 0.90 tons per hectare.

SPAM	**Cocoa yields in 2010 [Scenario 1]**				
	Global	**West Africa**	**South America**	**Central America**	**Southeast Asia**
Average (t/ha)	0.51	0.43	0.58	0.55	0.57
Median (t/ha)	*0.39*	*0.38*	*0.55*	*0.34*	*0.34*
Mode (t/ha)	*0.90*	*0.24*	*0.90*	*0.64*	*0.81*

Table 8: Global and regional average cocoa production yields in 2010 found in the SPAM (You, et al. 2014).

It is interesting to remark that that the global and regional yield averages found in the spatial production allocation model for cocoa tend to be closer to the yield average for cocoa agroforestry found by Niether, et al. in 2020 (Table 1). This discrepancy highlights the limitation the Niether, et al. study faces in terms of the small sample size used for the meta-analysis as well as challenges with bias in the case-study selection. Regardless, its findings were useful in providing an initial approximation for the potential average difference in cocoa yields between cocoa agroforestry systems and cocoa monocultures.

By applying the factor difference of 1.5 between mean agroforestry and monoculture yield found in their study (Table 1), converting monoculture production areas identified using the 30% threshold to agroforestry areas resulted in decreasing annual global production by approximately 1.15 million tons to a total production amount of 3.2 million tons (Table 9). This loss in production translates to a 26% decrease in the global average yield for cocoa to 0.38 tons per hectare.

30% threshold	Cocoa production [Scenario 2]				
	Global	**West Africa**	**South America**	**Central America**	**Southeast Asia**
Production (Mt)	3.2	2.0	0.4	0.1	0.7
Change from Scenario 1 (Mt)	-1.15	-0.80	-0.13	-0.03	-0.18
Change from Scenario 1 (%)	*-26%*	*-28%*	*-26%*	*-19%*	*-20%*
	Yield estimates [Scenario 2]				
Average (t/ha)	0.38	0.31	0.42	0.43	0.43
Change relative to Scenario 1 (%)	*-26%*	*-28%*	*-29%*	*-22%*	*-25%*

Table 9: Estimated changes to global and regional cocoa production quantities and yields if agroforestry was scaled to monoculture areas existing in 2010.

Transitioning monoculture areas identified using the 40% threshold resulted in a loss of approximately 1.31 million tons of cocoa to a total production amount of 3.1 million tons (Table 10). This loss in production translates to a 28% reduction in the global average yield for cocoa, from 0.51 tons per hectare to 0.37 tons per hectare.

40% threshold	Cocoa Production [Scenario 2]				
	Global	**West Africa**	**South America**	**Central America**	**Southeast Asia**
Production (Mt)	3.1	1.9	0.4	0.1	0.7
Change from Scenario 1 (Mt)	*-1.31*	*-0.91*	*-0.15*	*-0.04*	*-0.21*
Change from Scenario 1 (%)	*-30%*	*-32%*	*-29%*	*-27%*	*-23%*
	Yield estimates [Scenario 2]				
Average (t/ha)	0.37	0.30	0.41	0.40	0.41
Change relative to Scenario 1	*-28%*	*-31%*	*-30%*	*-26%*	*-27%*

Table 10: Estimated changes to global and regional cocoa production quantities and yields if agroforestry was scaled to monoculture areas existing in 2010.

Given the existing differences in the baseline yield values for each region, as shown in Table 8, the impact of scaling agroforestry on the amount of cocoa produced by each region also varies. Scaling agroforestry would have the largest impact on cocoa production amounts in West Africa, reducing cocoa production by 28% to 2.0 million tons of cocoa beans, assuming a 30% threshold, and by 32% to 1.9 million tons, assuming a 40% threshold. Impact on cocoa production quantities would be felt the least in cocoa producing regions in Central America. Production quantities in Central America would decrease by

0.03 and 0.04 million tons (assuming a 30% and 40% tree cover threshold, respectively) if agroforestry were scaled to all production areas existing in 2010. This is likely because approximately 47% of cocoa producing areas are already grown in agroforestry systems in Central America, if a 30% threshold is assumed. If a 40% threshold is assumed, about a quarter (23%) of all cocoa production areas in Central America in 2010 were agroforestry systems. Considering the existing presence of agroforestry farms in the region, familiarity among smallholder farmers with diversified agroforestry system designs, and the presence of local markets for cocoa beans and other fruit crops that grow in similar conditions, scaling agroforestry in Central America is likely to be more successful than doing so in other regions, such as West Africa, where the scale of the challenge is much larger and where both socio-economic and environmental conditions are likely to limit some of the benefits provided by agroforestry systems.

