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Enhancing Smallholder Farmer Climate Resilience in Cocoa and Banana Global Food Value Chains

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Abstract

The global food system is a complex socio-ecological system performing the critical service (with varying degrees of success) of nourishing humanity's food and nutrition needs. This system is under threat from, amongst others, a range of climate related shocks, including extreme weather events as well as more gradual stressors, such as changing rainfall patterns. The impacts of climate related shocks and stressors to the global food system, such as loss of income and hunger, are unequally distributed between food system actors with smallholder farmers (an incredibly diverse yet globally significant grouping) being particularly vulnerable. Increasingly, many smallholder farmers are embedded in global food value chains (GFVCs), producing crops for export, including fruits, vegetables and non-food commodities. GFVCs are international networks of actors that interact at the various stages (production, processing, distribution, retailing and consumption) of the food system. However, little is understood about how farmers engaged in GFVCs are affected by climate shocks and how the impacts are influenced by their participation in a GFVC. Resilience, the ability of a system to cope with shocks and maintain overall function, has emerged as a potentially useful concept for guiding the governance and management of food systems in the face of these evolving threats. Within the broader field of resilience, climate resilience is emerging as a priority topic in smallholder food production in the Global South. This thesis seeks to understand how climate shocks impact smallholders engaged in GFVCs and elicit ways to enhance the climate resilience of the vulnerable actors in these systems.

I created three linked objectives for this thesis : ***(i)*** Co-define, with stakeholders, "climate resilience" of smallholder farmers in GFVCs. ***(ii)*** Assess the climate resilience of smallholder farmers and its determinants in GFVCs. ***(iii)*** Assess and explore different opportunities to enhance climate resilience of smallholders in GFVCs. To operationalise these objectives, I investigated two smallholder driven GFVCs, that share many characteristics, such as polarisation of actor power and climate hazard exposure, but also have some key ecological and institutional contrasts. These are the Ghanaian - Swiss cocoa value chain and the Dominican Republic - UK banana value chain. Both of these GFVCs face regular and intensifying climate threats, with a severe shock being experienced in both GFVCs between 2015 and 2017. As a result of the El Niño oscillation in 2015 there was a strong drought experienced by cocoa farmers in Ghana during the 2015-16 production season. Contrastingly, banana farmers in the Dominican Republic were exposed to severe flood damage caused by two consecutive hurricanes, Irma and Maria, in September 2017. These climate shocks are the focus of my thesis.

To deliver on the objectives, I adopted (with many crucial collaborations) a four-phase approach: ***(i)*** Value chain stakeholder platform establishment, ***(ii)*** Characterising climate risks and co-defining climate resilience, ***(iii)*** Resilience assessment of smallholder producers in the context of GFVCs, ***(iv)*** Exploration of resilience enhancement opportunities. In each value chain, I utilise an overall transdisciplinary research approach, involving multiple methods including; multi-stakeholder workshops, focus groups, value-chain-actor interviews, household surveys, biophysical on farm assessments and satellite remote sensing. Chapter 2 takes the case of the 2015-16 drought shock, to cocoa production in Ghana, to examine whether sustainability certification, namely Organic, UTZ and Rainforest Alliance, can deliver climate resilience for smallholder farmers. In Chapter 3, I again take the case of cocoa producers but move beyond comparison of certification impacts to address the question: What determines the adoption of climate resilience strategies by smallholder farmers? In Chapter 4, taking the Dominican Republic banana case, I ask: What determines the resilience of smallholder farmers embedded in GFVCs to extreme weather events? I address four specific research questions; ***(i)*** How are smallholder farmers impacted by hurricane induced flooding? ***(ii)*** What actions or strategies do the actors of this GFVC adopt to enhance their climate resilience? ***(iii)*** How quickly did farmers recover? and ***(iv)*** What determined recovery rates?

Across the banana and cocoa value chains, I find that for climate resilience strategies to be effective they must be both generalisable across diverse (even unknown) threats, whilst also incorporating specificity versus key hazards. This is challenged by the fact that farmer agency relating to resilience strategy utilisation is scale-limited, exemplified by them having little power to act at a landscape scale. Moreover, resilience enhancing strategies are more than just the sum of their parts and therefore, both synergistic and antagonistic, interactions must be considered in their design and promotion. In particular, in relation to GFVCs, climate resilience strategies are not, by default, benevolent and important inter-actor tradeoffs occur, such as traders switching sourcing locations in the face of a shock. I find multiple determinants of climate resilience strategy adoption, including land tenure, income generating capacity and farm scale. Relatedly, I find access to markets for alternative agricultural products is key to developing climate resilient multifunctional agricultural systems. Additionally, the sub-national regional context strongly moderates climate resilience strategy adoption and extreme-weather-shock outcomes and, therefore, should be accommodated in policy and programme design. In terms of mechanisms to enhance the climate resilience of smallholders in GFVCs, certification has the potential to modify smallholder climate resilience but underperforms on the uptake of complex versus simple measures because of a strong commodity focus. I find that climate specific training enhances climate resilience strategy uptake but targeting is key to avoid smaller scale farmers being left behind. Spatial planning at a landscape scale, such as zoning using flood risk maps, can enhance climate resilience and should be pursued as a powerful resilience enhancing tool. Overall, participating in GFVCs is a "double-edged sword" for smallholders' climate resilience and, therefore, cooperation must be enhanced, for example via mechanisms to increase basin-scale collaboration and trader loyalty, so as to reduce the tradeoffs involved.

Zusammenfassung

Das globale Nahrungsmittelsystem, ein komplexes sozio-ökologisches System, dass die kritische Aufgabe hat den wachsenden Nahrungsmittelbedarf der Menschheit zu decken, ist bedroht, sowohl durch eine Vielzahl von Schocks (threats), wie zum Beispiel extreme Wetterereignisse, und plötzliche politische Unruhen, als auch durch Stressoren (stressors), wie die zunehmende Urbanisierung und den Klimawandel. Die Auswirkungen der klimabedingten Schocks und Stressoren auf das globale Ernährungssystem sind ungleich auf die Akteure verteilt, wobei Kleinbauern (eine unglaublich vielfältige jedoch global bedeutende Gruppierung) besonders verwundbar sind. Immer mehr Kleinbauern sind in globalen Lebensmittelwertschöpfungsketten (GFVCs) eingebettet und produzieren Feldfrüchte für den Export aber auch Obst, Gemüse und Non-Food-Güter. GFVCs sind internationale Netzwerke von Akteuren, die auf den verschiedenen Stufen des Lebensmittelsystems interagieren. Es ist jedoch wenig darüber bekannt, wie stark LandwirtInnen, welche Mitglieder von GFVCs sind, von Klimaschocks betroffen sind und welche Auswirkungen ihre Mitgliedschaft in einer GFVC hat. Resilienz, die Fähigkeit eines Systems mit Schocks umgehen und dabei die Gesamtfunktion weiterhin aufrechterhalten zu können, hat sich als nützliches Konzept erwiesen, im Sinne einer Orientierungshilfe für die Steuerung und das Management von Lebensmittelsystemen, angesichts dieser sich rasch entwickelnden Bedrohungen. Ich nehme dies als Ausgangspunkt für diese Arbeit und untersuche: Inwiefern ein besseres Verständnis der potenziellen Klimaschocks, der in GFVCs beteiligten Kleinbauern, die Klimaresilienz der verwundbarsten Akteure in diesen Systemen verbessern kann.

Für diese Arbeit habe ich drei miteinander verbundene Ziele formuliert: (i) Die Erarbeitung einer gemeinsamen Definition von Klimaresilienz von Kleinbauern in globalen Lebensmittelwertschöpfungsketten mit den involvierten Interessensgruppen. (ii) Die Bewertung der Klimaresilienz von Kleinbauern und ihren Faktoren in globalen Lebensmittelwertschöpfungsketten. (iii) Die Bewertung und Erforschung von Möglichkeiten zur Verbesserung der Klimaresilienz von Kleinbauern in globalen Lebensmittelwertschöpfungsketten. Um diese Ziele zu erarbeiten, untersuchte ich zwei kleinbäuerlich geprägte GFVCs, die viele Gemeinsamkeiten haben, aber auch einige wichtige Unterschiede aufweisen. Dies sind die Kakao-Wertschöpfungskette zwischen Ghana und der Schweiz und die Bananen-Wertschöpfungskette zwischen der Dominikanischen Republik und Großbritannien. Beide GFVCs sind regelmäßigen und sich verschärfenden Klimabedrohungen ausgesetzt, wobei es in beiden GFVCs zwischen 2015 und 2017 zu einem schweren Schock kam. Infolge der El-Niño-Schwankung im Jahr 2015 erlebten die Kakaobauern in Ghana in der Produktionssaison 2015-16 eine schwere Dürre. Im Gegensatz dazu waren die Bananenbauern in der Dominikanischen Republik schweren Überschwemmungsschäden ausgesetzt, die durch zwei aufeinanderfolgende Orkane, Irma und Maria, im September 2017 verursacht wurden. Diese Klimaschocks stehen im Mittelpunkt meiner Arbeit.

Um die Ziele zu erreichen, habe ich einen vier-phasigen Ansatz gewählt: (i) Etablierung einer Plattform für Interessensgruppen innerhalb der Wertschöpfungskette, (ii) Charakterisierung von Klimarisiken und die Erarbeitung einer gemeinsamen Definition von Klimaresilienz, (iii) Resilienzbewertung von Kleinproduzenten im Kontext von GFVCs, und (iv) Erforschung von Möglichkeiten zur Steigerung der

Resilienz. In jeder Wertschöpfungskette verwende ich einen ganzheitlich transdisziplinären Forschungsansatz, welcher mehrere Methoden enthält, wie Multi-Stakeholder-Workshops, Fokusgruppen, Interviews mit Akteuren der Wertschöpfungskette, Haushaltsbefragungen, biophysikalische Untersuchungen auf den Betrieben und Satellitenfernerkundungen. Kapitel 1 nimmt den Fall des Dürreschocks 2015/16 für die Kakaoproduktion in Ghana zum Anlass, um zu eruieren, inwiefern die Nachhaltigkeitszertifizierungen, namentlich Bio, UTZ und Rainforest Alliance Kleinbauern zu Klimaresilienz verhelfen können. In Kapitel 2 nehme ich wieder den Fall der Kakaoproduzenten, gehe aber über den Vergleich der Auswirkungen von Zertifizierungen hinaus, um der Frage nachzugehen: Was bestimmt die Akzeptanz von Klimaresilienzstrategien durch Kleinbauern? In Kapitel 3 erkundige ich die vier spezifischen Forschungsfragen anhand des Bananenbeispiels aus der Dominikanischen Republik: (i) Wie sind die Kleinbauern von den Orkan-bedingten Überschwemmungen betroffen? (ii) Welche Maßnahmen oder Strategien wenden die Akteure dieser GFVC an, um ihre Klimaresilienz zu erhöhen? (iii) Wie schnell erholten sich die Bauern? Und (iv) was bestimmte die Erholungsraten?

In den Wertschöpfungsketten von Bananen und Kakao stelle ich fest, dass Klimaresilienz-Strategien über verschiedene (sogar unbekannte) Bedrohungen hinweg verallgemeinerbar sein müssen und gleichzeitig die Spezifität der Hauptbedrohungen berücksichtigen müssen. Dies wird durch die Tatsache erschwert, dass die Handlungsfähigkeit der Landwirte in Bezug auf die Nutzung von Resilienz-Strategien begrenzt ist, da sie nur einen geringen Handlungspielraum auf der Landschaftsebene haben. Darüber hinaus sind resilienzfördernde Strategien mehr als nur die Summe ihrer Teile und daher müssen sowohl synergistische als auch antagonistische Wechselwirkungen in der Entwicklung und Förderung von wirksamen Strategien berücksichtigt werden. Insbesondere in Bezug auf GFVCs werden Klimaresilienz-Strategien nicht per se wohlwollend aufgenommen und die Akteure müssen untereinander einschneidende Kompromisse aushandeln. Ich finde mehrere Einflussfaktoren für die Akzeptanz von Klimaresilienz-Strategien, darunter Landbesitz und Einkommen. In diesem Zusammenhang stelle ich fest, dass der Zugang zu Märkten für alternative landwirtschaftliche Produkte entscheiden für die Entwicklung von klimaresistenten und multifunktionalen Landwirtschaftsystemen ist. Darüber hinaus hat der subnationale regionale Kontext einen starken Einfluss auf die Akzeptanz von Klimaresilienz-Strategien und die Auswirkungen von Extremwetterereignissen und sollte daher bei der Gestaltung von Politik und Programmen berücksichtigt werden. Was die Mechanismen zur Verbesserung der Klimaresilienz von Kleinbauern in GFVCs betrifft, so hat die Zertifizierung das Potenzial, die Klimaresilienz von Kleinbauern zu verändern, schneidet aber aufgrund des starken Rohstofffokus bei der Akzeptanz komplexer versus einfache Maßnahmen schlechter ab. Es hat sich gezeigt, dass klimaspezifische Schulungen die Akzeptanz von Klimaresilienz-Strategien erhöhen, aber eine gezielte Ausrichtung ist entscheidend, um zu vermeiden, dass Kleinbauern zurückgelassen werden. Räumliche Planung auf Landschaftsebene, wie z.B. Zonierung unter Verwendung von Hochwasserrisikokarten, kann die Klimaresilienz erhöhen und sollte im Sinne eines leistungsfähigen Instrumentes zur Verbesserung der Resilienz berücksichtigt werden. Insgesamt ist die Teilnahme an GFVCs ein "zweischneidiges Schwert" für die Klimaresilienz von Kleinbauern. Daher muss die Zusammenarbeit verbessert werden, zum Beispiel durch Mechanismen, welche die Zusammenarbeit der Einzugsgebiete und die Loyalität der Händler erhöhen, um die damit verbundenen Kompromisse zu reduzieren.

1.0

Introduction

1.1 The climate threat to food systems and smallholders

1.1.1 Food system vulnerability in a changing climate

The global food system is under threat from a myriad of shocks, ranging from extreme weather events to sudden political unrest, as well as stressors, including urbanization and climate change (Cottrell et al., 2019; Hamilton et al., 2020). The food system, comprising the multiple networks of actors involved in production, processing, distribution, retailing and consumption of food, provides (to varying degrees of success) the critical service of nourishing humanity's expanding food and nutrition security needs (Ericksen, 2008). When climate hazards, such as droughts or hurricanes, cause shocks to production or disrupt distribution, this can lead to widespread hunger and damage to producer livelihoods (FSIN, 2020). For example, in 2019 Mozambique was hit by two consecutive cyclones, during the main harvest season, negatively impacting the food security of an estimated 3.8 million people (OCHA, 2019). To some extent food systems have always faced shocks and stresses but on-going changes to human society, such as globalisation, and to the earth system, particularly climate change, are in many cases enhancing the frequency and severity of such shocks (Puma et al., 2015). Cottrell et al. (2019) analysed data on production shocks, from the last 50 years, across crop, livestock and seafood sectors and showed an increasing frequency of shocks across all sectors. If we are to improve the ability of the food system to deliver food and nutrition security for all humans, then it will be critical to understand the threats that the food system faces (and generates or exacerbates), its current ability to deal with these threats and to find ways to enhance its ability to deal with future threats.

Why does it matter if the global food system is disrupted? Climate related shocks and stressors, such as drought and flooding, cause disruption to food systems at all stages along the chain from field to fork (Vermeulen et al., 2012). These disruptions do not only affect the actors at one particular stage but often cascade up and down the chain via a series of feedbacks, generally in supply or demand (Wheeler and Von Braun, 2013). Between 2005 and 2015, the UN Food and Agriculture Organisation (FAO) estimates that natural disasters caused $96 billion in losses to crop and livestock production in low income countries alone (Markova et al., 2018). Disruptions in agricultural production can have direct impacts on food security and hunger, for example with severe droughts in 2020 in Haiti, Pakistan and Zimbabwe contributing to acute food insecurity for over 10 million people (FSIN, 2020). Distribution of food between areas of production and consumption can also be severely impacted by climate related shocks, such as flooding of transport infrastructure (Davis et al., 2021). In addition, climate shocks can also impact the consumption of food, whether this be through preventing proper preparation or causing increased food borne disease (Béné et al., 2015). Climate related shocks are not just experienced as temperature extremes and water deficits but can also be manifested in the form of pest outbreaks and storage problems (Myers et al., 2017). These shocks do not just have short term impacts, it is also seen that they can cause long term negative impacts on agricultural systems and on household consumption, as was observed 15 years after the 1984-85 drought in Ethiopia (Dercon, 2004).

The increasingly globalised nature of our food system, with ever more complex connections between geographically separate areas of production and consumption, has magnified the impact of climate shocks (Kummu et al., 2020). Given that it is estimated that approximately 80% of people live in a net food importing country (Porkka et al., 2013), it means that food system shocks that occur in one region will most likely cause disruptions in other regions. This was seen during the 2008-9 food crisis when global centres of grain production suffered simultaneous drought driven production losses, coupled with the effect of biofuel production constraining supply, leading to export bans and resulting in food price spikes and increased hunger (Headey, 2011). This is an example of the telecoupled nature of the global food system where socio-economic and environmental interactions occur across spatially distant locations (Liu et al., 2013). Whilst global trade presents opportunities for enhancing the function of the food system, it also poses new threats from often complex and unforeseen emergent behaviour (Gaupp et al., 2020; Tu et al., 2019).

1.1.2 Smallholders climate vulnerability

The impacts of climate related shocks and stressors to the global food system are unequally distributed between actors, with smallholder farmers (an incredibly diverse grouping) being actors that are particularly vulnerable (Harvey et al., 2014). This is because of factors such as high dependence on agricultural production (in many cases subsistence), capital scarcity, lack of formal safety nets (Donatti et al., 2019; Morel et al., 2019; J. Rurinda et al., 2014) and ultimately polarization of power in food systems (Chandra et al., 2017). In addition, climate threats may interact with existing vulnerabilities including human health challenges, such as infectious disease, environmental degradation and lack of land tenure (Cohn et al., 2017). There are approximately 500 million smallholder farms worldwide, with the vast majority being in Asia and Africa (Lowder et al., 2016). They therefore make up a critical group in the food system, with farms under 2 ha producing 30-34% of global food supply on 24% of agricultural area (Ricciardi et al., 2018). In addition, these producers are largely situated in tropical regions, where the threat of climate change and increased disruption from extreme weather events is very high (Fu, 2015).

A growing number of smallholders are connected to global food value chains, producing crops for export, including commodities such as cocoa, fruit such as bananas and vegetables such as green beans (Swinnen, 2007). Global food value chains (GFVCs) are chains or networks of actors that interact, across international borders, in the various stages (production, processing, distribution, retailing) of the food system from field to fork (Ericksen, 2008). Increasingly, these value chains take on a global nature with food produced in one country processed in a second and sold in a third, with international trade accounting for 24% of all agricultural land use (Weinzettel et al., 2013). Globally, over 100 million smallholder producers are estimated to sell their production for export in such chains (Author calculation based on key export crops). Many of these GFVCs are controlled, due to a polarisation of power, by lead companies often large transnational corporations headquartered in the Global North (Folke et al., 2019). In GFVCs, therefore, many aspects of smallholder production systems and livelihood outcomes are significantly influenced by these lead companies (Nyström et al., 2019). Participation in GFVCs by smallholders can create a double exposure to both climate change and globalisation, via global markets (O'Brien and Leichenko, 2000). In particular, there is a growing concern about the climate vulnerabilities of smallholders embedded in GFVCs and how to best reduce these.

1.1.3 Prologue

As awareness of the climate vulnerabilities of smallholder farmers engaged in GFVCs increases, so does a proliferation of attempts to reduce them. I take this as the starting point for this thesis: investigating how increased understanding of climate shocks to smallholders engaged in GFVCs in the Global South, led by companies in the Global North, can enhance the climate resilience of the vulnerable actors in these chains. In the rest of this section, I will introduce the following topics: food system resilience, approaches to enhancing smallholder climate resilience, resilience assessment, the two case study value chains (cocoa and banana), before concluding with an outline of the activities undertaken and the outputs created.

1.2 Resilience in food systems

As recognition of the future risks that extreme weather events pose to smallholder farmers and our food system has grown, "resilience" and in particular "climate resilience" has emerged as a theoretical, governance and management approach, to understand and reduce the impact of such shocks (Dixon and Stringer, 2015; Tendall et al., 2015). Resilience, although contentious in scholarly definition, can be summarised as the ability of a system to maintain function, recover and (even) improve in the face of a shock (Folke, 2006; Holling, 1973a; Walker, 2020).

1.2.1 Resilience in socio-ecological systems

In the past decades, "resilience thinking" has emerged as a prevailing theory for understanding perturbations to systems. Originally conceived in the field of ecology, by C.S Holling in the 1960's, resilience has since been applied to socio-ecological systems (Folke, 2006). Socio-ecological systems are complex coupled human and biophysical sub-systems, where human systems interact with nature at varying scales from local to global, key examples being fisheries and agricultural systems (Gallopin et al., 1989; Berkes, Folke and Colding, 2000). Resilience theory for socio-ecological systems has developed in parallel with theories of vulnerability and adaptive capacity (Gallopín, 2006). Vulnerability is described as the exposure to perturbation, the sensitivity to that perturbation and the capacity to adapt (Adger, 2006). Adaptive capacity is described as the capacity of a socio-ecological system to improve its ability to cope with perturbation and even improve its condition in the absence of perturbation (Smit and Wandel, 2006). Resilience has been described as a subset of vulnerability (exposure, sensitivity, capacity of responses cf. resilience) and adaptive capacity has been described as a subset of resilience (although there is much discussion in the literature) (Gallopín, 2006). Resilience is not always considered a positive attribute of a system, as it can maintain a system in an undesirable state, such as an agricultural system that is causing environmental damage and is resilient to change (Oliver et al., 2018; Hodbod and Eakin, 2015). Beyond this, there is the potential for inter-actor resilience trade-offs in a system, where one actor enhances their resilience at the expense of another and therefore equity and justice aspects must be considered (Béné et al., 2014). Temporal trade-offs may also occur when enhancing resilience at one point in time may be at the expense of future resilience (Cabel and Oelofse, 2012).

1.2.2 Resilience in food systems

More recently resilience thinking has been adopted to enhance the understanding, management and governance of food systems (Heckelman et al., 2018; Jacobi et al., 2018; Tendall et al., 2015). Tendall et al. (2015) define food system resilience as "the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances". Therefore, we can see that by applying such a normative framework resilience can be targeted as a positive system attribute. Beyond a food security linked framework, sustainability can also be incorporated to qualify the above definition within equitable and sustainable boundaries (Jacobi et al., 2018). Relatedly, resilience can be seen to be a key element of sustainability, enabling a system to chart a sustainable trajectory despite disturbances and conversely a sustainable approach can allow a system to remain resilient in the long term (Anderies et al., 2013). In this thesis, I will use the term resilience with a normative assertion of the benefits that resilience can bring in relation to climate driven disruptions of food systems.

1.2.3 Climate resilience in smallholder food systems

Enhancing the climate resilience (resilience specifically in the face of climate shocks) of smallholder farmers has been identified as an urgent societal task (African Union, 2014a). For smallholders, enhancing their climate resilience has the potential to reduce the impact of climate shocks on their incomes, food security and more broadly livelihoods (Suweis et al., 2015; Shiferaw et al., 2014). In addition, enhanced resilience of the producers, has the potential to protect societies against the transmission of climate shocks from agricultural production to the wider economy (Chavez et al., 2015). Beyond this, more resilient livelihoods can limit sprawling agricultural expansion into forests and biodiversity hotspots (Biazin and Sterk, 2013). Climate resilience can be seen as a specific form of resilience (specific to a particular threat), however by choosing to focus on enhancing resilience to a key threat this does not, necessarily, have to be at the expense of more general resilience.

Whilst smallholder production systems are incredibly diverse, common themes and strategies have been investigated in terms of their ability to enhance the climate resilience of smallholders (Rai et al., 2018). These are related to crop management, farm level strategies, livelihood strategies, wider community and landscape scale strategies as well as institutional strategies. In terms of crop management, key options evaluated include drought tolerant varieties, integrated soil management, shade cover, cover crops, intercropping, irrigation and mulching (Ngigi, 2009). At a farm scale measures and strategies include crop diversification, wind breaks, integrated crop and livestock and rotation systems (Harvey et al., 2018a). At a livelihood scale strategies include income diversification, insurance, collaboration and savings (Liu et al., 2016; Tanner et al., 2015). At a landscape scale, strategies include reforestation, terracing, flood protection, reservoir construction and riverbank enhancement (Fenta et al., 2019; Stefanes et al., 2016). From an institutional perceptive market structure, knowledge infrastructure, resource tenure and governance have been explored (Makate, 2019; Totin et al., 2018). The extent to which smallholders and the related institutions are able to adopt and deliver an appropriate range and combination of such measures and strategies will determine how resilient they will be to future climate shocks.

1.2.4 Climate resilience for smallholders engaged in GFVCs

Food systems in developing countries, particularly export orientated aspects, have transitioned from state control in the immediate post-colonial era of the 1950's - 1980's to a more liberalised and globalised system. These food systems have become characterised by consolidation and increasing vertical coordination, exemplified by structures such as GFVCs (Swinnen and Maertens, 2007). Whilst there has been considerable research into the participation of smallholders in GFVCs, in terms of benefits (e.g. poverty alleviation, technological upgrading (Maertens and Swinnen, 2009)) and risks (e.g. gender based exclusion , inclusiveness, disempowerment (Alford et al., 2017; Gumucio et al., 2018; Ros-Tonen et al., 2019)) there have been few studies relating to climate resilience in smallholder driven GFVCs. Davis et al. (2021) highlight that the majority of studies on food value chains and climate have focused on staple value chains (maize, wheat, rice) and shocks relating to rainfall and heat. Beyond this some studies have focused on commodities such as coffee and cocoa but in general these have focused at the agroecosystem level (Jacobi, *et al.*, 2015; Morris *et al.*, 2016) and not on farmers integration in GFVCs, via standards or trade relationships. Elements of smallholder GFVC participation that have been posited to affect climate resilience include potential gains from cooperative formation and price premiums (Sellare et al., 2020), as well as potential losses from price exposure (Kaplinsky, 2004) and quality pressures (Handschuch et al., 2013). In addition, farmers' climate resilience may benefit from easier access to financial instruments, such as weather index insurance; however, it has also been suggested that such instruments when coupled with agronomic stipulations may also lead to increased vulnerability to climate shocks (Isakson, 2015). Given the growth of smallholder participation in GFVCs and the increasing climate threat, there is an imperative to enhance the evidence base on smallholder climate resilience in GFVCs.

1.3 Enhancing climate resilience of smallholders (in GFVCs)

Recently, efforts to enhance climate resilience have begun to grow. Signals of this proliferation can be seen from governments and major funding bodies, such as the African Union's Malabo declaration (African Union, 2014b) and the European Investment Bank's commitment to mobilise 100 billion Euros between 2019 and 2026 to enhance resilience on the African continent (EIB, 2019). Multiple mechanisms (e.g. government policy, supply chain initiatives, certification, community action), covering multiple scales (international, national, value chain, landscape and farm), have been initiated to enhance the climate resilience of smallholder farmers globally. However, it remains unclear how best to promote and facilitate the adoption of climate resilience strategies by smallholder farmers as well as make the systemic transformations necessary to enhance climate resilience (Wood et al., 2014).

1.3.1 International and national strategies to enhance smallholder climate resilience

At an international level, several of the 17 Sustainable Development Goals (SDGs) have incorporated climate resilience implicitly and or explicitly, including SDG 13 Climate action and SDG 12 Responsible consumption and production. These goals serve as guides for governments and other institutions to develop policies that promote climate resilience in their jurisdictions. At a continental level, in 2014, the African Union endorsed the incorporation of climate smart agriculture, which has significant overlap with climate resilience, into the New Partnership for Agricultural Development (NEPAD) programme on agriculture and climate change (Williams et al., 2015). At a national level, there are multiple governments that have adopted climate resilience as a goal of their agricultural policy making. For example, in India the National Irrigation Policy makes climate resilience of smallholders an explicit goal.

In Ghana, the national cocoa extension provider COCOBOD has made climate resilience an explicit goal of its farmer extension training programme (Ghana Cocoa Board, 2018). Additionally, in the Dominican Republic the government promoted "climate change adaptation" in its 2010-2030 National Development Strategy plan. As yet there is little evidence about how these recent policy developments have influenced farmer climate resilience on the ground.

1.3.2 Market driven strategies to enhance smallholder climate resilience

Several non-state market-driven approaches have been utilised to enhance smallholder climate resilience, including voluntary sustainability certification and public-private partnerships (Cashore, 2002). Sustainability certification is a non-state market driven governance strategy widely used in attempts to improve the sustainability of commodity value chains, such as banana and cocoa. It has been posited as a key governance mechanism to enhance the climate resilience of smallholder farmers (Verburg et al., 2019). Many certifications explicitly include a selection of pathways, such as climate awareness education and adaptation training, to enhance the climate resilience of producers in their theory of change, standards and training (IFOAM, 2017; SAN, 2011; UTZ, 2017). Additionally, from a public private partnership perspective, landscape approaches (drainage basin or ecosystem scale integration of cross-sector actor's needs, also including jurisdictional approaches) are becoming increasingly implemented with enhancing climate resilience of stakeholders as a key goal of the intervention. However, to date, there have been few explicit assessments of the role of sustainability certification or landscape approaches in enhancing smallholder climate resilience.

1.3.3 Farmer and community driven strategies to enhance climate resilience

Many of these strategies to enhance climate resilience are top down (such as national policies and supply chain initiatives). One bottom up mechanism that has been successful in promoting the adoption of agricultural technology, in general, is the formation of cooperatives or agricultural producer groups (Abebaw and Haile, 2013). Farmers organisations can enhance access to market, provide extension and facilitate purchases of inputs, which in turn can support the adoption of climate resilient measures or strategies (Zhang et al., 2020). Another bottom up approach to enhancing climate resilience of smallholders that has been championed is the Campesino a Campesino movement in Latin America. Campesino a Campesino is a network of "peasant" farmers in Meso America and Cuba that, amongst other roles, facilitates the horizontal transfer of technology through farmer to farmer exchanges. This has been suggested as a viable mechanism to scale up climate adaptive strategies (Altieri et al., 2015). Despite this proliferation of efforts to enhance climate resilience, there remains a knowledge gap in understanding how climate resilience strategy adoption can be scaled up and out and how these mechanisms can be adapted to maximise their uptake and impact.

1.4 Resilience assessment

To fill this knowledge gap in scaling and refining climate resilience strategies, assessments of smallholder climate resilience under different interventions will be critical. There has been considerable work in the scientific and practitioner communities to design and implement methods to assess the resilience of food systems and their sub-components (Dixon and Stringer, 2015; Douxchamps et al., 2017; Feldmeyer et al., 2020; Heckelman et al., 2018). Multiple assessment approaches have been proposed with key differences between proposed approaches centering around the choice of resilience framework that the assessment is based on, the indicators or outcomes that are chosen for the assessment, the scale of the assessment and the method of measurement (Douxchamps et al., 2017).

1.4.1 Resilience assessment approaches

Key approaches that have been proposed and utilised, include indicator frameworks (Jacobi et al., 2015b), indexes (Tambo and Wünscher, 2017), qualitative self-assessment (FAO, 2020), system dynamics (Benabderrazik, 2020), longitudinal studies (Epstein et al., 2018), as well as studies conducted ex-ante (Monastyrnaya, 2020) and ex-post (Keshavarz and Moqadas, 2021). One influential set of indicators for agroecosystem resilience assessment was designed by Cabel and Oelofse (2012). Their "behaviour-based" indicator framework integrates social and ecological elements in a set of 13 indicators linked to the phases of the adaptive cycle (Holling, 2001). The indicators include socially self-organised, ecologically self-regulated, appropriately connected, high degree of function and response diversity, carefully exposed to disturbance, responsibly coupled with local natural capital, reflected and shared learning, globally autonomous and locally interdependent, honours legacy while investing in the future, builds human capital, reasonably profitable. Whilst the indicator set broadly captures theoretical aspects of resilience in socio-ecological systems, the indicators are not empirically supported with relation to agroecosystem outcomes in the face of specific shocks. More general critique of resilience assessments has covered the large scale of some assessments (e.g. at regional or district scale) and therefore using aggregation that does not capture distributional inequities between individual members of population (Williams et al., 2020). Given the multitude of methods available to assess resilience and the sizeable number of pitfalls that should be avoided in the assessment process, it was critical to this study to select an assessment method appropriate to the specific case of smallholders embedded in GFVCs.

1.4.2 Stakeholder engagement in resilience assessment

One aspect, that is near universally accepted as critical to effective resilience assessment, is to involve the system stakeholders in the process as much as possible (Beran et al., 2021; Sharifi, 2016). Participation by stakeholders is necessary to more accurately understand the challenges faced and design more appropriate solutions to them. This is particularly critical in the GFVC context given the polarisation of power in food systems and therefore the frequent inequitable framing of sustainability issues (Nelson and Tallontire, 2014a). Transdisciplinary research is a research framework that has precisely this objective – to integrate the stakeholders of the study system (and their practical knowledge) into the knowledge creation and exchange process – and therefore is increasingly used in resilience related studies (Deppisch and Hasibovic, 2013; Moser et al., 2019). Transdisciplinary research involves, inter alia, the co-defining of problems and co-generation of knowledge and solutions between scientists and stakeholders (Lang et al., 2012; Pohl et al., 2017; Pohl and Hirsch Hadorn, 2007). Pohl and Hirsch Hadorn (2007) describe three phases of transdisciplinary research: i) problem identification and framing, ii) problem analysis and iii) bringing results to fruition. The adoption of this research methodology, to varying extents, contributes to each of the studies conducted as part of this thesis and I will introduce this further in each chapter.

1.4.3 Resilience assessment framework for this thesis

After initial stakeholder interactions, I built on the work of Tendall et al. (2015) to develop the following overarching framework for the assessment and study of the resilience of individual actors in food systems. I felt it was necessary to develop a framework that was easy to communicate with different types of stakeholder in the food system and also allow for comparison between different actors. I briefly present the framework here as it is the basis for all three proceeding chapters. The framework is action orientated and dynamic, following a cycle of disturbance in the food system. The framework focuses on four linked stages in maintaining and enhancing food system (actor) function in the face of climate shocks by i) preparing for or ii) responding to, iii) recovering from and then iv) learning to improve future outcomes, either by incrementally adapting or radically transforming the system (Figure 1). The four sub-components of the framework (Preparation, Response, Recovery and Learning) are consistent with several commonly adopted models used to describe the resilience of socio-ecological systems and in particular agricultural systems (Ifejika Speranza et al., 2014; Meuwissen et al., 2019; Rist et al., 2014; Tendall et al., 2015). Preparation and response can be considered as relating to the concept of robustness, whereby these actions reduce the impact of a shock. The learning phase relates to both adaptability and transformability as highlighted by Meuwissen et al. (2019). (Limitations in 5.2).

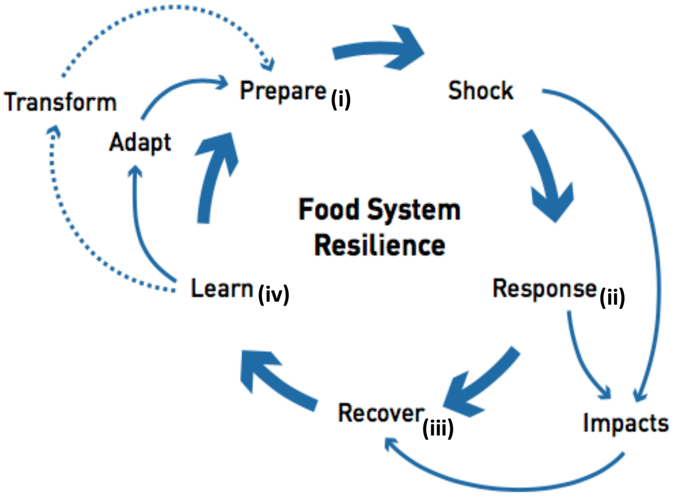

Figure 1 ***Food system resilience framework*** *(developed from Tendall et al., 2015). An action orientated framework focused on four sequential stages undertaken by food system actors.*

1.5 Research objectives and case studies

1.5.1 Objectives

Given the pressing need to understand and enhance the climate resilience of smallholder farmers engaged in GFVCs, this thesis adopts the following three linked objectives:

Objective 1: Co-define, with stakeholders, "climate resilience" of smallholder farmers in global food value chains.

Objective 2: Assess the climate resilience of smallholder farmers and its determinants in global food value chains.

Objective 3: Assess and explore different opportunities to enhance climate resilience of smallholders in global food value chains.

These objectives were selected to ensure the stakeholder inclusive conceptualisation of the challenges and solutions to the climate threat. The assessment of current climate resilience was chosen as it allowed the evaluation of the status quo and existing efforts to enhance climate resilience, as well as forming the basis to explore opportunities to enhance resilience. Smallholders are the focus of the resilience assessment rather than the whole value chain because in initial interviews with stakeholders it quickly became apparent that these were undeniably the most climate impacted actors in the system. Therefore, any effort to enhance resilience of these value chains must prioritise these actors. This necessity is based on this vulnerability but also because the producers are the entry point to the system for many climate shocks. The smallholder farmers, nevertheless, are not considered in isolation from the rest of the value chain. The value chain context and their interactions with other actors are captured by several methods at each phase of the study. This is important as systemic understanding and solutions across the whole value chain are critical to combatting the climate threat.

1.5.2 Choosing case study global food value chains

In order to deliver on the objectives of this PhD research, two value chains, cocoa and banana, were identified based on a review of smallholder driven global food value chains with significant climate exposure. This was informed by initial conversations with key representatives from stakeholders including scientists, World Food Programme, a European retailer and farmers. This process resulted in the selection of two value chains with multiple similarities and several key contrasting aspects that would provide a good opportunity to assess the climate resilience of smallholders embedded in GFVCs and explore diverse opportunities to enhance climate resilience in these value chains. In addition, the challenges faced by the farmers in these value chains typify those of several other GFVCs.

Key aspects shared by both value chains are a South-North topology, with production by smallholders in tropical regions of the Global South and consumption being predominantly in the Global North. Both cocoa and banana value chains are led by firms in the Global North, who control a significant proportion of the global trade and distribution of these food products. Both banana and cocoa value chains face significant climate threats to their production, both in terms of gradual climate change but also in terms of recurrent extreme weather events, such as droughts and hurricanes. Both value chains have a relatively high level of engagement in international sustainability initiatives, particularly regarding sustainability certification. As I intended to explore the role of sustainability certification, the Dominican Republic (DR) and Ghana were chosen as producing countries that had significant sustainability certification coverage, as well as a significant proportion of regional or global production. The global value chains for cocoa, Ghana to Switzerland and banana, DR to the UK, were natural choices as they were two of the largest importers, by volume, of cocoa and banana globally.

Key contrasts in these case study value chains include: banana being sold on both the domestic and export markets whereas cocoa is predominantly exported, the climate shock being hurricane for DR and drought for Ghana, Ghana being low to middle income and DR being middle income, banana being a perishable fruit and cocoa being storable commodity, as well as marketing being state controlled in Ghana and privately controlled in the DR. All of these were factors that could change the dynamics in relation to shock responses and mechanisms of resilience enhancement and therefore made this a valuable and interesting comparison (see summary Table 1).