Assessing whether scaling agroforestry will impact certain regions more than others requires looking into the conditions that are currently limiting cocoa production in certain regions and understanding whether agroforestry adoption would worsen or mitigate these constraints (Elzakker, 2021; Chavarría, 2021). Examples of limiting factors that could influence the impact of agroforestry adoption include cocoa bean varieties, mean temperatures, rainfall patterns, soil quality, nutrient retention, availability of fertilizers, ecosystem health, and use of chemicals. Although many case studies looking at the impact of agroforestry adoption on primary crop yields suggest that they are likely to decrease with increased shade tree presence, it is not clear to what extent other agroforestry system design parameters and other climate, or environmental conditions contribute to or mitigate these yield losses. In many ways agroforestry is a management design tool and so getting a better sense of what parameters are important in each region to optimize for carbon sequestration, yield performance or biodiversity restoration, for example, is critical when thinking about scaling it as a climate-smart and sustainable solution in different regions. Like for carbon sequestration, further research that compares the effect of different agroforestry system designs in similar areas on yield is needed. Studies such as these should also be complemented by research that compares similar agroforestry designs across regions to better understand the environmental conditions that may impact yields or carbon sequestration more than design choices, such as soil type, rainfall patterns or seasonality.

5. Limitations and further research

The results from the analyses conducted in this study are not robust. They are compromised by varying degrees of uncertainty present in the data regarding cocoa production, global tree cover, as well as total carbon stored in biomass and yields in cocoa agroforestry and monoculture systems, as previously discussed. These uncertainties are further compounded by the assumptions made in this study to define and distinguish cocoa agroforestry systems from monoculture systems at a global level.

The uncertainty found in the data used is largely associated with the resolution of images captured by remote-sensing and aggregations involved in the remote sensing-based spatial allocation models for cocoa production (SPAM) and global tree cover on agricultural land. Aggregations involved in the spatial analysis conducted in this study further compound these uncertainties. Moreover, approximately one% of the results from the zonal statistics were found to have errors with geometry as well as cocoa production allocation errors. For example, a few cells whose coordinates indicate a location over ocean bodies, were found to be attributed cocoa production areas, tree cover counts and production quantities. As such, margins of error need to be considered for each of the estimates provided.

The course resolution of the cocoa production layer creates ample uncertainty regarding the distribution of cocoa production areas within 5-arcminutes cells. In West Africa, it is estimated that 90% of cocoa was grown on smallholder farms (Wessel & Quist Wessel, 2015). Although there is a lack of clarity regarding the definition of a smallholder farm, they are generally considered to be farms managed by a single household and as such generally cover an area of 0.5 to 3.0 hectares (Lowder, et al., 2016) (HLPE, 2013). The approach in this study tries to overcome the uncertainty of cocoa production distribution within cells by assuming a uniform distribution. Determining a more appropriate distribution will require further research to improve the quality of data on the location and size of cocoa production plots. This can be achieved by collecting remote-sensing data at a finer resolution or collecting field data and coordinates of cocoa plots in each cocoa producing region. Both these endeavors require a lot of time and resources. As such, spatial analysis at regional or national scales are more feasible and likely to produce more robust results.

Although the resolution of data on tree cover is finer than the resolution of the cocoa production data, it is still considered unacceptably high by the authors who developed the dataset (Zomer, et al., 2016). Moreover, as cocoa trees are an understory crop with a canopy, it is unclear to what extent remote sensing data may confound understory canopies with shade tree canopies. Cocoa trees in production systems generally reach an average maximum height of five meters (Sassen, 2021) (Wessel & Quist Wessel, 2015). Remote sensing methods collecting data on continuous field vegetation generally capture and classify trees taller than five meters as forest tree cover (Sassen, 2021) (Alexander, et al., 2014). While this indicates that cocoa canopies are excluded from global tree cover assessments, a probability of error remains. As such, the approach in this study likely overestimates the presence of agroforestry in cocoa production areas.

The approach in this study also assumes a uniform integration of tree cover on agricultural fields containing at least 30% tree cover. This is a generous assumption. It has been found that many farms certified as agroforestry fulfill the 30% tree requirement by establishing practices with limited integration of tree cover throughout agricultural fields such woodlots, live fences, and riparian buffers (Chavarría, 2021). Moreover, it is unclear to what extent areas identified as agricultural land with tree cover overlap or encroach on protected forested areas or degraded forest areas at risk of further deforestation through agricultural development. Further research using alternative global datasets on land use and cover to examine the extent of overlap and exclude them from the analysis could improve the findings. Refining the extent of uncertainty present and improvements in this approach could also be achieved through validation by use of ground field data from existing monoculture and agroforestry cocoa plots.

The most significant limitation in this study's approach is the use of global averages to estimate the change in carbon storage if monoculture areas identified in 2010 were converted to agroforestry. There is a lack of clarity regarding the main determinants for carbon sequestration in the estimates provided by Niether et al. 2020 and the extent to which they may vary across regions. The large standard deviation given for carbon sequestration (±28.9) suggests there are various agroforestry system design parameters that influence carbon sequestration differently in the regions accounted for in the case studies sampled. Further research at a regional level that compares the provision of ecosystem service benefits across more similar agroforestry system designs would provide more robust regional level findings. Insights from such regional level studies could then be compared across regions to observe the most important determinants for carbon sequestration in agroforestry systems in different regions. Similar efforts are recommended to assess the impact of agroforestry practices on cocoa yields. Furthermore, it would be valuable to compare those findings with studies that project and assess the impact of climate change on cocoa yields in business-as-usual scenarios as well.