Table 1 Cocoa and banana global food value chain cases

Main crop	Cocoa	Banana
Production Country	Ghana	Dominican Republic
Regions	Eastern, Western, Ashanti	Monte Cristi, Valverde, Santiago
Economic status	Low income	Middle Income
Consumption focus	Switzerland	UK
	Eastern, Western, Ashanti	Monte Cristi, Valverde
Scale of production	Smallholder	Smallholder and large plantation
Production systems	Agroforests-monocultures	Diversified monocultures
Climate shocks	Drought	Hurricane induced flooding
Market	Export – state controlled	Export and domestic – co-operative
Sustainability strategies	Organic, UTZ, Rainforest Alliance, Uncertified	Organic, Rainforest Alliance, Fairtrade, Uncertified

1.5.3 Cocoa value chain

1.5.3.1 Cocoa as part of the global food system

Cocoa (*Theobroma cacao L.*), an understory tree crop, is grown in the humid tropics. Hard walled fruits formed from pollinated cocoa tree flowers, known as pods, contain seeds, known as cocoa beans. These cocoa beans are used for chocolate production and are economically important with the global exports worth 9.6 Billion USD in 2019 (FAOSTAT, 2021), and with the downstream chocolate produced worth an order of magnitude more. Global cocoa consumption is growing at 11% per year and is forecast to increase with changing dietary preferences linked to economic growth and globalisation (CBI, 2020). 70% of the global supply of cocoa is produced in West Africa (FAOSTAT, 2021).

1.5.3.2 Cocoa and Ghana

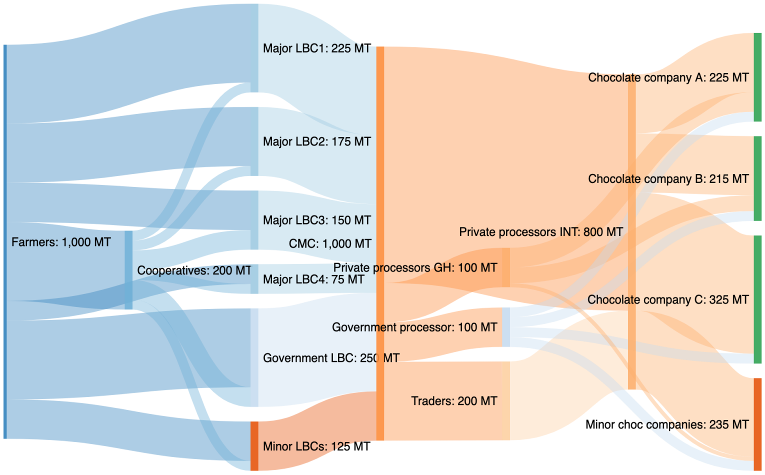

Figure 2 Stylised material flow of cocoa in the Ghanaian-Swiss GFVC *The majority of farmers sell via purchasing clerks to Licenced Buying Companies (LBCs) which sell to state run Cocoa Marketing Company (CMC), which in turn sells to traders, national and international processors, which sell to major and minor chocolate companies.*

Ghana is the world's second largest cocoa producer, producing over 900,000 tonnes annually (Ghana Cocoa Board, 2020). Cocoa is produced by smallholder farmers and is the source of livelihood for over 800,000 cocoa farming families in Ghana, making up 1.6% of GDP (CGIAR, 2018). However, many of the farmers and their farm labourers live below the poverty line (Bymolt et al., 2018). The government is directly involved in many aspects of the cocoa sector, including research, extension and marketing that is coordinated through the Ghanaian Cocoa Board (COCOBOD). Private companies, both Ghanaian and international also play a key role in the purchasing, trading and processing of cocoa beans (Figure 2)

1.5.3.3 Cocoa production and climate

Cocoa is produced in plots, ranging from complex agroforests, with multiple species of trees and canopy structures, to full sun systems with no other tree species present (Sonwa et al., 2019). Cocoa production is climate sensitive (Lahive et al., 2019). Precipitation levels for cocoa growth are optimum between 1200 and 3000 mm per year with a tolerance range of 900 to 7600 mm per year, with up to four consecutive dry months (<100mm rainfall) being tolerated. Temperatures are optimum between 21 °C and 32 °C and are tolerated between 10 °C and 38 °C (Ecocrop, 2021). In West African cocoa growing regions, increased length of dry seasons and higher dry season temperatures are forecasted because of climate change (Schroth et al., 2016). In addition to this, higher variability in rainfall patterns has been predicted. Schroth et al. (2016) show that these changes will inhibit cocoa production in Ghana and lead to a vast reduction in the area that is suitable for cocoa production. There are fears that the climate impacts will exacerbate poverty and lead to more deforestation nationally and in the wider Guinean forest region in West Africa.

Several adaptation strategies have been identified to increase the climate resilience of cocoa production at different scales, spanning national zoning strategies, landscape strategies, farm system strategies and cocoa management strategies (Noponen et al., 2014; Blaser et al., 2018; Bunn et al., 2019). At a national scale in Ghana, climatic predictions have been used to identify regions that should adapt incrementally, make systemic changes, transform, prioritise systemic resilience and give up cocoa all together (Bunn et al., 2019a). At the landscape scale, adaptation measures include improved governance, watershed protection, forest protection and are intended to have effects on farmer resilience. Farm system scale resilience enhancing measures that have been identified include food crop diversification, cash crop diversification and livestock diversification. Cocoa farm scale resilience enhancing measures include hybrid varieties, cocoa plant spacing, shade tree cover and diversity, smart fertiliser application, mulching, cover crops, manual weeding, biochar, irrigation, integrated pest management and cocoa pruning. The efficacy of some of these measures have been assessed at a plot level, including, shade (Blaser *et al.*, 2018), fertiliser, hybrids (Ahenkorah et al., 1987;), irrigation (Hutcheon et al., 1973) and variety breeding (Lahive et al., 2019).

1.5.3.4 Cocoa sustainability certification

Globally 29% of cocoa was certified as sustainable in 2016 with a further 18% potentially standard compliant (ITC, 2018). Sustainability certification has been strongly promoted in Ghana, with 19% UTZ, 14% Fairtrade, 8% Rainforest Alliance and less than 1% organic (Willer et al., 2019). These sustainability certifications cover a wide range of issues with Fairtrade focusing more on labour standards and income, UTZ and Rainforest Alliance on productivity and biodiversity and Organic on input use. To varying extents standards offer a price premium on certified cocoa. All of these certification schemes include climate resilience aspects in their standards. Cocoa sustainability certification has been evaluated against several objectives, including, income, poverty reduction, labour, biodiversity, environmental services and natural capital but not from a climate resilience perspective (Astrid Fenger et al., 2017a; Gockowski et al., 2013).

1.5.3.5 El Nino-driven drought shock in 2015-2016

As a result of the El Nino oscillation in 2015 there was a severe drought experienced in Ghana during the 2015/2016 cocoa production season. The climatic drought lasted for 20 months (authors analysis of data from (Arndt et al., 2020)). During this period the study regions experienced lower than average rainfall and higher than average temperatures, resulting in Palmer Drought Severity Index values dropping below -2 (moderate drought) for more than nine consecutive months. This shock will be the focus of the case study in Ghana.

1.5.4 Banana value chain

1.5.4.1 Bananas as part of the global food system

Bananas (*Musa acuminata Colla*) are a critical crop in the global food system, being in the top ten crops (when plantains are included) in terms of cultivated area, production quantity and calories provided (FAO, 2018). Bananas are a food source for millions globally, as well as a source of income for plantation labourers, smallholders and enterprise. Bananas are one of the leading food exports internationally, with exports totalling 19.1 million tonnes in 2017 (FAOSTAT, 2021). The largest exporting region is Latin America, which accounts for 80% of exports globally. Here, banana is an integral part of many economies with, for example, the banana sector providing 2.5 million jobs in Ecuador (Proecuador, 2016). The banana sector also has a long history of being involved in national and international politics, with several Central American states having their governments overthrown because of unpalatable policies towards US owned banana interests, namely United Fruit (Bucheli, 2008). Banana production for export is carried out by a mixture of large plantations (many internationally owned by trading companies) and smallholders. This varies by country, with Dominican Republic and Ecuador having a high proportion of smallholders and Costa Rica for example having a high proportion of large plantations. The banana sector is effectively an oligopoly with five key firms (Dole, Chiquita, Del Monte, Fyffes, Naboa) having an 80% share of the $25 billion market (Paggi and Spreen, 2003). The banana value chain, for export, is highly vertically integrated, with these importing companies often owning the farms, packing facilities, shipping lines and ripening centres.

1.5.4.2 Banana and the Dominican Republic – UK value chain

The Dominican Republic (DR) is a middle-income Small Island Developing State (SID) situated in the Caribbean. It occupies part of the island of Hispaniola, the rest being occupied by Haiti. The DR accounts for around 90% of banana exports from the Caribbean region (FAO, 2019). There are approximately 2,000 banana farms in the DR, of which the majority (80%) are small scale (> 3 ha) and medium scale (3 - 10 ha) and a minority (16%) of the producers are women (EEAS, 2018). These farmers are largely organised in cooperatives (farmer organisations) which manage sales to international traders (Figure 3). The main producing areas are located in the “North West Line” provinces of Valverde and Monte Cristi as well as the Southern province of Azua, which have a high incidence of poverty (55-65%). More than 300,000 people benefit directly or indirectly from the banana industry in the DR. It is estimated that approximately, 25,000 Haitian immigrants work on banana farms (EEAS, 2018). Historically the DR was an outsider in the conventional banana market but over the least 30 years it has created a niche in the organic banana trade, producing 60% of the worlds organic export bananas (WBF, 2016). The DR government is developing a new national strategy to convert all banana production to organic and market with a DR specific organic branding (personal communication, Van Rijn 2018). The UK currently purchases around 60% of the DR banana production which accounts for around 17% of UK imports (Make Fruit Fair, 2015).

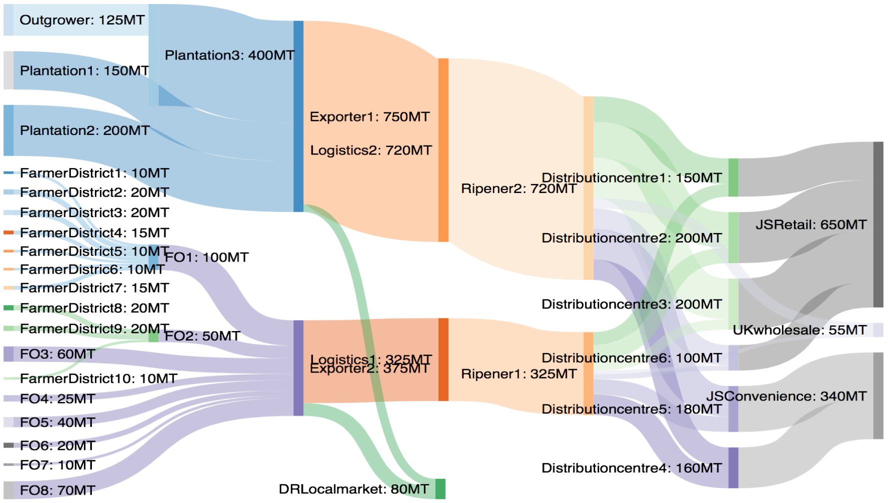

***Figure 3 Stylised material flow of the DR – UK Banana GFVC**. From left to right, key actors: farmers, farmer organisations (FO), plantations, domestic DR market, exporters, ripeners (importers), distribution centres (integrated with retailers), retailers.*

1.5.4.3 Banana production and climate

Bananas are rhizomatous herbs and are considered a perineal, as each plant issues suckers from a lateral shoot in a sequence that can be repeated for up to 50 generations (Turner and Mitra, 1997). It typically takes 7 – 9 months for the plant to flower and then a further 2 – 3 months for the fruit to ripen for harvest. Bananas are often grown by smallholders as intercrops for home consumption or the local markets, however, export banana (Musa spp., AAA, Cavendish sub-group cv. Grande Naine) production usually occurs in monocultures (even when produced by smallholders) with high inputs of synthetic agrochemicals. The extensive systems of drainage canals in banana plantations give a direct route for these agrochemicals to enter waterways. Bananas also require fertilisation to achieve optimum growth, with Nitrogen requirements being reported as high as 200kg ha^{-1} y^{-1} in a study in Uraba, Colombia (Sanchez and Mira, 2013).

Bananas grow optimally in areas with an annual mean temperature of 27 ^{o}C. Leaves die above 47 ^{o}C and growth stops at 38 ^{o}C, with heat stress beginning at 34 ^{o}C. The minimum temperature for growth is 13 ^{o}C and the chlorophyll in the leaves is destroyed at 6 ^{o}C. At 0 ^{o}C frost damage causes the leaves to die (Treverrow, 2003). Banana suffers from water limited growth with rainfall below 1500 mm per year. Irrigation is required below this and if the seasonal pattern of rainfall results in a water deficit in the dry seasons (Calberto et al., 2015).

The Long-term Climate Risk Index published by Germanwatch has the DR and Haiti, both, in the top ten for weather related damages over the last 20 years (1996-2016). Current projections suggest a change in rainfall pattern with decreased rain in May (currently a rainy month) and increased rainfall in December (currently a dry month). Average temperatures are predicted to rise by between 0.5 - 1.0 °C by 2030 and by between 1 - 2.5 °C by 2050 (Caffrey, 2013). This will further exacerbate water deficits in banana production. Key future risks to production of bananas in the DR include an increased water deficit from 1016 mm per year to 1113 mm per year by 2030 (Caffrey, 2013). The intensity of tropical storms in the region is predicted to rise with sea temperature rise. In addition, the intensity of rainfall linked to tropical storms is also projected to increase with anthropogenic warming (Knutson et al., 2020).

1.5.4.4 Banana sustainability certification

Organic production provides an alternative to synthetic inputs, using naturally occurring pest prevention methods and organic fertilisation. Currently though, only around 3% of global banana exports are organic (Willer and Lernoud, 2019). In addition to the environmental problems, there are many social challenges in the banana sector, particularly for laborers working on plantations, including; limited collective bargaining power, health and safety, low wages and poor living conditions (van Rijn et al., 2020). Certification has been proposed as a potential value chain measure to reduce the impact of social and environmental injustice stemming from the banana sector. Certifications including Fair Trade, Organic, Rainforest Alliance and WWF are active in this sector. Rainforest Alliance is the most common certification, with a global production volume of 7.3 million tonnes certified in 2016, with Organic second (1 million tonnes) and Fair Trade third (800,000 tonnes) (Voora, 2020).

1.5.4.5 Dual hurricane shock, Maria and Irma, 2017


Figure 4 Flooding on a banana farm in 2017 *after Hurricanes Maria and Irma caused the River Yaque del Norte to burst its banks.*

In September 2017 hurricane Irma, a category 5 (the highest on the Saffir-Simpson scale), passed the North West coast of the DR at a distance of 96 km. Windspeeds of up to 286 km h^{-1} and heavy rain caused severe damage to property and farms. The heavy rain lead to severe flooding in the Yaque del Norte drainage basin (Figure 4). Just seven days later a second hurricane, Maria, also grazed the North West coast as a category 3, bringing further flooding (Blake, 2018). The shock caused by this hurricane induced flooding, impacting approximately 20% of smallholder banana producers (DR government estimates), will be a focus of this thesis. Tragically the hurricane events lead to an estimated loss of over 3,200 lives across the Caribbean.

1.6 Research Approach

1.6.1 Phases of the study

To deliver on the objectives (1.5.1) I adopted a four-phase approach (see Figure 5): ***(i)*** Value chain platform establishment ***(ii)*** Characterising climate risks and co-defining climate resilience, ***(iii)*** Resilience assessment of smallholder producers in the context of GFVCs, ***(iv)*** Exploration of resilience enhancement opportunities.

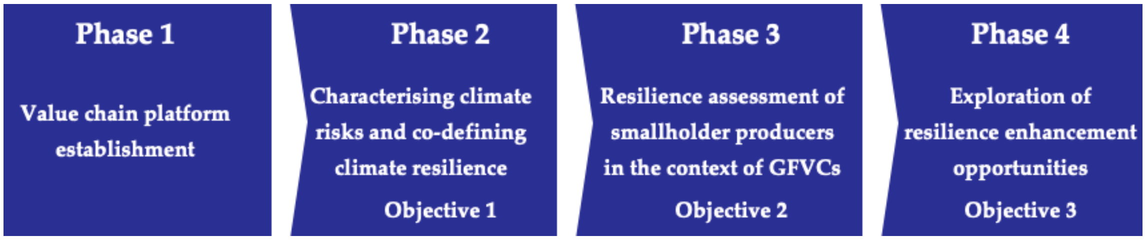

Figure 5 Overview of the four phases of the project with their linked objective

Phase 1: Value chain platform establishment

Phase 1 involved building stakeholder platforms consisting of relevant participants of the two case study GFVCs, cocoa and banana.

Cocoa value chain: In the cocoa value chain, I was fortunate enough to be able to build on a stakeholder platform established in a previous project from the Sustainable Agroecosystems Group and Kwame Nkrumah University of Science and Technology, Ghana. This included the following actors; farmers, transporters, input suppliers, government (COCOBOD), licensed buying companies, insurers and NGOs. I augmented this platform by establishing a collaboration with actors in the sustainably certified value chains, namely Organic, UTZ and Rainforest Alliance. These stakeholders were involved in multiple interactions, including; interviews, field visits, data collection, focus groups and workshops.

Banana value chain: In the banana case, I convened the value chain platform around the axis (Figure 4) of smallholder banana producers in cooperatives in the DR supplying a major UK retailer, incorporating all the intermediaries and auxiliary actors in this value chain. This was supported by several key actors from this value chain including Banelino (an organic cooperative based in Mao, DR), a multinational importer (and ripener) and a UK retailer. In addition, I formed a collaboration with Instuto Tecnologico de Santo Domingo (INTEC), DR, which enabled recruitment of platform members from the DR

Government and NGO sectors. The following actors were involved in the study (ranging from workshop participation to multiple interactions and data sharing): national and regional government, NGOs, waterboard, certifiers, cooperatives, farmers, retailer, DR exporters, multinational importers.

Phase 2: Characterising climate risks and co-defining climate resilience

This phase was conducted in both value chains by conducting a series of semi-structured interviews with key actors of the value chain, as well as focus groups and stakeholder workshops. Furthermore, I compiled and reviewed, remote-sensed climate data and downscaled climate model projections for the specific production regions.

Phase 3: Resilience assessment of smallholder producers in the context of GFVCs

Building on the previous two stages, assessments of smallholder climate resilience were performed using indicators co-generated with stakeholders. These indicators capture multiple dimensions resilience and therefore required multiple data collection techniques. This included household collection of socioeconomic indicators, farm management surveys, biophysical data collection for tree species diversity and shade cover and soil properties, satellite data collection for temperature, rainfall data, cocoa agroforest shade cover (Ghana) and flooding extent (DR), as well as value chain data collection for trading volumes. I conducted lab analysis of the soil samples at ETH Zurich. Following this econometric analysis of the resilience assessment data was conducted.

Phase 4: Exploration of resilience enhancement opportunities

I undertook several approaches to explore resilience enhancement opportunities:

Cocoa: Supply-chain initiatives for enhancing climate resilience were assessed in the form of cocoa sustainability certification. This was investigated with a quasi-experimental study (reported in Chapter 2). In the second cocoa study (Chapter 3), I elicit determinants of climate resilient strategy adoption and use these to make recommendations for implementing national and supply chain policies. Beyond these two studies, I explored different methods of promoting the adoption of climate resilient strategies, in particular agroforestry. To this end, I initiated a masters project, led by Nadin Schweizer (with Dr. Pius Kruetli), that looked at pre-competitive ways that cocoa value chain actors could collaborate to generate carbon finance for smallholders' agroforestry enhancement. In addition, to fill in methodological and knowledge gaps on shade cover recommendations, I designed (with Dr. Wilma Blaser and Dr. Jan Dirk Wegner) an MSc thesis (led by Megan Morrow) that looked to assess shade cover from space, using machine learning (results from this informed Chapter 2).

Banana: Outputs of the banana study were presented to and explored with key value chain collaborators, including the producer co-operative, multinational exporter and the retailer. This led to seven key recommendations being made to these diverse actors in the banana value chain to enhance climate resilience to hurricane induced flooding (Report C). Building on these discussions, I initiated an MSc thesis that explored the role that intercropping could play in enhancing climate resilience, through a design thinking approach led by Bianca Curcio (with Dr Pius Kruetli).

All these activities and outputs are summarised Table 2.

Table 2 A summary of the activities and outputs by each phase of the project

Case		Phase I & II: Understand value chain and shocks	Phase III: Evaluate resilience of smallholders to climate shocks	Phase IV: Explore resilience enhancing opportunities
Cocoa	**Activities**	• Value chain workshop with organic, conventional, and sustainably certified stakeholders • Focus groups	• Resilience assessment of 457 smallholder cocoa producers – Organic, UTZ, Rainforest Alliance and Conventional • Value chain actor interviews	• Resilience Strategy Index • Remote sensing and ML evaluation of shade cover • MSc led stakeholder workshop: innovative financing for agroforestry
	Outputs	• Enhanced value chain stakeholder platform	• Chapter 2 • Pre-print – on remote sensing of flooding	• Chapter 3 • MSc Thesis 1 • MSc Thesis 2 (recommendations presented to Swiss Ministry of Economic Affairs)
Banana	**Activities**	• Establish TD platform with banana value chain • Value chain workshop • Focus groups	• Resilience assessment of 160 smallholder banana farmers participating DR-UK value chain • Value chain interviews	• MSc led focus groups to explore the potential of intercropping to enhance climate resilience
	Outputs	• Value chain stakeholder platform • Field Report A • Workshop Report B	• Chapter 4 • Resilience Assessment Report C	• MSc Thesis 3 • Recommendations presented to 3 key stakeholders (Farmer co-operative, Exporter and Retailer)

1.6.2. Preview and contextualisation of chapters

Chapter 2: "Can Sustainability Certification Deliver Climate Resilience for Smallholder Farmers? The Case of Ghanaian Cocoa" Whilst many sustainability certifications now include climate resilience in their standards and training, their ability to deliver climate resilience for smallholder farmers is still untested. Here, I take the case of the 2015-16 El Niño Southern Oscillation driven drought shock to cocoa production in Ghana to examine whether sustainability certification, namely Organic, UTZ and Rainforest Alliance, can deliver climate resilience for smallholder farmers.

Chapter 3: "What determines the adoption of climate resilience strategies by smallholder farmers?" To deliver programmes, policies and interventions that enhance the resilience of smallholder farmers it will be important to understand which factors determine the uptake of climate resilient strategies by these farmers. Here, I take the case of Ghanaian smallholder cocoa producers to ask the question "What determines the adoption of climate resilient strategies by smallholder farmers?".

Chapter 4: "Racing to recover: Both farmers and the markets they serve determine their resilience to extreme weather events" There remains a gap in understanding how smallholder farmers embedded in global food value chains (GFVCs) are impacted by extreme weather events and how they respond to and recover from such events. Here, I investigate how flooding induced by Hurricanes Maria and Irma, in 2017, impacts smallholder banana farmers in the Dominican Republic engaged in a GFVC and what determines their recovery from these events.

2.0

Can Sustainability Certification Deliver Climate Resilience for Smallholder Farmers? The Case of Ghanaian Cocoa

This chapter has been submitted to Land Use Policy (16/11/2020) as Thompson, W.[1], Blaser-Hart,W.[1,2], Joerin, J.[1,3], Krütli, P.[1], Evans Dawoe, E.[4], Kopainsky, B.[5], Chavez, E.[6], Garrett, R.[7], Six, J.[1] Can Sustainability Certification Deliver Climate Resilience for Smallholder Farmers? The Case of Ghanaian Cocoa

Abstract:

In the context of a changing climate, smallholder farmers need to become more resilient in order to ensure livelihoods and reduce environmental burdens in the face of shocks, such as drought and floods. Sustainability certification has been posited as a key governance mechanism to enhance climate resilience of smallholder farmers. Whilst many sustainability certifications now include climate resilience in their standards and training, their ability to deliver climate resilience for smallholder farmers is still untested. Here we take the case of the 2015-16 El Niño Southern Oscillation driven drought shock to cocoa production in Ghana to examine whether sustainability certification, namely Organic, UTZ and Rainforest Alliance, can deliver climate resilience for smallholder farmers. We used a novel approach that combines transdisciplinary outcome definition, integration of household surveys, on-farm measurements, and satellite data across regions with different socioeconomic and historical contexts, and econometric analysis with Coarsened Exact Matching of certified and non-certified farmer properties. We find that certification has a strong effect on the adoption of basic management, such as fertilisation, but a weak influence on more complex resilience strategies, such as agroforest diversification. We find that certified farmers are conferred better adaptability, in the form of group memberships, access to extension and higher levels of natural capital but lack elements critical to mobilising these assets into climate resilient strategy adoption. Beyond certification we identify strong regional patterns in resilience attributes, based on differences in asset structure between a forest frontier region and a post-forest transition region. Together these findings suggest that sustainability certification has some potential to deliver climate resilience for smallholder farmers, but currently there are context specific gaps in this delivery that must be filled before certification can be effective.

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2.1 Introduction

A transition to a more sustainable food system is necessary given the range of issues that our current system is both facing and generating, including, poverty, biodiversity loss, deforestation and climate change (Godfray et al., 2009; Christiaensen et al., 2011; Vermeulen et al., 2012; Newbold et al., 2015). However, achieving a more sustainable food system is a non-stationary target. Changes in climate, trade connectivity, population and dietary preferences are constantly shifting the context within which food is being produced and consumed (Alexander et al., 2015; Lesk et al., 2016; Puma et al., 2015). These changes bring both gradual stresses, such as reduced yields and worsening trade conditions, and abrupt shocks, such as political crises and floods, that can drastically affect the functioning and reduce the sustainability of the food system (Cottrell et al., 2019).

New and improved strategies to achieve a sustainable food system must reflect these changing global contexts, shocks, and stresses. Resilience, the ability of a system to cope with shocks and maintain overall function (Holling, 1973; Folke, 2006, Walker, 2020), has emerged as a useful concept for guiding the governance and management of food systems in the face of these evolving threats (Pimm et al., 2019; Schipanski et al., 2016a; Tendall et al., 2015). Within the broader field of resilience, climate resilience has emerged as a priority topic in smallholder food production in the global South (Dixon and Stringer, 2015a; Ifejika Speranza, 2013; Kangogo et al., 2020; Whitfield et al., 2019), since these producers are particularly vulnerable to both gradual changes in climate and extreme events (Harvey et al., 2014.; Nyantakyi-Frimpong and Bezner-Kerr, 2015). Enhancing the climate resilience of smallholders is not only critical to their own well-being (incomes, food security, and livelihoods) (Shiferaw et al., 2014; Suweis et al., 2015), but may also help reduce the impacts of climate shocks on the wider economy, by making supply more stable (Chavez et al., 2015) and prevent additional losses of native ecosystems through preventing farmers from seeking out new agricultural areas (Biazin and Sterk, 2013).

The degree to which international governance initiatives can improve smallholder resilience remains an under-researched topic (Delaney et al., 2018). In the context of growing corporate influence in global food systems, private sector sustainability initiatives, including company commitments, certification programs, and direct investments, have been presented as a promising leverage point for improving food system sustainability (Garrett et al., 2016; Lambin et al., 2014; Newton et al., 2013; Swinnen, 2007; van der Ven et al., 2018). Sustainability certification, in particular, has been posited as a key governance mechanism to enhance the climate resilience of smallholder farmers (Verburg et al., 2019). Sustainability certification has seen prolific growth in recent years, with over 20 million hectares of agricultural land now certified globally (ITC, 2019). For over a decade certification programs, including UTZ, Rainforest Alliance, Fairtrade and Organic have acknowledged the evolving climate risk and have attempted to build climate resilience elements into their standards (Lemeilleur and Balineau, 2016). Many certifications explicitly include a selection of pathways, such as climate awareness education and adaptation training, to enhance the climate resilience of producers in their theory of change, standards and training (IFOAM, 2017; UTZ, 2017; SAN, 2011).

There has been much debate in the literature about the benefits of sustainability certification, centering around power, governance, legitimacy, impact on poverty and impact on the environment (de la Plaza Esteban et al., 2014; Glasbergen, 2018; Meemken et al., 2019; Tscharntke et al., 2015). Similarly, several attempts have been made to build replicable frameworks to assess smallholder climate resilience (Dixon and Stringer, 2015a; Ifejika Speranza et al., 2014; Meuwissen et al., 2019). However, there remains a gap in testing the ability of sustainability certification to deliver climate resilience. In general, certification studies relating to resilience have focused on one type of certification or one sub-component of resilience (e.g. adaptive capacity) and have not investigated responses and outcomes to a shock (Heckelman et al., 2018; Jacobi et al., 2015). Elements that have received focus include how certifications influence farmers': i) capacities to adapt to climate change (Borsky and Spata, 2018; Frank et al., 2016), ii) perceptions of climate change (Otieno et al., 2017) and iii) ability to communicate to the consumer (Lemeilleur and Balineau, 2016). However, to the best of the authors' knowledge, there have been no causal inference studies assessing the ability of sustainability certification to enhance the climate resilience of smallholders.

To fill this research gap, we assessed what role sustainability certification can play in enhancing the resilience of smallholder farmers to climate shocks? We do this by taking the case of smallholder cocoa production in Ghana, the second largest cocoa producer in the world (FAOSTAT, 2020), and comparing certified and non-certified systems, namely: UTZ, Rainforest Alliance (RA) and Organic. We focus on UTZ, RA and Organic certifications as they are prominent both globally as well as in Ghana. In addition, these certifications have made specific attempts to address climate resilience in their standards. The resilience of these different systems is assessed in the face of a drought shock that occurred across West Africa in 2015-2016. Using this case, our study provides a new perspective on sustainability certification; the ability to operationalise climate resilience for smallholder farmers, thus informing the potential strategy of certification bodies, governments, retailers, non-governmental organisations and farmers.

2.2 Methods

The study was designed in three phases. These are i) transdisciplinary generation of the climate resilience indicator framework, ii) resilience assessment based on biophysical and socio-economic data collection and processing, and iii) causal inference analysis.

2.2.1 Case selection and case introduction

In Ghana, cocoa is produced predominantly by smallholder farmers and is the source of livelihood for over 800,000 families (CGIAR, 2018). Cocoa production is climate sensitive, and vulnerable to predicted changes in the West African climate (Lahive et al., 2019). Schroth et al. (2016) predict that the decrease of dry season rainfall and increased maximum temperatures will reduce the suitable area for cocoa production in Ghana by 41% by 2050. The severe 2015-2016 El Niño-driven drought experienced in Ghana provides a case study of an extreme event that is predicted to become more common place, in the already drought prone context of the West African monsoon (Shanahan et al., 2009; Sylla et al., 2016).

Smallholder cocoa production in Ghana provides an important case to understand the role of sustainability certification in climate resilience, as certification programs are expanding rapidly in the region and the challenges of cocoa farms in the region (i.e. capital scarcity, low incomes, and increasing climate vulnerability) typify those faced by smallholder farmers across the tropics (Cohn et al., 2017). Several studies have looked at the role different measures, such as enhanced shade cover (Blaser et al., 2018) and irrigation (Hutcheon et al., 1973), can play in reducing the impact of climate shocks on cocoa production, as well as factors influencing their adoption (Akrofi-Atitianti et al., 2018). Previous studies have also evaluated cocoa sustainability certification against several objectives, including; income, poverty reduction, labour, biodiversity, environmental services and natural capital (Astrid Fenger et al., 2017; Gockowski et al., 2013; Meemken et al., 2019). However, none of these studies have looked at the ability of certifications to catalyse the adoption of climate resilience measures and strategies.

2.2.2 Transdisciplinary generation of the climate resilience indicator framework

To generate the climate resilience indicator framework, with which to assess the different sustainability certifications' impact on cocoa farmers, we adopted a transdisciplinary approach. This is critical given the polarisation of power in such tropical commodity value chains and therefore the frequent inequitable framing of sustainability issues (Nelson and Tallontire, 2014b). Transdisciplinary research involves, inter alia, the co-framing of problems between stakeholders and scientists and are chosen here to co-frame climate resilience with farmers and cocoa value chain stakeholder (Lang et al. 2012). This involved setting up a stakeholder platform, building on a previous project, including several actors from the certified and non-certified elements of the cocoa value chain in Ghana, specifically, farmers, certifiers, transporters, licensed buying companies, cocoa processors, input companies, insurers and the Ghanaian government (COCOBOD the Ghana Cocoa Board). The approach had three stages i) stakeholder workshop (30 participants), ii) focus groups with cocoa farmers (6 groups with 9 to 21 farmers each), and iii) bilateral expert interviews (7 interviewees) with value chain stakeholders.

In the participatory activities, we presented the stakeholders with a framework of resilience for food systems modified from Tendall et al. (2015), which they were familiar with through the previous project. This framework included the components of; *Robustness*, *Recovery* and *Adaptability*. *Robustness* was considered as the ability of a farm system to reduce the impact of a shock, through general good agricultural practice, as well as specific climate resilient measures and strategies. For *Robustness*, we accommodate the dynamics of shock experience, dividing it into three aspects *preparation*, activities before a shock, *response*, activities during a shock and *impacts*, the outcome of the shock. *Recovery* was considered the process by which farmers return to their "normal" or new system state. For the *Adaptability* component, cf. adaptive capacity, we considered it the ability to alter the socio-ecological system to increase the robustness and enhance recovery to existing and future threats (Gallopín, 2006). We investigated *Adaptability* at the household scale, using the Sustainable Rural Livelihoods Framework to identify assets (i.e., resources, stores, claims, and access, which provide the means to engaging in activities) that can be utilised in adaptation (Chambers and Conway, 1992). However, criticism of adaptive capacity assessment has centred on the ability of households to utilise such assets, therefore we include mobilising and enabling factors, related to market integration, training, and governance (Eakin et al., 2014; Mortreux and Barnett, 2017; Pelling and High, 2005).

Through participatory activities, we specified, together, relevant indicators of these resilience components with cocoa farmers and cocoa value chain stakeholders. Firstly, at the workshop, through a series of group activities, we asked participants to map their cocoa production knowledge and experiences to the resilience framework described. This was then refined with cocoa farmers in focus groups in the Eastern and Western Region where our study sites were located. Finally, semi-structured interviews, with cocoa farmers and other value chain stakeholders were used to validate this framework. Table 1 maps the individual variables we collected and then used to assess farmers' resilience to drought.

Table 1: Climate resilience indicator framework for smallholder cocoa farmers *defined by farmers and value chain actors during the participatory process. Indicators are divided between the resilience components Robustness, Recovery and Adaptability.*

Resilience component	**Robustness**			**Recovery**	**Adaptability**	
	Preparation	**Response**	**Impacts**		**Characteristic**	**Type**
Measure, Characteristic or Outcome	Good Agricultural Practice	Farm inspections	Tree death	Sale of physical assets	Bank account Raise capital	Financial capital
	Water harvesting	Irrigation	Fire driven tree death	Mitigate agricult. work	Ag network Cocoa group	Social capital
	Fire belt	Change in pruning	Change in pest and disease	Mitigate non agricult. work	Soil Carbon Primary forest Secondary vegetation	Natural capital
	Crop diversity	Change in fertilisation	Change in cocoa yield	Sell livestock	Training intensity GAP knowledge	Human capital
	Alternative ag income	Change in weeding	Change in income	Income dependency	Livestock	Physical capital
	Shade tree cover	Integrated Pest Managmnt.		Alternative non-ag income	Other ag groups Drought training Market integration	Mobilising factor

2.2.3 Resilience assessment data collection and processing

2.2.3.1 Study area

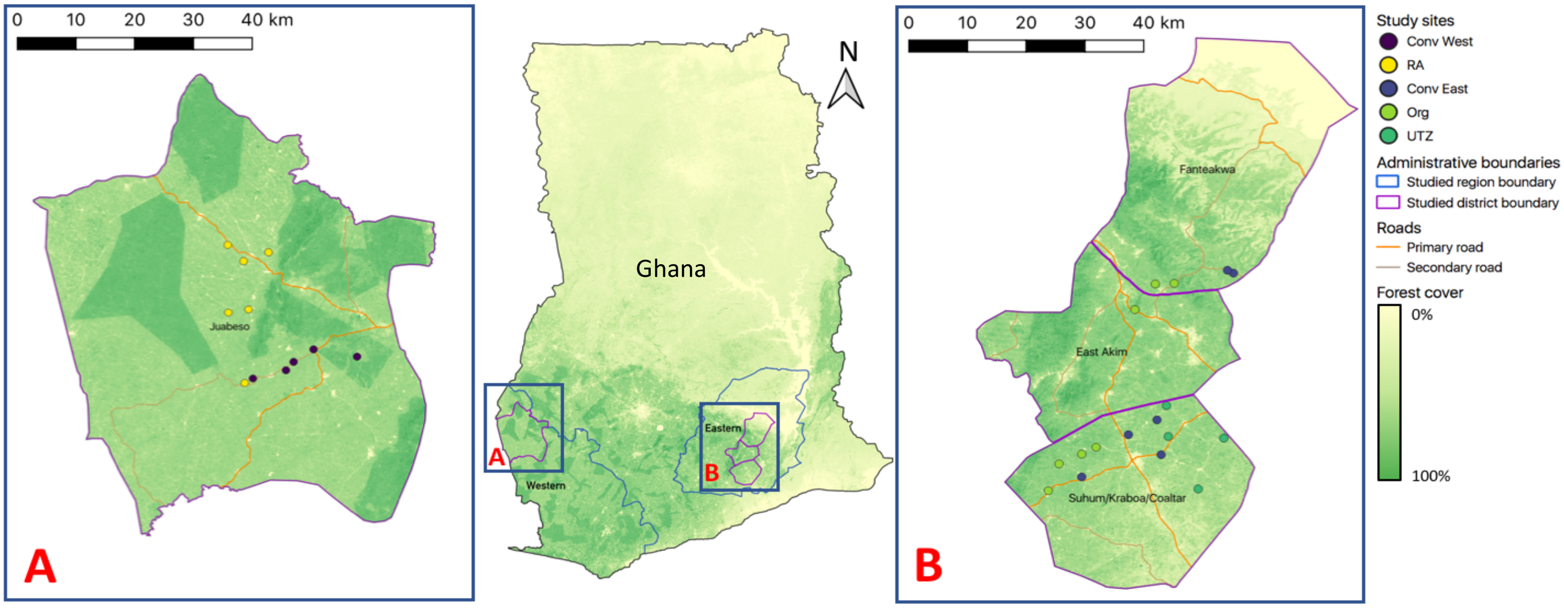

Figure 1 Map of the sampled cocoa communities. *Centre: Country scale map of Ghana. A): Western Region. B): Eastern Region. Symbols show location of sampled communities with the type of certification present in the community specified. Forest cover in 2000 from Hansen et al. (2013).*

The data collection for the socio-economic and biophysical elements of the resilience assessment was performed in Juabeso district, Western Region and Fanteakwa South, Abuakwa North and Suhum districts, Eastern Region, of Ghana. The Western and Eastern Regions provide contrasting agroecological and socio-economic conditions under which to explore the role of certification on climate resilience. Western is a forest frontier region where cocoa production is still expanding into primary forest areas, whereas in Eastern the forest transition has already taken place and is now a mosaic of secondary forest and agricultural land (Figure 1). Western is historically wetter than Eastern with an average annual rainfall of 1370 mm versus 1260 mm, respectively (Funk et al., 2015). During 2015 and 2016 both regions suffered a drought lasting 20 months (authors analysis of data from Osborn et al., 2018). During this period the study regions experienced lower than average rainfall and higher than average temperatures, resulting in Palmer Drought Severity Index values dropping below -2 (moderate drought) for more than consecutive 9 months (see Supplementary Materials, A1).

The distribution of certified cocoa area in Ghana is: 19% UTZ, 14% Fairtrade, 8% RA and less than 1% organic (ITC, 2019). The town and district of Suhum, 60 km North of Accra, as well as the neighbouring districts of Fanteakwa South and Abuakwa North have been a centre of organic and UTZ cocoa production in Ghana since 2007. A private sector cocoa licensed buying company with a focus on organic cocoa has catalysed the uptake of organic production in the region, facilitating the use of organic inputs and coordinating farmer group formation and certification audits. As of 2019, there are over 2750 organic farmers certified in the region. UTZ certification has also been catalysed from this hub and there are over 800 certified farmers in these districts. For RA certification, there is a concentration in Western Region around the town of Juabeso in Juabeso District (Figure 1). Since 2010, RA has been certifying famers in the Juabeso-Bia landscape. These farmers have been some of the first to be trained on the climate module of the Sustainable Agriculture Network Standard (SAN, 2011). RA has led a landscape approach in the area forming landscape management boards and community cocoa growing groups. Over 3000 farms in the district are now certified. The standards of the three certifications assessed were reviewed for the presence of climate resilience aspects, the results of this review are summarised in Table 2.