Using tree cover as a criterion to determine whether an agricultural field is managed as an agroforestry system is limited. In interviews with experts involved with cocoa agroforestry management projects, respondents identified the nature of tree incorporation, number of strata, shade tree density, shade tree diversity, crop diversity and use of external inputs as additional criteria beyond percentage of tree cover to evaluate whether cocoa production system could be categorized as a partially shaded cocoa monoculture, fully shaded cocoa monoculture, partially shaded cocoa agroforestry or fully shaded cocoa agroforestry systems (Chavarría, 2021) (Elzakker, 2021) (Sassen, 2021).

Agroforestry system designs will vary according to resources made available to the farmer, interventions perceived as necessary by the farmer to manage their crop, as well as the climate conditions present in the region in which they operate (Chavarría, 2021). These conditions influence the criteria that are relevant to determine an agricultural management system as agroforestry beyond tree cover (Elevitch, et al., 2018). As such, exclusively using tree cover as a threshold to define agroforestry is generally found to oversimplify what constitutes an agroforestry system in practice (Elevitch, et al., 2018). It has also been found to be misused by producers who grow cocoa in monoculture systems situated next to forest reserves that are considered part of a producer's agricultural property (Chavarría, 2021) (Elzakker, 2021). Some argue that fields with riparian buffers and woodlots should not be considered agroforestry systems (Chavarría, 2021).

The approach in this study also does not consider the potential contribution of existing tree cover on agricultural areas even if they do not reach a 30% threshold to be qualified as agroforestry. As such, the potential carbon storage estimate for the 40% threshold scenario does not factor in the carbon storage contribution of areas with 30% tree cover. This means that the potential carbon gains of agroforestry adoption are likely overestimated. Moreover, the model does not consider the temporal distribution of benefits from adopting agroforestry management in cocoa production. The gains in carbon storage attained by integrating trees onto production plots occur over the growth period of these trees

(Bennett, et al., 2015). In addition, growth curves and carbon sequestration capacities vary widely depending on the species of trees introduced in an agroforestry system (Jose, 2009).

Determining growth curves and carbon benefits of different crop and shade tree species that can be used in agroforestry management systems require further research and will involve projects that collect data on the growth of biomass over longer periods. These long-term data collection projects are needed to observe changes in sequestration rates along the growth periods of different tree species. Further research projects that collect and report data on growth curves, planting characteristics of different tree species, as well as their performance across different climate-smart indicators in different environmental and projected climate change conditions are sorely missing. Consolidating such information on a publicly available database would support a lot of research into the climate benefits of different reforestation and sustainable land management practices. Moreover, it could support smallholder farmers make decisions about how best to design their plots to optimize production and conservation or climate-smart performance. Efforts to create such a database tends to be lagging because of technical limitations, costs and the stakeholder management challenges involved in collecting and managing highly useful and competitive information. However, university related projects may offer an opportunity to overcome the gap created by this competition.

Finally, the benefits gained from tree integration in cocoa production plots also assume the permanence of trees on these land areas. Guaranteeing such permanence in practice confronts many challenges related to the socio-economic conditions of cocoa farmers and development policy priorities in the various countries where cocoa is produced (Bennett, et al., 2015). Further research on the needs of cocoa farmers could also provide some guidance on how to structure programs seeking to support farmers towards adopting agroforestry management practices and ensuring their success along both environmental and social sustainability standards.

6. Conclusion

Using 2010 as a reference year for existing cocoa production and tree cover area, this study found that the carbon sequestration potential of scaling agroforestry could reach approximately 175-199 million tons of carbon. In 2010, cocoa production covered approximately 9.8 million hectares of land globally and produced around 4.4 million tons of cocoa beans (You, et al., 2014). Of the 9.8 million hectares of global production area, this study found that 2.1 million hectares were covered by cocoa agroforestry systems. This area was found when defining agroforestry as an agriculturally productive area with at least 30% tree cover. As such, this study found that about 21% of cocoa production was cultivated in agroforestry systems globally in 2010. Using average values from Niether, et al. on total carbon stored per hectare by cocoa agroforestry systems and monocultures globally, global cocoa production was estimated to have sequestered approximately 187 million tons of carbon in 2010. Approximately 7.7 million hectares of cocoa production area in 2010 was found to grow cocoa as a monoculture. If agroforestry practices were scaled to those areas, cocoa production areas would be able to store approximately 175 million tons of additional carbon globally. Given the findings currently available in the academic literature regarding impacts of agroforestry adoption on yields, scaling agroforestry to existing cocoa monoculture areas would likely result in a 26% loss in global production. This loss amounts to a reduction of 1.2 million tons of cocoa beans per year.