Table 2: Climate resilience aspects, from indicator framework, included in certification schemes studied. *In addition, COCOBOD is the government body responsible for cocoa in Ghana and provides general extension to all cocoa farmers. (SAN, 2011, IFOAM, 2017, Naturland 2014, 2020, UTZ, 2015, COCOBOD, 2016)*

Resilience Component	Aspect	Organic	UTZ	Rainforest Alliance	COCOBOD
	Explicit climate resilience goal	✓	✓	✓	✓
	Climate specific module	✗	✓	✓	✗
Robustness					
	Drought resistant seedlings	→	👥	→	✗
	Crop diversification	→	◷	✗	→
	Income diversification	✗	◷	✗	→
	Shade tree cover	✓	✓	✓	→
	Shade enhancement plan	→	→	✓	✗
	Soil structure management	→	→	→	✗
	Cover crops	→	✗	✓	→
	Smart fertilisation	✓	◷	◷	✗
	Water harvesting	✗	◷	→	→
	Climate record keeping	✗	✗	→	✗
Recovery					
	Group savings mechanisms	✗	✗	✗	✗
	Insurance	✗	✗	✗	✗
Adaptability					
	Group governance	👥	👥	👥	✗
	Farm management planning	→	→	✓	→
	Training on climate aspects	👥	👥	👥	✗
	Climate risk assessment	✗	→	→	✗
	Training on general aspects	→	👥	👥	→
	Community engagement	→	→	👥	✗

✓ **Present/Mandatory** ◷ **Mandatory after year X** → **Recommended** 👥 **Group mandatory** ✗ **Not present in standard**

2.2.3.2 Sampling

The socio-economic and biophysical elements of the resilience assessment were carried out with a stratified random sample of farmer groups, taken from lists of all the Organic and UTZ groups located in Fanteakwa South, Abuakwa North and Suhum districts, Eastern Region, and all the RA groups in Juabeso district, Western Region. To establish a counterfactual of how climate resilient local cocoa producing households would be in the absence of certification, control groups of non-certified farmers were sampled in both regions. The control group was taken from a random stratified sample of villages in the districts where certified groups were present and farmers were selected randomly from the purchasing clerk lists of the government run cocoa purchaser in Ghana (Produce Buying Company). Originally a total of 480 households were sampled. After discarding several interviews due to missing data, 457 households were included in the analysis, describing 846 cocoa plots (non-certified Eastern n = 104, Organic n = 80, UTZ n = 60, non-certified Western n = 105 and RA n = 108). On a randomly selected subsample of 66 cocoa plots, proportional to the household sample size across the certification treatments, biophysical measurements were taken (non-certified Eastern n = 12, Organic n = 13, UTZ n = 10, non-certified Western n = 16 and RA n = 15).

2.2.3.3 Data collection

To assess the impact of certification on the climate resilience indicators (Table 1), we carried out a survey between July and August 2018 using a digitised questionnaire on tablets. The questionnaire was designed based on the transdisciplinary process described in 2.1 and included the following sections: household characteristics, cocoa plot management, cocoa production, marketing, drought shock experience, preparedness, response, impacts, recovery and adaptability. Cocoa production was recalled by farmers at the plot level and was verified with their individual COCOBOD passbooks (farmers record of cocoa transactions) and certification audit data. Gross cocoa income was estimated from the passbook transactions and farmers' recall of production volumes and prices (list of all socio-economic variables in A2).

For the biophysical indicators, in each sampled cocoa plot we mapped the perimeter using a GPS device and a 0.05 ha (20 m x 25 m) data collection area was randomly located within the perimeter. A 100 m transect was then placed through the centre of this area to capture the maximum variation in topography across the whole cocoa plot for soil sampling. Five soil samples were taken from the first 30 cm depth of soil at 25 m intervals along this transect. These samples were then composited, air dried and passed through a 2 mm sieve. These samples were dried at 105 °C to constant weight and ground using a ball mill. The samples were analysed for total C and N content using a dry combustion analyser (CN-2000, LECO Corp.). Within the 0.05 ha area, we assessed cocoa tree density, shade tree density and identified all shade tree species. On-farm tree species richness was based on the count of shade tree species identified on each plot. Shade cover was analysed for each plot using the GPS polygon of the plot perimeter. QGIS was used to identify the proportion of shade cover by identifying shade tree canopy polygons from satellite photo interpretation from Google and Bing base maps (list of all biophysical variables in A3).

2.2.4 Data analysis

2.2.4.1 Econometric methods:

To evaluate the impact of sustainability certification schemes on smallholder farmer climate resilience indicators we used Coarsened Exact Matching (CEM) (Iacus et al., 2012), followed by estimation of the average treatment effect on the treated (ATT). A key challenge in evaluating the impact of certification schemes on smallholder farmer outcomes is the non-random nature of farmer participation in such schemes. By matching certified sampled farmers to non-certified farmers using observable characteristics, such as age and farm size, we can reduce selection bias (the degree to which underlying attributes that may be correlated with climate resilience influence adoption). Many studies evaluating the impact of sustainability certification use a propensity score matching (PSM) approach; however, it has recently been shown that using propensity scores for matching can increase imbalance, model dependence and bias (King, 2019). To overcome these flaws with the PSM approach, we chose to use CEM, which is a member of the generalised class of matching methods known as "Monotonic Imbalance Bounding" (Iacus et al., 2012). This implies that the imbalance between the treated and control groups is chosen ex-ante, before the matching, and post-hoc sensitivity tests do not have to be carried out.

First, we defined the control variables that are to be matched between the treatment (certified) and control (non-certified) samples. The control variables (age, education years, household size, gender of household head, total farm size and farm ownership) were chosen based on theoretical and empirical evidence that they influence the probability of being certified and associated outcomes, but are not affected by certification (Blackman and Naranjo, 2012; Lampach and Morawetz, 2016). We manually defined the strata boundaries based on institutional knowledge; a table of the strata boundaries is presented in A4. Following this, the CEM algorithm temporarily coarsened the control variables into the strata that we defined. The observations were placed into strata based on their non-coarsened control variables. Strata that did not include at least one control and one treatment observation were pruned from the data set. The matching outcomes can be found in A5. The remaining matched data, i.e. observations occurring in the same strata, were then used to estimate ATT with the original non-coarsened values. We estimated ATT as the mean difference in the outcome variable between matched certified and non-certified farmers. The analysis was carried out using R (R Core Team, 2020) and the MatchIt package (Ho et al., 2011).

2.2.4.2 Regional comparison

Regional comparisons between non-certified farmers in the Eastern and the Western region were made using independent two sample t-tests of unmatched data.

2.3 Results

2.3.1 Robustness

In terms of robustness, the econometric analysis reveals the strong effect that certification has on the adoption of basic agronomic practices and the lack of effect on the adoption of more complex resilience enhancing measures and strategies (Figure 2, A6)

2.3.1.1 Preparation

All certification programs had a significant impact on the agronomic management of cocoa farms (Figure 2a, A6). For Organic farmers, we see clear effects on management in terms of fertilisation, with less farmers using mineral fertiliser (-14.9 percentage points (pp), $p < 0.01$) or inorganic liquid fertiliser (-20.5 pp, $p < 0.01$) amendments and more farmers using organic alternatives (33.3 pp, $p < 0.01$). This pattern is replicated for UTZ farmers (mineral -10.1 pp, $p < 0.1$, liquid -31.6 pp, $p < 0.01$, organic 44.1 pp, $p < 0.01$). On the other hand, RA farmers are more likely to use mineral fertiliser than their non-certified counterparts (11.7 pp, $p < 0.1$). Beyond certification there are significant regional patterns in input use, with Western farmers more likely to use liquid inorganic fertiliser (70% of farmers vs 45%, $p < 0.01$) and insecticides (92% vs 54%, $p < 0.01$).

Certification had no significant impact on climate resilient measures taken in preparation for a drought (Figure 2b, A4). Certified farmers were no more likely than non-certified farmers to use hybrid cocoa seedlings, enhance shade cover, use water harvesting or construct fire belts. The predominating effect was regional for the measures, i.e., using hybrid varieties (Eastern 54% vs Western 37%, $p < 0.05$), fire belt construction (Eastern 35% vs Western 20%, $p < 0.05$), and water harvesting (Eastern 10% vs Western 29%, $p < 0.05$).

The adoption of climate resilient strategies, a suite of coordinated measures, were in general not affected by certification (Figure 2c, A4). There was no effect of certification on the diversification of farm income sources (UTZ - 0.04 income sources ($p = 0.79$), Organic - 0.23 ($p = 0.21$), RA - 0.14 ($p = 0.31$)). There was, however, a significant regional difference in the diversity of agricultural income streams (Eastern mean number of income sources 2.09 vs Western 1.75, $p < 0.05$). For crop diversity, marketed and self-consumption, Organic certification had a small effect, increasing diversity by 0.6 crops per person on average ($p < 0.1$). The other certifications had no significant effect. In Eastern, certification had no effect on the diversity of shade trees on cocoa farms but there were significant regional effects seen, with Eastern having a mean species richness of 3.1 and Western of 0.7 ($p < 0.05$). In Western, RA farms had significantly higher shade tree species richness (+ 1.05 species ha^{-1}, $p < 0.05$).

Certification has no significant effect on the use of responsive measures during the 2015-16 drought (Figure 2d and A4). Very few farmers had irrigation available to them as a response option (4.8%) and certification did not make farmers more likely to adopt this measure. Plot management practices, i.e., pruning (82%) and weeding (54%), were modified by the majority of farmers in the face of drought, but there is no evidence that this was linked to certification.

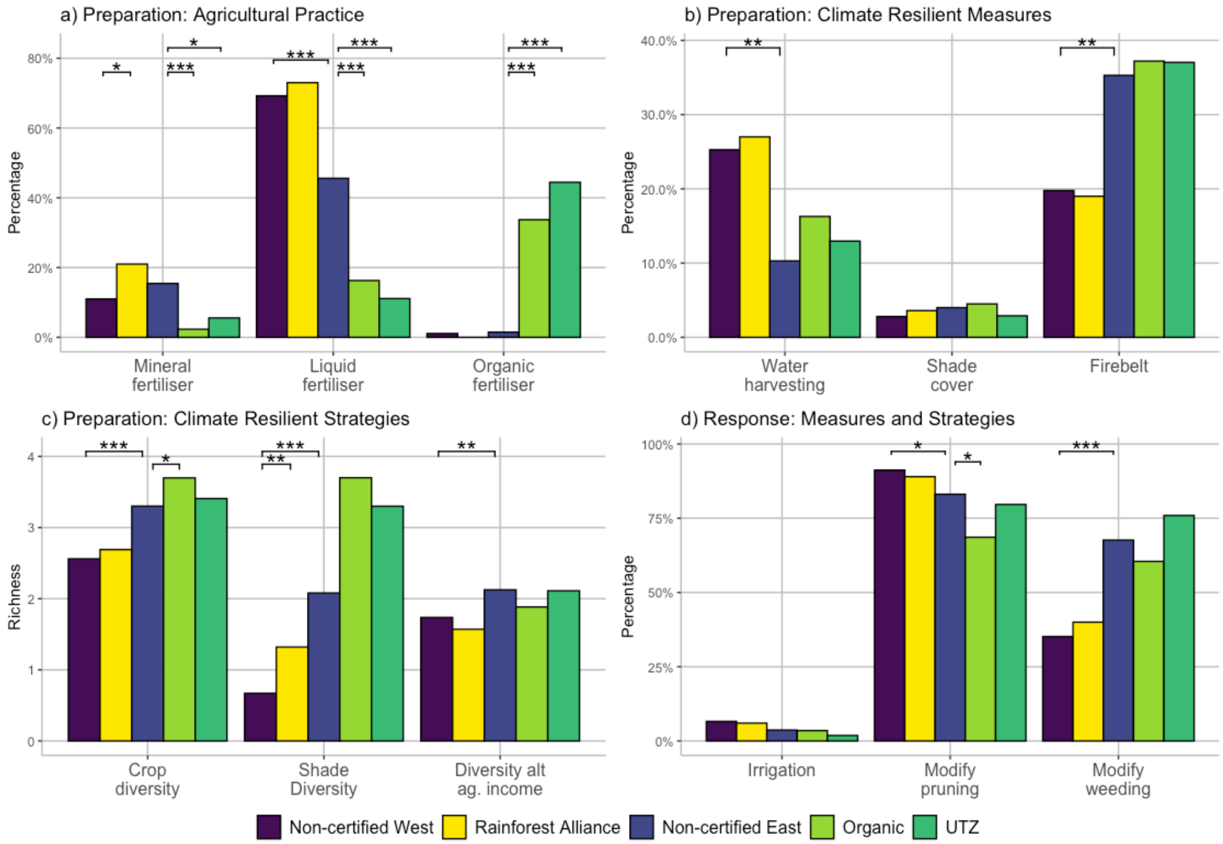

Figure 2: Effect of certification on Robustness indicators ***a) Preparation: Agricultural practices*** *(percentage using measure)* ***b) Preparation: Climate resilient measures*** *(percentage using measure, Shade cover is % of plot area)* ***c) Preparation: Climate resilient strategies*** *(Richness is number of different shade-tree or crop species or income types (non-cocoa agricultural products))* ***d) Response: Measures and strategies*** *used in the face of a drought (percentage using measure). Means are presented for all indicators after matching. Significance of average treatment effect on the treated and also difference between non-certified in the two regions (* $p < 0.10$, ** $p < 0.05$, ***$p < 0.01$)*

2.3.1.3 Impacts

Yields were substantially higher in Western (540 kg ha^{-1}, p < 0.01) versus Eastern (304 kg ha^{-1}) for the "normal" 2017-18 season (Figure 3a). Within Western, they were higher on RA farms (+ 58 kg ha^{-1}, p = 0.13) relative to non-certified farms, whereas in Eastern they were lower for Organic (- 59 kg, p < 0.05) and for UTZ (-49 kg ha^{-1}, p = 0.13) versus non-certified farms. As the government sets cocoa prices for all farmers, incomes were directly proportional to yields. Cocoa prices for the 2015-16 and 2017-18 seasons were 6.7 GHC kg^{-1} and 7.6 GHC kg^{-1} respectively (1 USD = 5.77 GHC). However, premiums were received by both certified and non-certified farmers to varying extents (46% of non-certified Eastern, 96% UTZ, 94% Organic, 37% non-certified Western, 97% RA) and values (mean per 64 kg bag: 15 GHC non-certified Eastern, 19 GHC UTZ, 26 GHC Organic, 11 GHC non-certified Western, 13 GHC RA).

Comparing the "drought" year of 2015-16 to the "normal" year of 2017-18, reported cocoa yields were on average lower by 70 kg ha^{-1} across the total sample in 2015-16. Non-certified farmers in Eastern lost on average 54 kg ha^{-1} versus 60 kg ha^{-1} in Western. Certification did not reduce these yield impacts, nor did it reduce other drought impacts (tree death, fire tree death, disease), with the exception of RA certification, which was associated with lower farmer reports of cocoa tree disease exasperation (- 0.16 pp, $p < 0.1$) (Figure 3b, A4). It was common for farmers (82% of all farmers) across all certifications and regions to experience the death of one or more cocoa trees due to drought.

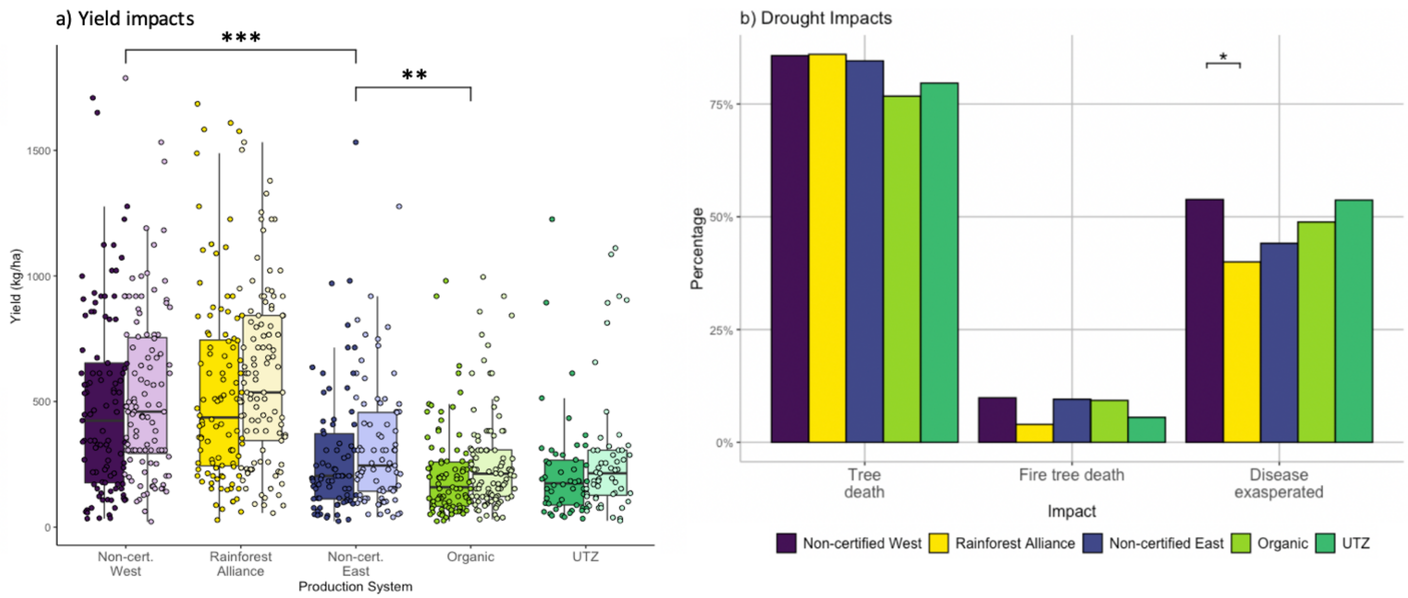

*Figure 3 **Impacts of 2015-2016 drought**. **a) Yield impacts** (total of major and minor harvest) in drought season 2015-16 (dark colour) and "normal" season 2017-2018 (light colour). Yields are included from plots with cocoa trees over four years old at the end of the season described. Stars denote significant differences between yields within 2017-18 (after matching for certified versus non-certified) **b) Percentage of farmers experiencing drought impacts** as measured by tree death, fire induced tree death, and disease exasperation. Indicator means are presented after matching. Significance of average treatment effect on the treated (* $p < 0.1$, ** $p < 0.05$, ***$p < 0.01$)*

2.3.2 Recovery

We found different recovery strategies between certified and non-certified farmers (Figure 4, A7). RA farmers had a significantly higher dependence on cocoa income than non-certified farmers (2.5 pp, $p < 0.1$) (which reduces their ability to recover), however, RA farmers were more likely to sell livestock to raise financial capital during the drought than non-certified farmers (13.5 pp, $p < 0.05$), (which enhances recovery). In Eastern, certification had no discernible impact on recovery. Regional differences were much larger than those associated with certification. Farmers in Western had a greater diversity of non-agricultural income streams, which should aid recovery, although had higher dependency on cocoa income in general (Eastern 68% of total income vs Western 86%, $p < 0.01$). While farmers in Eastern more frequently sold off physical assets, such as livestock (Eastern 25% vs Western 8.6%, $p < 0.01$) and agricultural equipment (Eastern 54% vs Western 29%, $p < 0.01$).