When increasing the minimum tree cover threshold to 40% to define agroforestry areas, approximately 1.1 million hectares of land were found to be covered by cocoa agroforestry systems in 2010. Under this assumption, approximately 10% of cocoa production was cultivated in agroforestry systems globally. As such, global cocoa production was found to store about 163 million tons of carbon, 24 million tons of carbon less than when including production areas with 30% tree cover. Given the change in threshold condition, approximately 8.7 million hectares of cocoa production area in 2010 was identified by the model as a cocoa monoculture area. Converting those areas to agroforestry would increase carbon stored in global cocoa production areas by 199 million tons. This finding is not robust and likely overestimated as it does not consider the carbon storage contribution of cocoa production areas with less than 40% tree cover. In terms of impact on cocoa production, scaling agroforestry would likely reduce global production by 30% or 1.3 million tons per year.

Given certain model assumptions and limitations in the data used to estimate the benefits, these carbon sequestration benefits of upscaling agroforestry to 2010 cocoa production areas are likely overestimated. As a global top-down assessment of the benefits and trade-offs of scaled agroforestry adoption, this study overlooks a lot of the nuances that may be critical in both determining and enabling potential benefits of agroforestry adoption in each cocoa producing region. Although tree integration is a defining characteristic of agroforestry systems, the extent of the carbon sequestration benefit tree integration will provide will vary according to various factors including the type of tree species, tree density, competition with other species, rainfall patterns and soil quality in different regions (Nair, 2012). Moreover, using tree cover as a proxy to identify cocoa agroforestry areas, as well as assuming uniform distributions of tree cover and cocoa production within regions, is likely to overestimate the global presence of cocoa agroforestry systems. However, given the lack of publicly available high-resolution data on the location of cocoa farms, this approach provides an initial basis to assess the amount and scale of areas available to adopt climate-smart practices on. Furthermore, it can be used to apply findings from different studies assessing the potential ecosystem service benefits and trade-offs observed through agroforestry adoption in different regions. Further research that improves the data available on ecosystem services provided by agroforestry systems at different regional levels will contribute to improving the robustness of findings in this study in the future.

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Appendix

The subsequent sections outline in further detail the steps taken (i) to examine and identify data relevant to the scope of the study and (ii) to analyze relevant information using Geographic Information System (GIS) software.

Data Collection for Spatial Analysis

Cocoa Production

Global georeferenced estimates of the physical area of cocoa production in 2010 were identified in the Spatial Production Allocation Model (SPAM) (International Food Policy Research Institute, 2019). The SPAM is a model that uses land cover data as well as crop production statistics from various datasets to provide georeferenced images containing information about global crop production for 42 different crops (International Food Policy Research Institute, 2021). The SPAM uses the following input data to develop the allocation model (You, et al., 2014):

- cropland data from the M-3 Crops database (reference year: 2008);
- land cover, production and yield data from the FAO's GAEZ data portal (reference year: 2010);
- data on irrigated and rainfed crop areas from the MIRCA database (reference year: 2012); and
- yearly national and sub-national statistics on crop production collected by the FAO.

For each of these 42 crops, the SPAM disaggregates and processes the input data to calculate the following four output variables: physical area, harvested area, production, and yield. The physical area output constitutes the sum of all physical areas of the four production processes used to grow a given crop within a georeferenced cell at a resolution of 5-arcminutes (International Food Policy Research Institute, 2021). The following production processes are considered for all crops captured by the model: (i) irrigation and high input production, (ii) rainfed and high input production, (iii) rainfed and low input production, and (iv) rainfed and subsistence production (International Food Policy Research Institute, 2021). Physical area therefore reports the total land area in hectares used to grow a given crop within each cell. As such, the sum of the physical areas used to grow a crop does not exceed the area contained by the 5-arcminute cell in which the physical area value for a crop is stored (International Food Policy Research Institute, 2021).

Harvested area, which is also measured in hectares, accounts for the physical area across all production processes as well as the number of harvests of a crop on each plot accounted for in the physical area (International Food Policy Research Institute, 2021). As such, values for harvested area are at least as large as the physical area and can exceed both the total physical area used to grow a given crop and the area contained by the 5-arminute cell (International Food Policy Research Institute, 2021).

The production output is measured in metric tons and is calculated for a given crop across all production systems by multiplying the harvested area of a crop with its yield (International Food Policy Research Institute, 2021). Yield is the amount of cocoa produced per hectare harvested and is measured in kilogram/hectare (International Food Policy Research Institute, 2021). It is calculated as a weighted average of the yields across the four production processes (International Food Policy Research Institute, 2021).

The model outputs – physical area, harvested area, production, and yield – are allocated to and stored as values in raster cells at a resolution of 5-arc minutes (approximately 10x10 km cells at the equator) (You, et al., 2014). Each output is stored in a separate raster layer containing the georeferenced cell images and saved as a Geo TIFF file. These cells can be projected onto a map to observe the spatial distribution of the stored data output.

Only the output layer for physical area was considered for the spatial analysis. This is because this study is only concerned with the area occupied by cocoa production that could potentially be converted to agroforestry. Estimates of cocoa yield provided by the Niether et al. 2020 analysis were used to quantify the impact of agroforestry adoption on cocoa production instead.

SPAM data outputs are made available online and can be downloaded directly at https://www.mapspam.info/data/. SPAM provides a global dataset of physical area, harvested area, production, and yield for 42 crops for the years 2000, 2005 and 2010. Their most recent dataset, which is from 2017, only provides data for all these variables in Sub-Saharan Africa.

Tree cover on agricultural land

Data on global tree cover on agricultural land was obtained from a research study published by Zomer et al. in 2016. The study performed a tree cover analysis on agricultural lands at a global scale to estimate the contribution of agroforestry to global and national carbon budgets between 2000 and 2010. One of the main contributions of the study was the creation of a dataset of georeferenced satellite images that reported values on the percentage of tree cover existing in areas of agricultural production in 2000 and 2010. The authors combined remote sensing data collected by the MODIS satellite on continuous fields of vegetation (MOD44B MODIS Vegetation Continuous Field - Collection 5 (2000–2010)) with the Global Land Cover 2000 database classifying land areas into various land cover categories to identify and extract the percentage of tree cover occurring on agricultural production areas (Zomer, et al., 2016). Global estimates of tree cover on agricultural land were obtained by using geospatial analytical techniques (Zomer, et al., 2016). These estimates are stored in a raster layer as a Geo TIFF file. The resolution of the raster layer providing information on the percentage of tree cover existing on agricultural land is $1km^2$ (1x1 km cells).

A dataset containing the results of their analysis is made available online and can be downloaded directly at https://apps.worldagroforestry.org/global-tree-cover/index.html.

Spatial Analysis

As shown in Figure 11, the spatial analysis involved three overarching steps: (i) process raw data, (ii) analyze using zonal statistics, and (iii) visualize results from analysis. Each of these steps will be discussed in detail in the following sections.