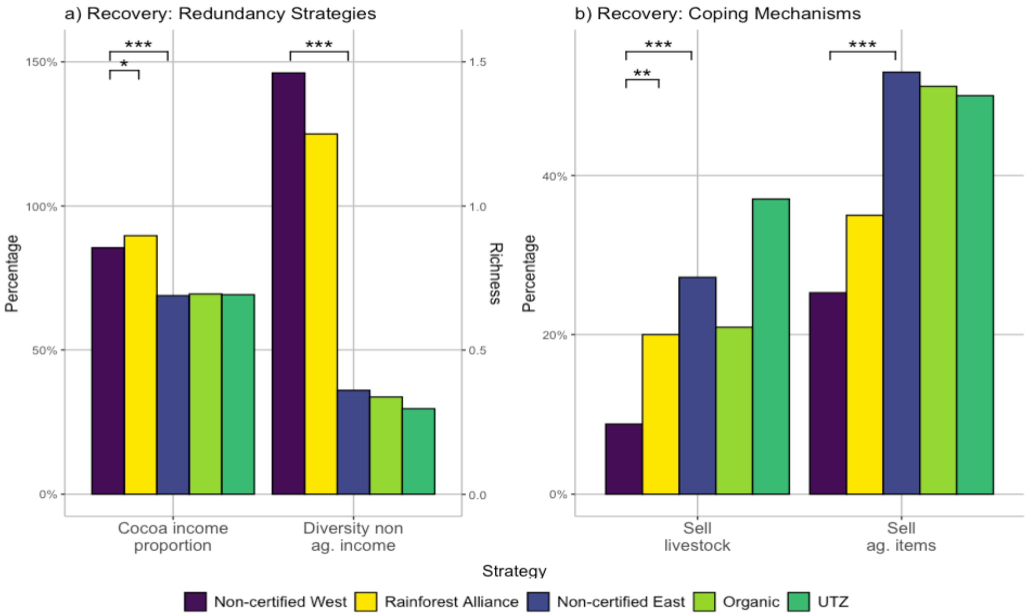

Figure 4: Effect of certification on Recovery indicators: ***a) Redundancy strategies*** *that reduce reliance on cocoa (proportion of cocoa income and diversity of non-agricultural income)* ***b) Coping mechanisms*** *to respond to the aftermath of a shock (selling of livestock or selling of agricultural items). Means are presented for all indicators after matching. Significance of average treatment effect on the treated and also difference between non-certified in the two regions (* $p < 0.10$, ** $p < 0.05$, ***$p < 0.01$)*

2.3.3 Adaptability

Certification was associated with greater adaptability (Figure 5) via larger agricultural networks for farmers (UTZ + 3.13 people, $p < 0.1$) and membership in cocoa producer groups for Organic (26 pp, $p < 0.01$) and RA (35 pp, $p < 0.01$), as well as greater training for RA and Organic farmers (Organic farmers 3 more trainings per 5-year period ($p < 0.05$), RA farmers 4 more ($p < 0.05$)) (Figure 5, A8). Regarding natural capital, Organic and UTZ farmers had 7% ($p < 0.01$) and 4% ($p < 0.05$) more uncultivated secondary vegetation. Certification had a small positive effect on the proportion of farm area remaining as forest for Organic farmers (1.6 pp, $p < 0.1$) and a negative effect on soil carbon stocks for UTZ farmers (- 0.67% carbon content, $p < 0.05$) but otherwise there was no effect of certification on these aspects. For physical capital, Organic farmers owned significantly less livestock than non-certified farmers, by 0.36 Tropical Livestock Units ($p < 0.1$), the equivalent to a young donkey. Certified farmers were more likely to have received specific drought training (UTZ 26.1 pp, $p < 0.1$, Organic 21.7 pp, $p < 0.1$, RA 23.9 pp, $p < 0.01$). Certified farmers were not significantly more likely to be part of non-cocoa agricultural groups.

Regarding market integration, certified farmers were not significantly more likely to have a purchase agreement with a licensed buying company.

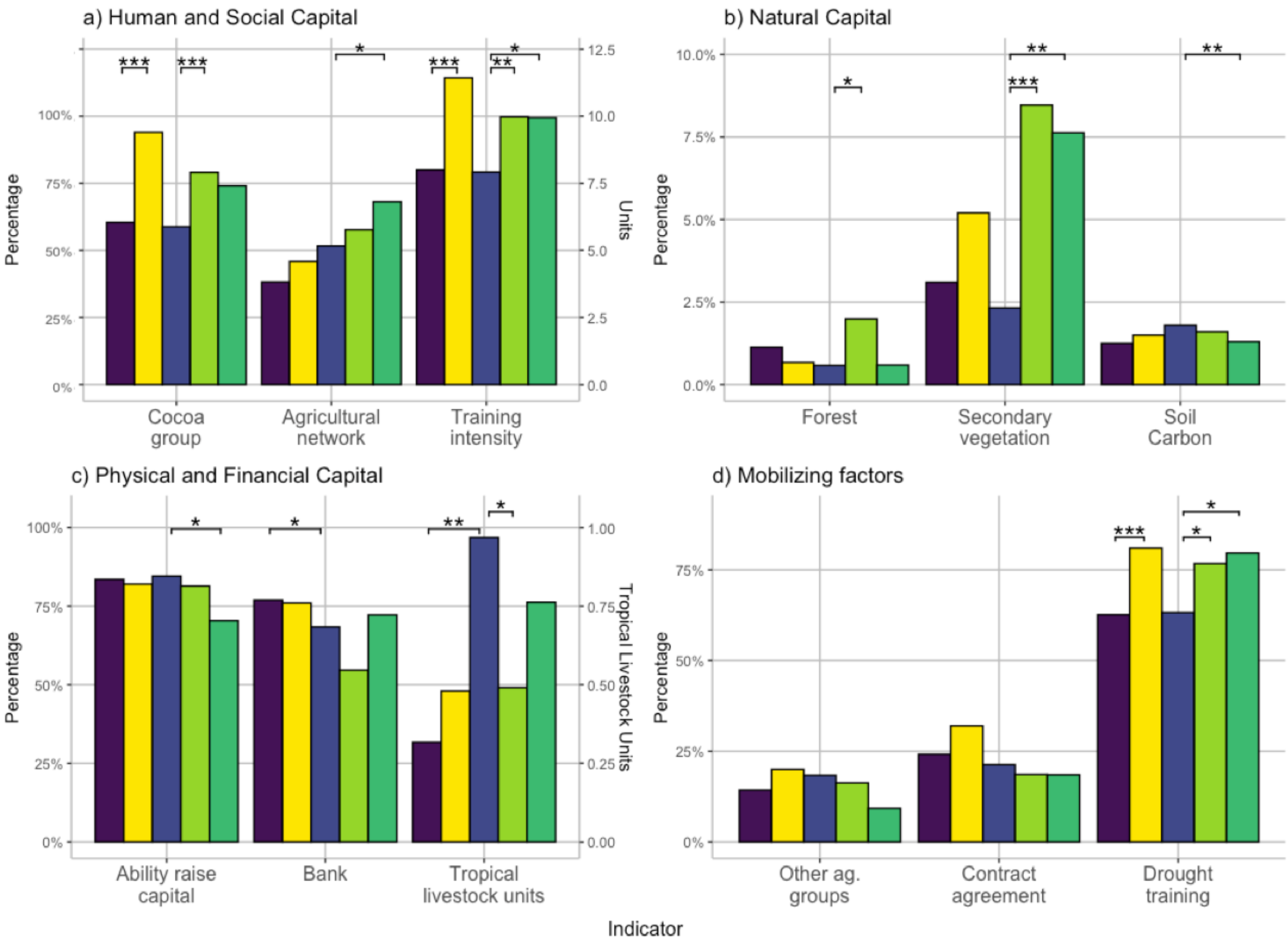

Figure 5 Effect of certification on Adaptability indicators: a) Human and Social capitals *(percentage of farmers participating in a cocoa group, size of agricultural network (people) and number of trainings per 5-year period)* ***b) Natural capital*** *(percentage of forest and secondary vegetation on farm, percentage of carbon in soils)* ***c) Physical and Financial capital*** *(percentage of farmers with ability to raise capital or access to bank accounts, Tropical Livestock Units per household)* ***d) Mobilising factors*** *(percentage of farmers with access to non-cocoa agricultural groups, with contract agreements with cocoa licensed buying companies and who received drought specific training). Means are presented for all indicators after matching. Significance of average treatment effect on the treated and also difference between non-certified in the two regions (* $p < 0.10$, ** $p < 0.05$, ***$p < 0.01$)*

2.4 Discussion

The climate resilience indicator framework, developed through the transdisciplinary approach, allowed us to assess the ability of sustainability certification to deliver “climate resilience”, defined inclusively with farmers and cocoa value chain stakeholders. Our findings suggest that sustainability certification has marginally enhanced climate resilience for smallholder cocoa farmers in Ghana, via changes in robustness and adaptability to drought. Certification is associated with enhancement of some aspects of robustness, via changes in agronomic practices, but does not lead to more transformative climate resilience enhancement, via the adoption of specific drought resilient measures and strategies as proposed in the certification standards. Consequently, we find no influence of certification on yield responses to drought. Certification is associated with improvement in some adaptability indicators, mostly via social and knowledge capital dimensions (access to cocoa producer groups and training programs). However, drought recovery potential is more strongly influenced by regional differences, rather than certification.

2.4.1 Certification enhances some aspects of robustness and adaptability to drought via changes in agronomic practices, farm diversity, as well as social and knowledge capital

Our findings that certified farmers modify their input use, Organic switching to non-artificial inputs, RA using less pesticides but more fertiliser and UTZ using less pesticides, are consistent with prior studies of UTZ-certified-cocoa in Cote D'Ivoire (Ingram et al., 2014) RA-certified-coffee in Uganda (Vanderhaegen et al., 2018) and Organic-certified-coffee in Costa Rica (Blackman and Naranjo, 2012; Ibanez and Blackman, 2016). Support is also found in the literature for our finding that certified farmers have higher adaptability in the form of group memberships, training, and higher levels of natural capital (Akrofi-Atitianti et al., 2018; Borsky and Spata, 2018b; Jacobi et al., 2015; Maguire-Rajpaul et al., 2020). For example, Jacobi et al. (2015) show that Organic-certified farmers in Bolivia have larger agricultural networks than conventional farmers. In Ghana, Akrofi-Atitianti et al. (2018) show that openness to cocoa group membership is greater amongst RA and Organic farmers.

Contrary to prior studies that suggest certification often leads to greater specialisation (Rueda and Lambin, 2013; van Rijsbergen et al., 2016), we found that Organic farms have higher diversity of crops in their systems, and RA farms have slightly higher shade-tree diversity (A6, Figure 2c). Diversity is thought to improve resilience by conferring redundancy in the face of a shock as well as offering ecosystem services, such as reducing pest pressure, that might offset other climate stresses (Loguercio et al., 2009). Additionally, such diversification can help address concurrent challenges from market variability and shocks (Bowman and Zilberman, 2013). However, our results demonstrate that the higher crop diversity does not necessarily translate into higher income-stream diversity (Figure 2c).

Building resilience is a dynamic process – the state a system is in before a shock is also relevant to the outcomes during and after a shock. Regarding yield outcomes in a "normal" year, our findings that RA have greater productivity than conventional, Organic lower productivity and UTZ having no significant difference (Figure 3a) find mixed support in the literature (Armengot et al., 2016; Astrid Fenger et al., 2017b; Schneider et al., 2017). Although, a study in Western Ghana reported higher yields for Organic farms (Akrofi-Atitianti et al., 2018). In our study area, on the other hand, the premiums paid to organic farmers for each bag (64kg) of cocoa produced, on average 26 GHC (4.5 USD or 7% producer price), do not fully compensate the lower yields, corroborating predictions based on premium-yield relationships (Nalley et al., 2012). For RA farmers, higher incomes from higher yields and premiums (13 GHC, 2.25USD on average), place them in a stronger position to confront a shock. The lack of impact from certification on yield response to drought can be understood from the lack of impact on climate related adaption at the production system level (Figures 2 and 3).

2.4.2 Broader contributions to improved resilience are limited by the commodity-focus of existing certifications

Despite higher levels of training for certified farmers (Figure 5, A8), we find a dichotomy in the adoption of more basic, required, and auditable agronomic practices (e.g. fertilisation) versus more complex adaptation strategies (e.g. diversified incomes), with high adoption of basic strategies and low adoption of more complex aspects (Figure 2). While agronomic practices likely have clearer importance to cocoa farmers, the lack of impact on more complex drought adaptive measures (e.g. water harvesting) and resilience enhancing strategies (e.g. diversified agricultural income) is problematic from a broader perspective, since these have been identified as critical to enhancing climate resilience (Abdulai et al., 2018; Bunn et al., 2019b; Maguire-Rajpaul et al., 2020). The wider pattern of no effect on more systemic adaptation strategies is partially supported by studies from Ghana and Bolivia that find certified farms have higher agricultural diversity but lower or similar income diversity (Akrofi-Atitianti et al., 2018; Jacobi et al., 2015).

The lack of impact on adopting more complex measures may be due to the single commodity focus of the certifications assessed. This narrow focus tends to conflict with imperatives to diversify farming systems to reduce vulnerability to climate and market shocks and the need to develop alternative crop markets to support this diversification. It also reflects the marginalisation of farmers vis-à-vis the supply chain actors that have encouraged these commodity-centred forms of governance (Bastos Lima and Persson, 2020). Farmers have generally had limited power to influence how certification systems are developed, for example, to better accommodate diverse livelihood portfolios (Winters et al., 2015).

To deliver climate resilience, we see from the indicator framework (Table 1), that multiple types of modifications; measures, strategies and asset structure; must be made by cocoa farmers to their livelihood systems. These modifications vary in complexity, from fire inspections to diversifying incomes, and feasibility, from pruning to installing irrigation, both from the farmers "adopting" perspective as well as the certifiers' "delivery" perspective. The key mechanisms by which sustainability certification can catalyse these changes in livelihoods system, include training, auditing, group formation, price premiums and providing infrastructure for the supply of adaptation (Baffoe-Asare et al., 2013; Borsky and Spata, 2018; Lebel et al., 2006; Verburg et al., 2019). Our findings show that these mechanisms are strong at delivering adoption for measures that have high feasibility and low to medium complexity, such as enhanced fertilisation. For more complex strategies, the current delivery mechanisms are not, on their own, able to catalyse the uptake of measures that have lower feasibility and higher complexity, such as diversifying agricultural income. In terms of adoption theory, the current delivery mechanisms are able to increase awareness but not necessarily motivation, do not enhance risk baring capacity and do not increase supply of adaptation (Fankhauser and McDermott, 2014; Marra et al., 2003). Notable exceptions that can inform the improvement of delivery mechanisms, include; RA supply of shade trees and the licensed buying company supply and financing of organic fertilisers to Organic and UTZ farmers.

2.4.3 Certification has the potential to influence recovery from shocks

Despite similarities in the sensitivity to drought in terms of yield losses for certified and non-certified farmers, certification showed a significant effect on some of the recovery mechanisms employed, such as selling livestock (Figure 4, A7). This showed that certification has the potential to influence the recovery component of resilience, an aspect that has not been investigated before. These differences in selling livestock (RA with higher propensity) are likely to be influenced by differences in asset structure that has been driven by the certification process, such as RA promoting small livestock rearing. What is not seen are changes in recovery strategy driven by certification directly. Currently certification standards do not focus explicitly on drought recovery mechanisms. This could be an opportunity to apply the resilience lens to certification program design. Though we caution that our findings also highlight the importance to understand the local context in terms of coping mechanisms, so as to design such approaches intelligently (Hirons et al., 2020).

2.4.4 The importance of underlying regional attributes in certification program design

Beyond certification effects, we find that regional differences predominated in terms of resilience metrics for farmers, across robustness, recovery and adaptability. This is an important finding as these differences are not explained solely by agroecological differences (e.g. climate and soil type) and exemplify that socio-economic differences are critical too (Adger, 2003). Our findings show differences in livelihood systems between Eastern and Western, where Eastern livelihoods are characterised by the post-forest frontier agricultural mosaic, diversification, intermediate cocoa reliance, and more livestock while Western livelihoods are shaped by the forest-frontier; high cocoa reliance, younger and larger farms. These regional differences in livelihood system are also highlighted by Abdulai et al. (2018) in terms of income diversification. Our study allowed to identify a link between these different livelihood structures and the resilience of producers to shocks, for example, livestock ownership and choice of recovery mechanisms, as well as natural capital and adaptability. These factors are rooted in the economic geography of Ghana, with Western undergoing agricultural transformation much later than Eastern (Knudsen and Agergaard, 2015).

Given recent suggestions to plan for climate resilient transformation using agro-climatic zoning (Bunn et al., 2019), we suggest that the underlying socio-economic structures that affect climate resilience should be critically considered in regional zoning for certification. The mechanisms by which certification can enhance resilience are also moderated by this regional context, for example the higher yielding forest-frontier Western Region makes premium payments to certified farmers more effective compared to the lower yielding Eastern Region. Beyond this, differences in agroforest diversity and proximity to large urban areas, both higher in Eastern Region, mean that strategies to enhance resilience via alternative agroforest income streams also have different potentials. These differences within the national context of Ghana can be expected to be mirrored in other commodity producing countries, in terms of forest-frontier regions versus post-forest transition agricultural mosaic regions, and therefore efforts to contextualise certification to these sub-national contexts should be made. In addition, we would expect wider differences between the Ghanaian context and other commodity producing countries to further moderate the effects of certification on climate resilience. For example, we would expect differences in access to and stability of domestic markets for alternative agroforest products between West African and South American cocoa producing countries to influence the effectiveness of farm diversification strategies in enhancing resilience (Cerda et al., 2014; Russell and Franzel, 2004).

2.4.5 Strengths and limitations of the study

By adopting a transdisciplinary approach, we have been able to frame our assessment through the perspective of the cocoa farmers and value chain stakeholders, whose outcomes are of primary concern. The co-creation of the climate resilient framework benefited from the fact the stakeholders had all recently experienced a severe climatic event, in the form of the 2015-16 drought, and therefore were familiar with aspects of their systems that were beneficial in facing such a shock. The framework is specific to smallholder cocoa production; however, the vast majority of indicators are relevant to other forms of smallholder production and therefore it can be replicated and applied to other contexts. Though we caution that this would require some specification for the crop and local context. In addition, by using the Coarsened Exact Matching approach we have been able to make a comparison that accommodates for farmer self-selection into certification schemes. Beyond this, the interdisciplinary approach, combining the socio-economic survey with biophysical measurements, allowed us to operationalise the resilience framework by evaluating both household and on-farm resilience enhancing pathways. A limitation in this approach is that biophysical measurements are limited to plot-level and do not incorporate landscape scale attributes that could also impact the farmers' resilience. Conducting the study post-shock is also a limitation as we are unable to track the changes in capitals as a result of the shock, although sales records for cocoa proved useful in verifying yield recall.

2.5 Conclusion

This article examined whether sustainability certifications can deliver climate resilience benefits to cocoa farmers in Ghana, the second largest cocoa producing region in the world. Using a novel, co-produced resilience indicator framework, we found that certification has strong effects on aspects of farm management that support resilience, but the effects of certification become weaker as the complexity of the resilience-enhancing practices increase. Thus, we find that sustainability certification in its current form is not a sufficient tool for improving the climate resilience of smallholders. Specifically, existing certifications suffer from major gaps between ambition and implementation on the ground, in terms of standards, training, adopted practices and outcomes. However, sustainability certification appears to have indirect benefits for climate resilience, by supporting group formation and strengthening good agronomic practices.

Despite their potential to support some farm and institutional transitions, sustainability certifications may also pose risks to developing climate resilient farming systems. As currently designed such certifications focus heavily on a single commodity, which stands at odds with the potential benefits associated with diversification and multifunctional farming. In addition, we find that accommodating the sub-national regional context as being critical to the effectiveness of certification delivering climate resilience. Therefore, we suggest sustainability certification should be considered as part of a policy mix, that supports the farming system as a whole, not just a single commodity, and builds on broader collaborations by certifiers and the public and private sector to bridge the gaps in adaptation pathways.

3.0

What Determines the Adoption of Climate Resilience Strategies by Smallholder Farmers?

This chapter will be submitted to Climate Risk Management as Thompson, W. [1], Blaser-Hart,W.[1,2], Joerin, J.[1,3], Krütli, P.[1], Evans Dawoe, E.[4], Kopainsky, B.[5], Chavez, E.[6], Spaeth, L.[1], Monastyrnaya., E[1], Benabderrazik., K[1], Six, J.[1] What determines the adoption of climate resilience strategies by smallholder farmers?

Prologue: *This chapter moves on from comparing certification and "who is" or "who is not" climate resilient but seeks to go a step further and looks to explain which factors determine the adoption of climate resilience strategies by smallholder farmers. The idea being that this information will be critical to design policies and interventions to promote the uptake of such strategies.*

Abstract:

Limiting the impact of extreme weather events on smallholder farmers and increasing their ability to recover from such climatic shocks requires the adoption of climate resilience strategies. It is, thus, crucial to understand which factors determine the uptake of climate resilience strategies by farmers, to enhance the design of programmes, policies and interventions that increase the climate resilience for both farmers and the food systems they contribute to. Here, we take the case of Ghanaian smallholder cocoa producers, whose climate related challenges typify many smallholder producers in the tropics, to address the question "What determines the adoption of climate resilience strategies by smallholder farmers?". In a first step, we conducted a stakeholder workshop to co-define climate resilience practices to be included in an index of climate resilience strategy. Following this, we collected data for this index via a household survey of 457 cocoa farmers in Ghana. We then empirically validated the stakeholder co-defined indicators against resilience-linked outcomes using the household data and a machine learning approach. Finally, we used factor and fractional regression analysis to explain the differences in adoption of climate resilience strategies. We find that there is a large variation in the adoption of climate resilience strategies between farmers and that adoption is increased with "Drought training and value chain integration", "Income generating capacity", "Agricultural market access" and "Land tenure and household size". Our findings highlight the need to broaden extension engagement and its climate specificity, to develop markets for secondary agricultural products, as well as to facilitate formal land tenure to give farmers certainty to invest in climate resilience strategies.

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3.1 Introduction

Climate driven shocks and stresses to smallholder agriculture, such as drought and flooding, can have severe consequences for producers themselves, as well as for the functioning of the wider food systems they are part of (Puma et al., 2015). These shocks can cause food insecurity, reduced incomes, increased environmental degradation and food price volatility (Cottrell et al., 2019; Morton, 2007). Smallholder farmers' high dependence on rainfed agricultural production, the dominant mode in Sub-Saharan Africa, makes their livelihoods particularly vulnerable to such disruptions (Harvey et al., 2014; Müller et al., 2011; J Rurinda et al., 2014). In addition, increasingly many smallholder farmers are engaged in global food value chains and thus experience a dual exposure to both climate as well as demand shocks from the Global North (O'Brien and Leichenko, 2000), as seen during the ongoing COVID-19 crisis (Tröster and Küblböck, 2020). Climate driven shocks are becoming increasingly frequent and, in some cases, increasingly intense (Cottrell et al., 2019), particularly in the tropics where the majority of smallholders are located (Fu, 2015). Hence, there is an urgent need to find ways to protect the food system and particularly keystone participants, such as smallholder farmers, against such shocks (Cohn et al., 2017; Whitfield et al., 2019).

The growing consensus on the need to adapt to these climate shocks and stresses has led to the emergence of climate resilience as a key topic in the study, management and governance of smallholder food systems (Dixon and Stringer, 2015b; Ifejika Speranza, 2013). Resilience, the ability of a system to maintain function and recover in the face of a shock or stress, was first conceptualised as a property of ecological systems (Holling, 1973b) and has since been adapted to socio-ecological systems (Folke, 2006) and more recently food systems (Tendall et al, 2015; Schipanski et al. 2016; Doherty et al. 2019). Enhancing smallholder climate resilience will be critical for the farmers (income, food security, livelihoods) (Shiferaw et al., 2014), for food systems (Suweis *et al.*, 2015) and the wider economy (Chavez et al., 2015).

Whilst enhancing the climate resilience of smallholders is an increasingly recognised challenge amongst decisions makers, which climate resilience strategies farmers would most benefit from adopting is still unclear and, additionally, there is a lack of knowledge on the levers to influence the adoption of such strategies (Makate, 2019). Here, we define a climate resilience strategy as a suite of coordinated measures and practices that enhance the robustness to a climate shock, accelerate recovery and facilitate learning that can lead to adaptation and or transformation. Multiple studies have investigated individual practices and measures that can enhance a smallholder farmer's ability to respond to a climate shock, such as a drought. These have identified and tested practices that can enhance robustness, such as drought-tolerant seeds, shade cover, and irrigation (Blaser et al., 2018; Cacho et al., 2020; Xie et al., 2014) but less frequently from a recovery perspective, based on measures such as index insurance, government safety nets and diversification (Bertram-Huemmer and Kraehnert, 2018; Ibrahim et al., 2019). Beyond this, from a learning perspective, several key attributes to enhance adaptive capacity have been identified, including economic resources, access to information and skills (Adger, 2003; Smit and Wandel, 2006; Tessema et al., 2018). Several studies have also looked at factors that influence the adoption of individual practices and measures largely related to production (Cohn et al., 2017). Recently it has also been hypothesised that bundles of practices may be required for transformations to more resilient food systems to occur (Barrett et al., 2020). This aligns with the multidimensional nature of resilience and prevailing thinking that an overall resilience strategy is critical, as opposed to the adoption of just one or two measures.

Where there is less consensus is how to influence the uptake of such climate resilience strategies (Tittonell 2014; Hellin et al. 2018; Makate 2019). Few studies go beyond individual practices to investigate determinants for the adoption of an overall resilience strategy by smallholder farmers. Tambo and Wunscher (2017) find that "innovators", are more likely to have a climate resilience strategy than "non-innovators". Makate et al. (2019) find that access to land, credit information and education enhance the adoption of multiple climate-smart practices although they do not look at the broader set of resilience indicators. As resilience strategies are in general multifunctional the levers to be considered are likely to be diverse (Thompson et al, in submission). Williams et al. (2020) highlight the risk that interventions to enhance resilience may not deliver positive impact for all of the intended recipients. Therefore, heterogeneity in smallholder preferences and their ability to adopt climate resilience strategies must be resolved in interventions designed to promote them (Shapiro-Garza et al., 2020). Thus, further evidence is required to understand what influences the uptake of resilience strategies by smallholders. This will enable decision makers to design policies, programmes and interventions to catalyse the necessary transformations in smallholder agricultural systems that can enhance climate resilience.

For this study, we asked the overall question: Which factors influence the adoption of climate resilience enhancing strategies by smallholder farmers? To answer this question, we carried out a case study of smallholder cocoa production in Ghana, the second largest cocoa producer in the world (FAOSTAT, 2021).We chose this case as it exemplifies many challenges faced by smallholder producers across the tropics, particularly those engaged in global value chains, such as capital scarcity, low incomes, and increasing climate vulnerability (Cohn et al., 2017; Schroth et al., 2016). To capture the multiple dimensions of climate resilience strategies we synthesised composite indices of measures and practices, based on indicators co-defined by farmers and cocoa value chain stakeholders. Using factor analysis, we then explore the drivers of climate resilience strategy adoption across a range of climatic, socio-economic and institutional contexts.

3.2 Methods

The study had five phases: **(*i*)** defining the indicators for a climate resilience strategy index **(*ii*)** surveying cocoa producer households to collect data for each indicator, **(*iii*)** empirically validating the co-defined indicators with household data, **(*iv*)** synthesising a climate resilience strategy index (RSI) and **(*v*)** explaining the adoption of climate resilience enhancing strategies with factor and fractional regression analysis of the index.

3.2.1 Identifying the indicators of a climate resilience strategy

3.2.1.1 Theoretical framework of smallholder resilience strategy

The resilience concept has been adapted and applied to food systems and smallholder agriculture in several contexts (Dixon and Stringer, 2015b; Tendall et al., 2015). In this study, we used the action-orientated resilience framework (see Figure 1) from Thompson et al. (in submission) adapted from Tendall et al. 2015. We focused on four linked stages in reducing impacts of a climate shock by **(*i*)** preparing for, **(*ii*)** responding to, **(*iii*)** recovering from and then **(*iv*)** learning to improve future outcomes, either by incrementally adapting or radically transforming the system (Figure 1). The four components of the framework (Preparation, Response, Recovery and Learning) are consistent with several commonly adopted models used to describe the resilience of socio-ecological systems and in particular agricultural systems (Ifejika Speranza et al., 2014; Meuwissen et al., 2019; Tendall et al., 2015).

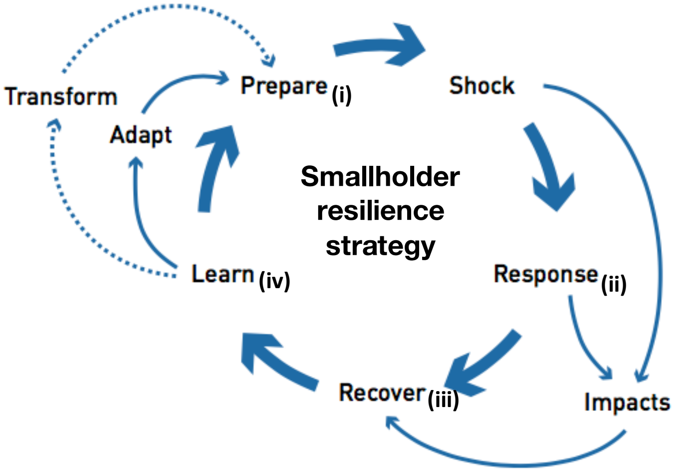

Figure 1 Smallholder resilience strategy framework. *Used in the workshop to identify indicators for each of the components (i-iv). The framework consists of a cycle of actions that food system actors take before (preparation (i)), during (response (ii)) and after (recovery (iii), learning (iv): adaptation, transformation) a shock.*

3.2.1.2 Co-defining indicators for the climate resilience strategy index

To develop a measure for the degree to which smallholder farmers utilise a climate resilience strategy, we adopted a set of indicators for each of the components of climate resilience (Figure 1: *i – iv*) and used them to synthesise a climate resilience strategy index (RSI). Using indices to summarise multiple, potentially diverse, indicators of livelihood strategy is an attractive option in investigating complex properties of socio-ecological systems, particularly because they allow these concepts to be encapsulated in one intuitive metric (Saisana and Tarantola, 2002). The use of indices in relation to studies of climate change impacts and adaptation has become increasingly common (Wiréhn, Danielsson, and Neset, 2015). Indices have been used in previous studies of smallholder farmer vulnerability (Bedeke et al., 2020; Gbetibouo et al., 2010), adaptive capacity (Below et al., 2012; Chepkoech et al., 2020), as well as more recently for climate resilience (Asmamaw et al., 2019; Tambo and Wünscher, 2017). The use of such indices has advantages such as capturing multiple dimensions of complex phenomena, integrating diverse datasets and ease of communication, as well as draw backs such as loss of information richness and a lack of transparency (Greco et al., 2019). Therefore, the use of indices to study resilience is not a panacea and here we strive to use the latest developments in composite index generation to reduce the trade-offs in applying the approach to smallholder climate resilience.

To construct the RSI we first ***(i)*** defined indicators for a climate resilience strategy, ***(ii)*** collected a dataset for all indicators, ***(iii)*** Empirically validated the indicators using collected data, ***(iv)*** aggregated an equal weighted and unequal weighted RSI and ***(v)*** conducted a sensitivity analysis to test the reliability of the index.

To generate the RSI, we utilised indicators, representing key resilience strategy components of cocoa systems, identified in a cocoa value chain stakeholder workshop, held in June 2018, in Ghana (Thompson et al., in submission). Co-defining with stakeholders the indicators was important to ensure their relevance and validity in the specific study system. During this workshop the stakeholders co-defined practices that contribute to more climate resilient cocoa production systems. This was done via mixed groups of stakeholders from different activities of the cocoa value chain (i.e. with farmers, certifiers, NGOs, government, cocoa licensed buying companies and cocoa processors). Thirteen indicators were selected to represent the four key resilience components: preparation, response, recovery and learning (Table 1). These indicators are also supported individually by the literature for their role in enhancing climate resilience in different contexts (further evidence is given in Table 1). Indicators for learning were co-defined using the Sustainable Rural Livelihoods Framework to identify assets (i.e. stores, resources, claims, and access, that give the means to engage in activities) that can be utilised in adaptation (Chambers and Conway, 1992; Scoones, 1998).

Table 1 ***Indicators for the climate resilience strategy index*** *- co-defined by farmers and stakeholders of the Ghanaian cocoa value chain*

Resilience component	Practice	Description	Units	Evidence of climate resilience role
Preparation	Water harvesting	Farmers harvested rainwater to use for fire control or irrigation	Dummy	(Anschütz *et al.*, 2003)
	Fire belt	Farmers constructed a fire belt around their cocoa plots	Dummy	(Appiah et al., 2010)
	Hybrid variety	Farmers have planted improved hybrid varieties of cocoa	Dummy	(Medina and Laliberte, 2017)
Response	Irrigation	Farmers irrigated their cocoa trees in response to drought conditions	Dummy	(Carr and Lockwood, 2011)
	Modify pruning	Farmers modified their pruning strategy in response to drought conditions (increase cocoa pruning – decrease shade pruning)	Dummy	(Niether et al., 2018)
	Modify weeding	Farmers modified their weeding strategy in response to drought conditions (increase and leave residues)	Dummy	(Patterson, 1995)
Recovery	Diversity non-agricultural income	The number of non-agricultural income sources of the household	Count	(Antwi-Agyei et al., 2014)
	Diversified crop production	The number of crop types produced on the farm	Count	(Lin, 2011)
Learning (Adaptability and transformability)				
Financial capital	Bank account	Farmer has a bank account	Dummy	(Li et al., 2020)
Physical capital	Livestock ownership	Tropical livestock units	Continuous	(Seo and Mendelsohn, 2007)
Natural capital	Secondary vegetation on farm	Percentage of the farm that is not in agricultural production and has secondary vegetation established	Percentage	(Ambroser-Oji, 2003)
Knowledge capital	Knowledge of integrated farm management strategies (IPM)	Farmers can explain how to implement an integrated pest management strategy	Dummy	(Heeb et al., 2019)
Social capital	Cocoa group membership	Farmer are active members of a cocoa producer's group	Dummy	(Kangogo et al., 2020)

3.2.1.3 Validation of indicators before data collection with focus groups

The indicators co-generated by the participants of the cocoa value chain stakeholder workshop were validated, to ensure their relevance at a farm scale, in a series of focus groups with cocoa farmers in Eastern Region and Western Region, Ghana, held in July 2018, lasting 45 minutes to 1 hour each (N=7, with between 8 and 16 farmers). The farmers were presented with the components of our resilience framework (preparation, response, recovery and adaptability) and asked to describe what measure or practices they take at each time period related to these components, reflecting the same activities as undertaken in the workshop. Farmers were not presented with the results of the workshop initially. Later in the focus groups, workshop indicators that were not identified by the focus-group-farmers where then highlighted to elicit the farmers input on their relevance. All indicators identified in the workshop were considered relevant across the seven focus groups. Irrigation was consistently raised as something that is not performed widely; however, we include this in the index as farmers (and field trials, Carr and Lockwood 2011) strongly indicate the potential to protect production in the face of a drought.

3.2.2 Cocoa producer household survey to collect indicators

To collect the farmer data related to these indicators for generating the RSI, we conducted a household survey with smallholder cocoa farmers, in July and August 2018, across a range of climatic, socioeconomic and institutional contexts.

3.2.2.1 Questionnaire

The survey used a questionnaire constructed with inputs from the stakeholder workshop to measure the indicators of climate resilience strategy. The questionnaire consisted of the following sections: household socio-economic characteristics, farm management, cocoa production, sales, drought shock experience, preparedness, response, impact, recovery and learning. Cocoa production volumes were recalled by farmers at the plot level and were verified with their individual COCOBOD passbooks (farmers record of cocoa sales) and certifier audit data. Gross cocoa income was estimated from the passbook transactions and farmers' recall of production volumes and prices (list of all variables collected in B1).

3.2.2.2 Study sites and sampling

We conducted the household survey in two contrasting cocoa producing regions in Ghana: Western Region, which is a highly productive forest frontier region still undergoing the transition from forest to agricultural mosaic and Eastern Region, which is a post-forest transition region near Accra, the Ghanaian capital (Figure 2). The survey was conducted in the following districts; Juabeso district in Western Region and Fanteakwa South, Abuakwa North and Suhum districts in Eastern Region. Western Region is historically wetter than Eastern Region with mean annual rainfall of 1370 mm versus 1260 mm, respectively (Funk et al., 2015). The sample was selected using a stratified random approach. Villages were sampled from lists curated from Ghanaian census data, Licenced Buying Companies and certification organisations. The sampling of villages was stratified by region, district, population size and certification (i.e. Non-certified, Organic, Rainforest Alliance, UTZ). We selected farmers at random from the purchasing clerk lists of the Licensed Buying Companies and certification organisations, resulting in a total of 480 households being sampled. After discarding several interviews due to missing data, 457 households were included in the analysis, describing 846 cocoa plots (See B2 for overview of sample).

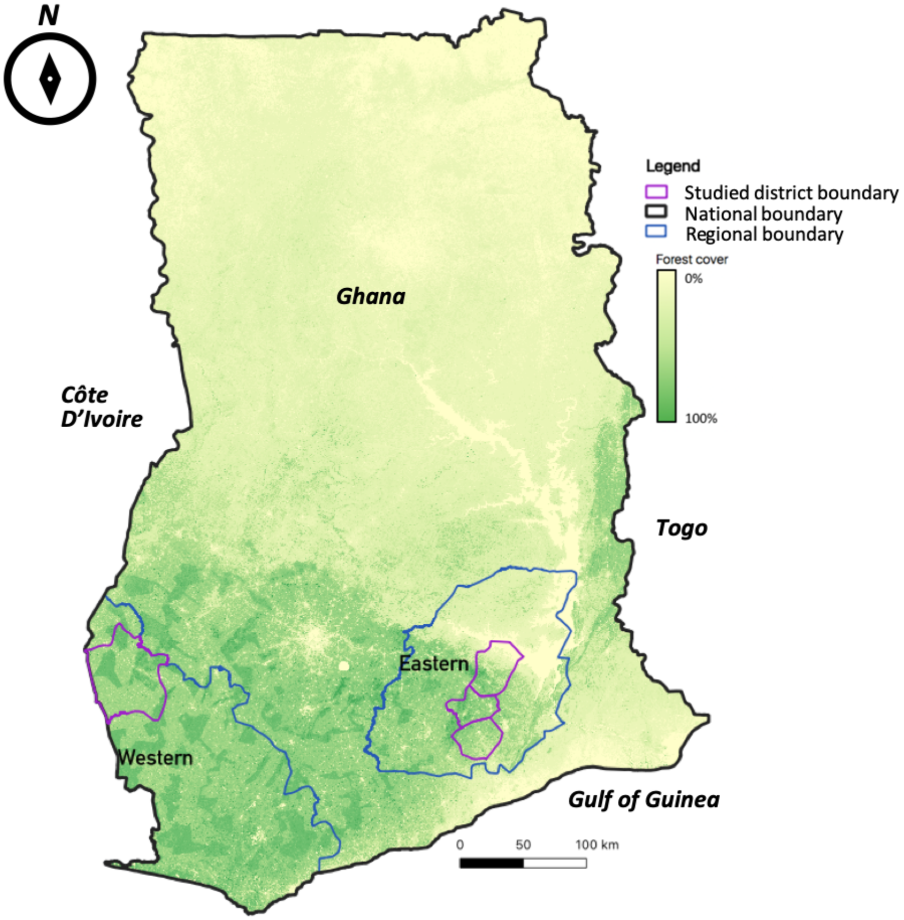

Figure 2 ***Map of Ghana.*** *Eastern and Western Regions are outlined in blue. Studied districts are shown in purple. Tree cover is shown from 2000 using satellite data from Hansen et al. (2013.)*

3.2.3 Empirical validation of co-defined resilience indicators with machine learning

In order to empirically test if the 13 stakeholder co-defined indicators influence farmers' climate related outcomes, following Feldmeyer et al. (2020), we used a random forest machine learning approach (Liaw and Wiener, 2001) with the collected household survey data. This required selecting outcomes that are aligned to the concept of "climate resilience" to validate the indicators against. As suggested in the literature (Bakkensen et al., 2017; Feldmeyer et al., 2020), because resilience is multi-dimensional and no single outcome fully captures the concept, therefore multiple outcomes should be considered for validation. Here we chose three drought-linked outcomes, highlighted in the stakeholder workshop, subsequent focus groups and literature, that integrate drought-impacts on multiple aspects of farmers livelihood. We chose "Cocoa productivity", "Death of trees due to fire" and "Coping via consumption smoothing" (Asante et al., 2017; Schroth et al., 2016). Cocoa productivity was chosen as it integrates multiple production factors. Death of trees due to fire was chosen as it is a specific negative outcome from a drought. Coping via consumption smoothing was chosen as it integrates the outcome of a shock at the livelihood level.