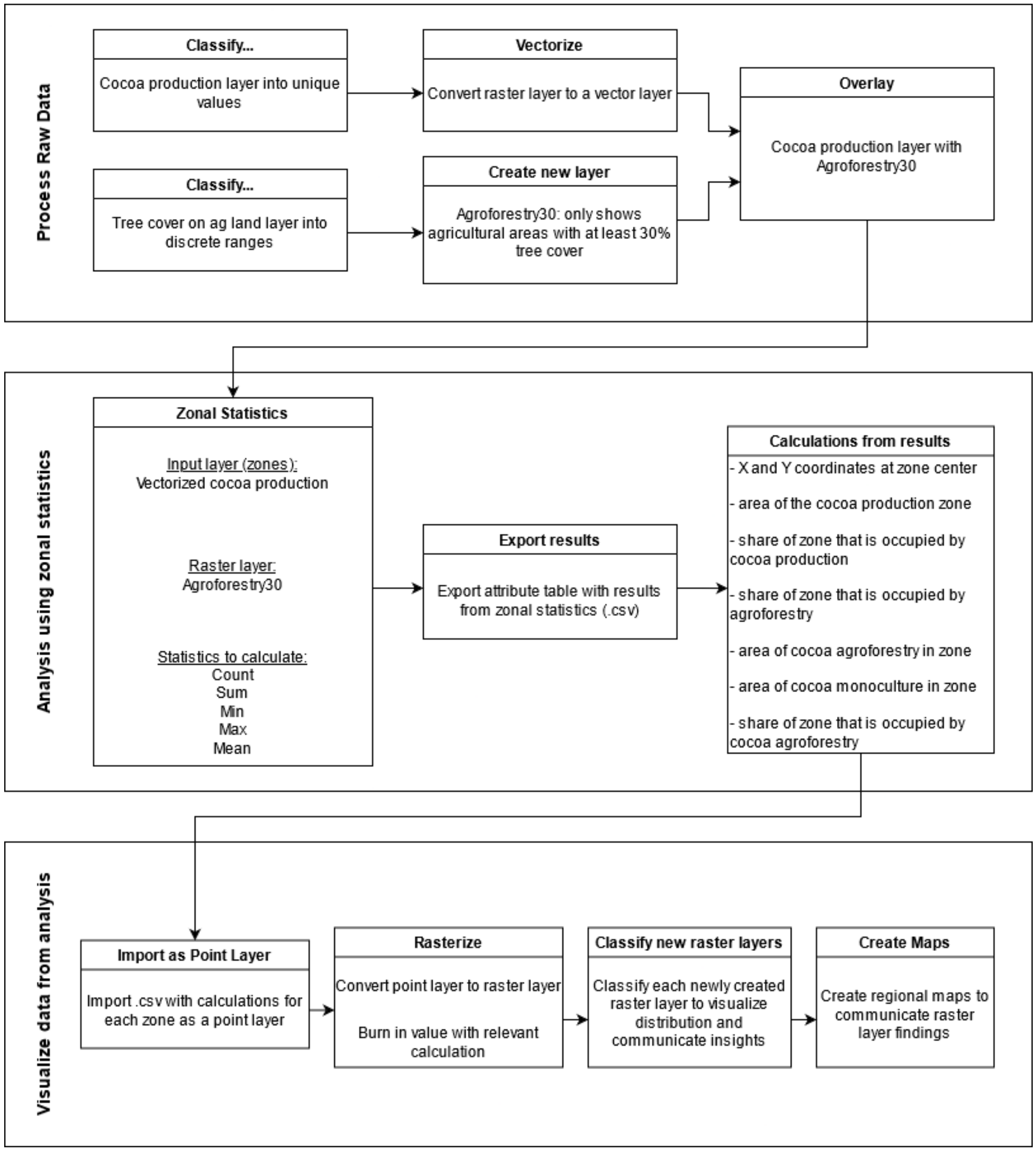

Figure 11: Overview of steps take in the spatial analysis

Process Raw Data

Data on the physical area of cocoa production layer is first classified into unique values. Doing so creates a unique ID for each cell. This raster layer is then polygonised to create a vector layer with an attribute table that contains the unique ID of a polygon, its respective X and Y coordinates, and the value for the physical area of cocoa production within that polygon.

Data on tree cover on agricultural land is classified into discrete ranges. A threshold for tree cover on agricultural land was then defined to determine whether an agricultural production area with tree cover could be considered an agroforestry system or not. The criterion on minimum canopy cover for shade-tolerant crops used by Rainforest Alliance for agroforestry certification was used to define this threshold. This criterion in the most recent standard released in 2017 states that the minimum canopy cover allowed for cocoa production to be considered agroforestry is 30% (Rainforest Alliance, 2017). Using this threshold, a new layer called "Agroforestry30" is created to show only the agricultural land areas that have at least 30% tree cover. Cells in this new layer have a value of either one or zero. Those cells that have a percentage of tree cover greater than or equal to 30% are stored in this new layer with a value of one. Cells that have a percentage of tree cover less than 30% are stored in this new layer with a value of zero. Once Agroforestry30 is generated, it is saved such that cells with a value of zero appear as 'no data values'. Performing this step will facilitate the zonal statistics conducted later in the analysis.

To visualize where agricultural land containing more than 30 precent tree cover overlaps with cocoa production areas, the cocoa production layer was overlayed with the newly created Agroforestry30 layer. Both the cocoa production and tree cover on agricultural land layers were georeferenced using WGS 84 as the coordinate reference system and mapped onto a Mercator projection in degrees. As such, no reprojection was needed to perform the overlay.

Analysis using zonal statistics

The next step involved performing zonal statistics on the overlayed layers. Zonal statistics is used to identify the number of Agroforestry30 cells occurring within in each cocoa production polygon. The cocoa production layer is used as the zonal layer, creating unique zones with a corresponding ID stored in the vector layer's attribute table. The Agroforestry30 raster layer is used as the input layer.

The statistics performed for each zone are "count", "sum", "min", "max" and "mean". The "count" function counts the number of Agroforestry30 cells existing in a cocoa production zone. The "sum" function takes the sum of the tree cover cells existing in a zone. As the value stored in each Agroforestry30 cell equals 1, this function should report the same number as the "count" function. The "min" function reports the minimum value of the tree cover cells existing in a zone. The "max" function reports the maximum value of the tree cover cells existing in a zone. The "mean" function reports the mean value of the tree cover cells existing in a zone. As the value of the tree cover cells can only be 1, the reported values for min, max and mean should always equal 1. The "sum", "min", "max", and "mean" functions are thus used as a mechanism to check no errors occurred in the zonal statistics.

The output of the zonal statistics is stored in the attribute table for the corresponding zone in the cocoa production vector file. The information reported in the attribute table includes:

- Zone ID
- X coordinate
- Y coordinate
- Physical area of cocoa production
- Count of Agroforestry30 cells
- Sum of Agroforestry30 cells
- Min of Agroforestry30 cells
- Max of Agroforestry30 cells
- Mean of Agroforestry30 cells

This attribute table containing the results of the zonal statistics is exported as a comma separated value (.csv) file.

The following variables are calculated using the zonal statistics results:

- X and Y coordinates of a zone at its center
- area of a cocoa production zone
- share of a cocoa production zone that is occupied by cocoa production
- share of a cocoa production zone that is occupied by Agroforestr30
- area of cocoa agroforestry in zone
- area of cocoa monoculture in zone

X and Y coordinates at zone center

Coordinate points of a polygon in a vector layer are by default taken at the bottom left corner of a polygon, as shown in Figure 12.

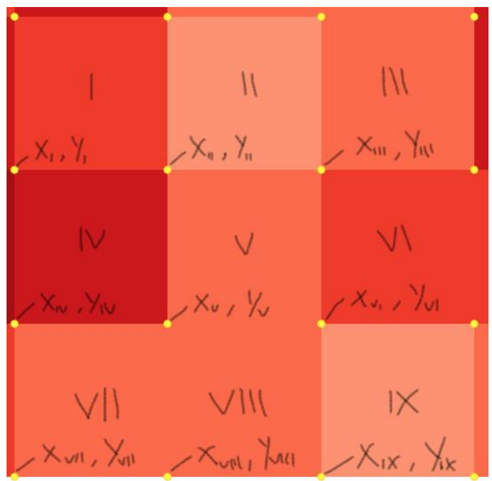

Figure 12: Default coordinate position of the cocoa production zone polygon

As the dimensions of the cocoa production zones are 5-arcminutes (5/60 degrees x 5/60 degrees), 2.5/60 degrees were added to both the X and Y coordinates given for each zone to identify the X and Y coordinate at the center of a zone as shown in Figure 13.

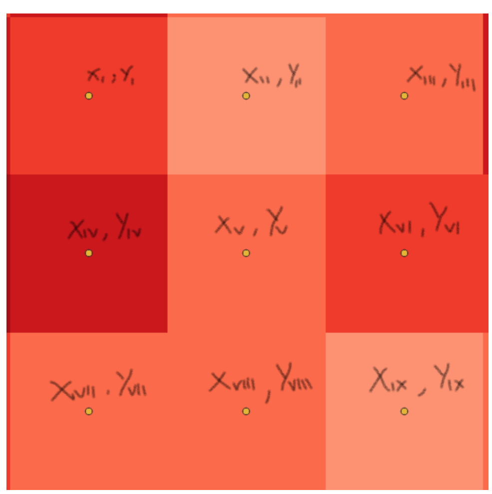

Figure 13: Polygon coordinates adjusted to cocoa production zone center

Area of cocoa production zone

Considering the resolution of the cocoa production zone at 5-arcminutes and the coordinate reference system at which it is projected, the area contained within the 5-arcminute dimension of the zone will vary depending on the latitude at which its corresponding coordinate is projected to. The haversine formula was thus used to calculate the area of each cocoa production zone at each degree latitude between and including 23.125˚ North and -24.708˚ South. The X and Y coordinates at the zone's center were used to calculate its total area.

Share of a zone that is cocoa production

Given the area contained by the cocoa production zone at latitude Y and the area of cocoa production occurring in that respective zone, the share of a zone that is occupied by cocoa production can be calculated as follows:

$$share\ of\ cocoa\ production\ in\ zone\ i\ (\%) = \frac{total\ physical\ area\ of\ cocoa\ production\ in\ zone\ i\ (ha)}{area\ of\ zone\ i\ \ (ha)} \cdot 100$$

Share of zone that is Agroforestry30

As the resolution of a single Agroforestry30 cell is 1km^2, this study assumes that the number of cells existing in a zone correspond to the area in km^2 of agroforestry land cover occurring in that zone. In other words, if the zonal statistics counted 1 tree cover cell in a zone, the total area of agroforestry land cover in that zone is 1 km^2 (100 ha), as shown in Figure 14. The red rectangle represents one zone/polygon of the cocoa production layer. The green rectangle represents one cell of the Agroforestry30 layer.

Figure 14: Overlay of the agroforestry and cocoa production layers.

Therefore, the area of agroforestry land cover in a zone equals the count of Agroforestry30 cells occurring in that zone. The units of that area are then converted from square kilometers to hectares.

$$count\ of\ Agroforestry30\ cells\ in\ zone\ i = area\ of\ agroforestry\ production\ in\ zone\ i\ (km2)$$

$$1\ km2 = 100\ ha$$

Given the area contained by the cocoa production zone at latitude Y and the area of agroforestry land cover occurring in that respective zone, the share of a zone that is occupied by agroforestry can be calculated as follows:

$$share\ of\ agroforestry\ in\ zone\ i\ (\%) = \frac{area\ of\ agroforestry\ production\ in\ zone\ i\ (ha)}{area\ of\ zone\ i\ (ha)} \cdot 100$$

Area of cocoa agroforestry and cocoa monoculture in zone

To determine the amount of cocoa agroforestry present in a cocoa production zone, this study assumes that the physical area of cocoa production present in a zone is distributed uniformly. Doing so allows this study to further assume that the share of cocoa agroforestry is equivalent to the share of agroforestry in the cocoa production zone. For example, if the share of agroforestry in zone i is 10%, it is assumed that 10% of the physical area of cocoa production present in that zone is grown in an agroforestry system. The area of cocoa agroforestry in a cocoa production zone is thus calculated as follows:

$$area\ of\ cocoa\ agroforestry\ in\ zone\ i\ (ha) =$$

$$total\ physical\ area\ of\ cocoa\ production\ in\ zone\ i\ (ha) \cdot\ share\ of\ agroforestry\ production\ in\ zone\ i\ (\%)$$

Once the area of cocoa agroforestry is calculated for every zone, the area of cocoa monoculture for every zone can be calculated as follows:

$$area\ of\ cocoa\ monoculture\ in\ zone\ i\ (ha) =$$

$$total\ physical\ area\ of\ cocoa\ production\ in\ zone\ i\ (ha) -\ area\ of\ cocoa\ agroforestry\ in\ zone\ i\ (\%)$$

Given the calculated area of cocoa agroforestry, the share of cocoa agroforestry occurring in a cocoa production zone can also be calculated as follows:

$$share\ of\ cocoa\ agroforestry\ in\ zone\ i\ (\%) = \frac{area\ of\ cocoa\ agroforestry\ in\ zone\ i\ (ha)}{area\ of\ zone\ i\ (ha)} \cdot 100$$

Visualize data from analysis

Results from each of the calculations are saved as a .csv file, which is then imported to QGIS as a point layer with a corresponding attribute table. This point layer is then converted to a raster file. Different attributes can be burned into the raster cells when creating the layer to project a desired attribute on a map. The information stored in the created raster layers is then classified in a way that best communicates the projected attribute of interest. Maps conveying this information are then created to communicate the quantified findings of this study.

Upscaling Niether et al. 2020 findings

The highlighted fields in Figure 15 below show the mean estimates and standard deviations (one sigma) for cocoa yield and total C stored in cocoa agroforestry systems and cocoa monoculture systems from the Niether et al. 2020 meta-analysis (Niether, et al., 2020). The size of the sample used in the statistical analysis for each variable is indicated by N. The levels of significance of the results are indicated as follows, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s.: not significant.

			Cocoa agroforestry system		Cocoa monoculture			
Group	Variable	Unit	Mean	SD	Mean	SD	N	
Yield								
	Cocoa yield	Mg ha^{-1}	0.6	± 0.4	0.9	± 0.7	36	***
	System yield	Mg ha^{-1}	9.8	± 9.2	0.6	± 0.4	8	*
Economic performance								
	Costs	USD ha^{-1} a^{-1}	571.5	± 322.8	652.9	± 464.4	7	n.s.
	System revenue	USD ha^{-1} a^{-1}	1094.3	± 594.7	1299.7	± 905.9	8	n.s.
	Net present value	USD ha^{-1}	998.8	± 736.8	1108.9	± 729.7	4	n.s.
Soil chemical properties								
	Soil C	%	14.5	± 2.4	13.8	± 2.3	20	n.s.
	Soil N	%	1.8	± 0.7	1.7	± 0.6	22	n.s.
	Soil available P	mg kg^{-1}	13.7	± 14.2	17.2	± 16.9	9	n.s.
	Soil available K	g kg^{-1}	0.1	± 0.1	0.1	± 0.1	10	n.s.
	Soil organic carbon	%	1.7	± 0.5	1.7	± 0.5	8	n.s.
	pH		6.3	± 0.4	6.4	± 0.5	6	*
Soil physical properties								
	Mean weight diameter	mm	1.0	± 0.4	0.9	± 0.2	10	n.s.
	Bulk density	g cm^3	1.3	± 0.3	1.4	± 0.2	4	*
	Volumetric water content	%	20.1	± 5.4	21.8	± 5.7	6	**
Fungal diseases								
	Frosty pod rot	%	28.8	± 24.5	21.2	± 16	4	n.s.
	Black pod	%	3.4	± 2.2	3.0	± 2.0	5	*
	Witches' broom	%	1.9	± 1.4	3.7	± 2.4	5	*
Microclimate								
	Maximum temperature	°C	32.4	± 2.5	34.7	± 3.3	8	*
	Minimum temperature	°C	18.6	± 3.1	17.9	± 3.4	8	***
	Mean temperature	°C	24.7	± 1.8	25.0	± 1.8	8	*
	Mean relative humidity	%	81.5	± 16.5	80.5	± 15.6	3	n.s.
	Vapor pressure deficit	kPa	1.1	± 0.7	1.3	± 0.8	4	n.s.
Stand structural parameters								
	Basal area cocoa trees	m^2 ha^{-1}	7.7	± 2.9	9.4	± 3.2	22	***
	Basal area shade trees	m^2 ha^{-1}	10.2	± 2.2	0.2	± 0.4	4	***
	Total C in cocoa trees	Mg ha^{-1}	9.5	± 6.3	13.2	± 6.9	30	***
	Total C in shade trees	Mg ha^{-1}	24.7	± 26.3	1.0	± 4.6	27	***
	Total C in system	Mg ha^{-1}	37.0	± 28.9	14.2	± 9.0	30	***

Figure 15: Mean values and standard deviations of ecosystem service parameters in cocoa agroforestry systems and cocoa monocultures (Niether et al. 2020).

The mean estimates for cocoa yield and total C stored by each production system are measured in ton per hectare[1]. These parameters can thus be upscaled by the total area of cocoa agroforestry and cocoa monoculture existing in a given year to estimate the amount of cocoa produced (tons) and the total C stored (tons) by each production system in 2010.

The values calculated for the area of cocoa agroforestry in the spatial analysis are summed across all cocoa production zones to get a global estimate of the total area of cocoa agroforestry production in 2010.

[1] One megagram is equal to one metric ton.

$$\text{total area of cocoa agroforestry} = \sum_{i=1}^{64,365} \text{area of cocoa agroforestry in zone } i$$

Similarly, the values calculated for the area of cocoa monoculture in the spatial analysis are summed across all cocoa production zones to get a global estimate of the total area of cocoa monoculture production in 2010.

$$\text{total area of cocoa monoculture} = \sum_{i=1}^{64,365} \text{area of cocoa monoculture in zone } i$$