After checking the continuous indicators for normal distribution (histogram) and linearity (Kolmogorv-Smirnov-Test), we implemented three random forest models, one for each of these three outcomes as a prediction (Liaw and Wiener, 2001). For "cocoa productivity", as a continuous variable, a regression model was used and for "fire driven tree death" and "consumption smoothing", as binary variables, classification models were used. For each model the contribution of the indicator in question to reduce the test error was evaluated. We discarded the indicator "Modify weeding" because this indicator did not contribute to decreasing the test error of one of the three outcomes. All other indicators contributed to a decrease in the test error of at least one outcome model and were maintained. This analysis was performed in R using the RandomForest Package (Liaw and Wiener, 2001).

Table 2 Empirical validation of indicators of with machine learning *– contribution to decreasing test error of the model is indicated with ✓ or ✗.*

Indicator	Yield	Tree death	Consumption smoothing
Water harvesting	✗	✓	✓
Fire belt	✗	✓	✗
Irrigation	✓	✓	✓
Pruning	✓	✓	✓
Modify weeding	✗	✗	✗
Diversity non-agricultural income	✗	✓	✓
Bank account	✓	✓	✓
Livestock ownership	✓	✗	✓
Secondary vegetation on farm	✓	✗	✗
Knowledge (IPM)	✗	✓	✗
Cocoa group membership	✗	✓	✗
Crop diversity	✗	✗	✓
Hybrid	✓	✗	✓

3.2.4 Climate resilience strategy index synthesis

To describe the extent to which cocoa producers have adopted a climate resilience strategy we synthesised the twelve co-defined indicators into a composite RSI. Firstly, as the indicators were measured on different scales, we normalised them using min-max normalisation (Equation 1). Where N_i is the normalised observation *i*. V_i is the original observation *i* of variable ***V.***

$$Equation\ 1: N_i = \frac{V_i - V_{min}}{V_{max} - V_{min}}$$

Using the normalised indicators, we synthesised both equal weighted and unequal weighted climate resilience strategy indices. There are several methods to assign weights including expert ranking of indicators, equal weighting and statistical methods (Balaei et al., 2018). We chose to use both equal weighted (RSI) and an unequal weighted (uRSI) principal component analysis (PCA) approaches to compare the impact of weighting on our results (Krishnakumar and Nagar, 2008; Nájera Catalán 2019a). For the unequal weighting via PCA, weights were assigned using the Eigen vectors of the first principal component following extraction without rotation. The following weights were generated Fire belt (0.56), Water harvesting (0.50), Irrigation (0.50), Hybrid (0.15), Pruning (0.15), Non ag. Income (0.22), Crop diversity (0.54), Bank account (0.08), Cocoa group membership (0.31), IPM Knowledge (0.26), Secondary vegetation (0.24), tropical livestock units (0.36). Both indices were aggregated linearly and the sum divided by the hypothetical maximum (12) to give RSI values between 0 and 1. As a final stage in the construction of RSI, we conducted a global sensitivity analysis of the two indices, using a Bayesian approach implemented in the "tgp" package of R (B3, Gramacy 2007). Further, RSI and uRSI were compared based on household characteristics using t-tests (B4).

3.2.5 Explaining resilience strategy adoption

3.2.5.1 Factor analysis

To explain what drives differences in climate resilience strategy adoption (summarised by the indices) we used exploratory factor analysis (Fabrigar and Wegener, 2011) and a fractional regression model (Papke and Wooldridge, 1996). During the study we identified potential explanatory factors for resilience strategy adoption from existing literature, the workshop, as well as the focus groups and interviews. The identified variables are presented in B5.

We used these variables to conduct an exploratory factor analysis, following Fabrigar et al. (2011). Initially, to test for issues of multiple collinearity, we conducted a correlation analysis using Pearson's correlation coefficient. We selected variables based on significant correlation coefficients with the RSI. To test for the suitability of these variables for factor analysis we conducted Bartlett's Test of Sphericity, exploring the relatedness of these variables. We determined the sampling adequacy using the Kaiser-Meyer-Olkin (KMO) approach. After this an unrotated PCA was conducted to establish the number of factors to extract. This was chosen based on the KMO approach, with factors having Eigen values above 1 being selected. These factors were then extracted and rotated using the Oblimin technique, as we assume relationships between the factors and to maximise the loading of individual variables on each factor, thus enabling easier interpretation. The analysis was carried out using the "psych" package in R (Revelle , 2017).

The correlation analysis revealed that out of 26 tested 15 variables (Cocoa farms, Drought driven tree death, Forward sale agreement, Household size, Farm ownership, Total farm size, Total HH income, Training frequency, Drought training, Diversity ag. income, Distance to market, Region, Cocoa income dependency, Climate focused certification, Rainfall) were corelated with equal weighted or unequal weighted RSI (B6). Of these 15 variables, 14 met the KMO criterion (Measure of Sampling Adequacy score > = 0.5) as well as not being highly corelated with other variables (R>0.9) and were thus included in the factor analysis, with "Distance to market" being excluded for not meeting these criteria. Bartlett's test of sphericity indicated (Chi squared = 1541.6, p < 0.001) that with these 14 variables there was sufficient correlation between the variables to conduct factor analysis. The initial unrotated factor extraction generated six factors with eigenvalues greater than one. Therefore, six factors, explaining 67% of the variation, were extracted and rotated (Table 3).

Table 3 Factors related to resilience strategy adoption. *Factor loadings from exploratory factor analysis, after rotation, with interpretations based on variable loadings over 0.3 following (Stevens, 2009) .*

Variable	Regional context	Drought training and value chain integration	Income generating capacity	Agricultural market access	Land tenure and household size	Severe drought shock experience
Annual rainfall	**0.92**	-0.07	0.06	0.01	-0.15	0.00
Region	**0.88**	0.08	0.04	-0.12	0.13	0.01
Farm ownership	**0.54**	-0.10	-0.19	0.07	**0.48**	-0.11
Cocoa income dependency	**0.45**	0.06	0.00	**-0.56**	0.08	0.12
Total HH income	**0.40**	0.09	**0.61**	0.20	-0.10	0.05
Training frequency	0.02	**0.83**	0.00	0.09	-0.03	-0.05
Drought training	-0.06	**0.77**	0.13	0.00	-0.05	0.06
Climate focused certification	-0.02	**0.40**	-0.16	-0.32	**0.53**	-0.03
Forward sale agreement	0.26	**0.36**	-0.25	**0.52**	-0.01	0.08
Number of cocoa plots	-0.09	0.14	**0.76**	-0.25	0.05	-0.04
Total farm size	0.08	-0.10	**0.70**	0.19	0.17	-0.03
Diversity alt. ag. income	-0.22	0.13	0.11	**0.64**	0.16	0.04
Household size	-0.04	-0.12	0.23	0.11	**0.76**	0.08
Experienced cocoa tree death	-0.01	-0.01	-0.03	-0.01	0.02	**0.99**
Eigen values	2.45	1.66	1.67	1.3	1.23	1.03

3.2.5.2 Fractional regression

Following the factor analysis, we used a fractional regression model (FRM) (Papke and Wooldridge, 1996) to determine the effect of the 6 extracted factors on the climate resilience index as a dependent variable. We chose FRM because it is suitable for dependent variables that are bound between 0 and 1, as with RSI, as predicted values are confined to this range. In our FRM we model the mean of y (RSI) conditional on covariates x:

$$Equation\ 2: E(y|x) = G(x\beta)$$

Where $G(.)$ is a known function satisfying $0 \leq G(x\beta)0 \leq 1$. This, therefore, means that the predicted values of y lie between 0 and 1. We specify this equation with the logit functional form, $G(x\beta) = e^{x\beta}/(1 + e^{x\beta})$. In Equation 2, β is a vector of parameters for estimation and x is a vector of the factors extracted in the exploratory factor analysis. These parameters are estimated using a quasi-maximum likelihood method in the R package FRM (Ramalho, 2019).

3.3 Results

In this section, we present the following; ***(i)*** descriptive results of adoption of the subcomponents of a climate resilience strategy ***(ii)*** resilience strategy index (RSI) ***(a)*** distribution of RSI scores and ***(b)*** a comparison based on household characteristics ***(iii)*** we then explore ***(a)*** factors that determine the RSI and finally, ***(b)*** we present the effect of these factors on the RSI.

3.3.1 Adoption of resilience enhancing practices is low but heterogenous between farmers

There was a large variation in the number of subcomponents (practices and measures) of a climate resilience strategy adopted by cocoa farmers, with a maximum of 11 and minimum of one of the 12 subcomponents adopted (regardless of intensity of adoption – later RSI also encapsulates intensity of use not just "adoption") and a minimum of one. Only 8% of farmers had adopted 9 or more of the subcomponents. The majority of farmers 75% adopted 5 to 8 subcomponents, with the mean being 6 subcomponents. The most common subcomponents to be utilised were crop diversity (89% of farmers adopted), responsive pruning (82%) and cocoa producer group membership (73%) (Figure 3A). The least common was irrigation (5%). Despite being widely adopted, "crop diversity" showed large variations in intensity of adoption, ranging from seven additional crop types being incorporated into the cocoa farm to just one. Farmers showed a tendency to adopt certain measures in bundles or pairs (Figure 3A), for example water harvesting and responsive irrigation were likely to be adopted in unison ($p<0.01$). In addition, farmers joining cocoa groups were also more likely to own a bank account ($p<0.05$). Adoption rates of some of the subcomponents of the RSI were very different between the Eastern and Western Region, such as tropical livestock units and non-agricultural income (Figure 3B).

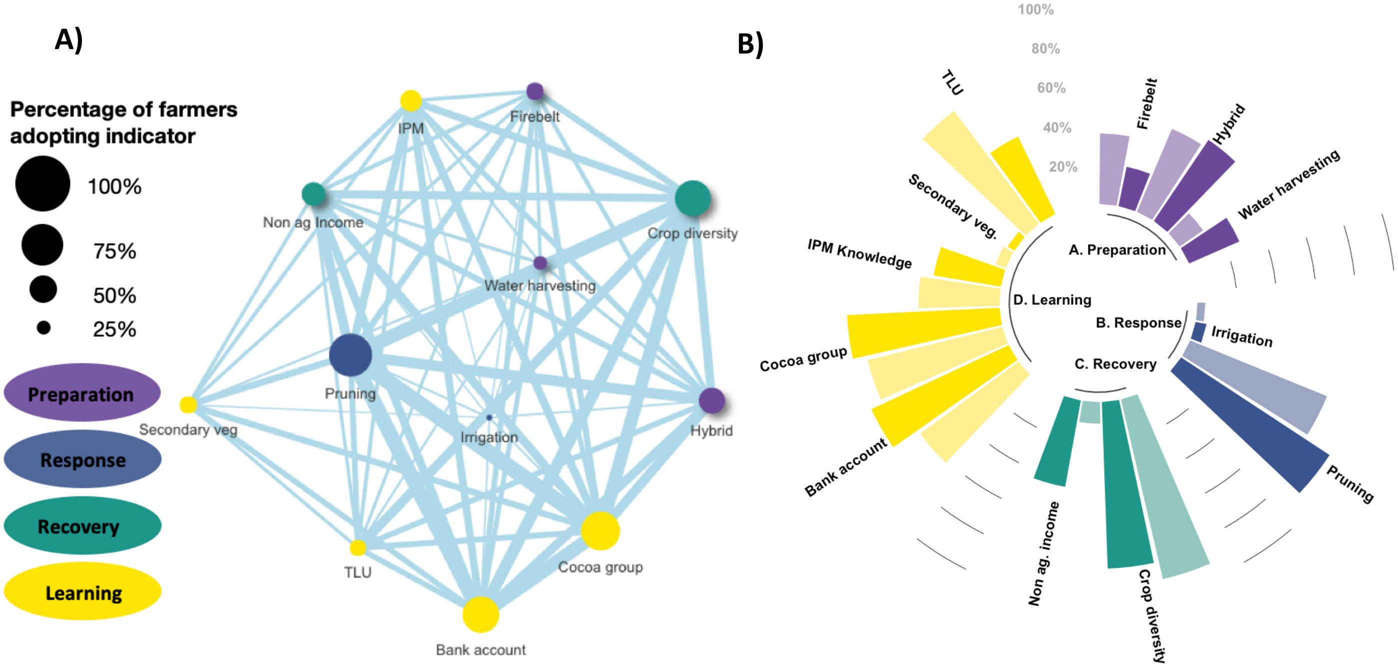

Figure 3 A) ***Interactions in adoption of subcomponents of resilience strategy.*** *The size of the node indicates the number of farmers adopting. The width of blue lines connecting the nodes is proportional to the number of farmers adopting the measure at both nodes. The layout is driven by Fruchterman-Reingold algorithm, with related nodes closer together.* ***B) Adoption of resilience strategy subcomponents by region*** *(Eastern in light shading and Western dark shading). The percentage of farmers adopting a particular indicator is shown. TLU = tropical livestock units; IPM = integrated pest management.*

3.3.2 Climate Resilience strategy adoption is low with large variations between farmers

The two indices (RSI and uRSI) both revealed large variation between farmers in terms of climate resilience strategy adoption, with values ranging from 0.001 to 0.726 for equal weighted RSI and 0.004 to 0.776 unequal weighted RSI (i.e. uRSI). For RSI the mean value was 0.371 (standard deviation 0.124) and uRSI the mean value was 0.270 (standard deviation 0.136), which was significantly lower ($t = 11.98$, $p < 0.001$). The majority of farmers (57%) have "low adoption" RSI scores ($0.2 < \text{RSI} < 0.4$). The distribution of resilience levels for the uRSI was skewed more to the low adoption end of the spectrum versus RSI (Figure 4 Panel 1).

A comparison of RSI and uRSI based on household characteristics revealed common patterns (t-test results reported here for RSI) between the two indices with larger household size ($p < 0.01$, $t = 2.56$), larger farm area ($p < 0.001$, $t = 4.38$), ownership ($p < 0.001$, $t = -3.75$) and Western Region residents ($p < 0.001$, $t = -3.87$) all showing significantly higher scores for RSI and the same patterns for uRSI (Figure 4, B5). The global sensitivity analysis (B3) revealed that weighting in the uRSI approach relegates several indicators to close to zero influence on the index therefore we choose to present the results with a focus on RSI.

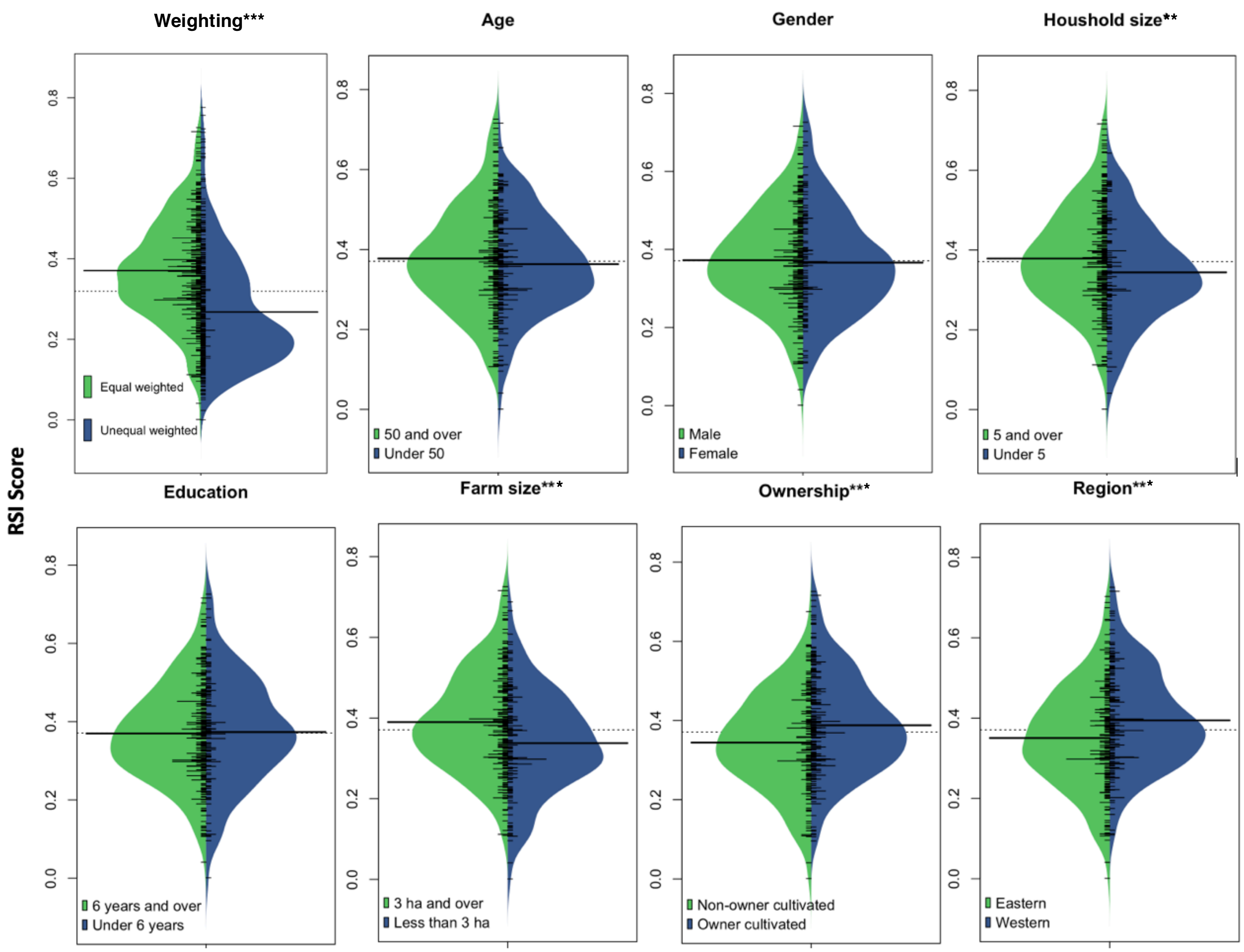

*__Figure 4 Comparison of Resilience Strategy Index distributions based on household characteristics.__ The first panel presents the distribution of scores for equal (RSI) and unequal (uRSI) weighted indices. The subsequent panels show distribution of equally weighted RSI based on household characteristics (gender, age, household size, education, farm size, ownership, region). The long black lines represent means for each sub-sample. Stars indicate significance of t-tests *** P<0.001, ** P<0.01, *p<0.05.*

3.3.3 Diverse socio-economic, biophysical and institutional factors determine climate resilience strategy adoption

We identified six factors that influence climate resilience strategy adoption by smallholder cocoa farmers. These were "Regional agricultural and socio-economic context" (based on the variables: Rainfall, Region, Farm ownership, Cocoa income dependency, Household income) "Drought training and value chain integration" (based on the variables: Training frequency, Drought training, Forward sale agreement, Climate focused certification), "Income generating capacity" (based on the variables: Number of cocoa plots, Total farm size, Total household income), "Non-cocoa agricultural market access" (Diversity of alt.

ag. Income, Cocoa income dependency, Forward sale agreement), "Land tenure and household size" (based on the variables: Farm ownership, Household size, Climate focused certification) and "Severe drought shock experience" (based on the variable: Experienced cocoa tree death) (Table 3).

Of the six factors, five positively and significantly influenced the equal weighted RSI (Figure 5), with "Severe drought shock experience" having a positive influence but not being significant ($p = 0.099$). These six factors had the same direction of influence on unequal weighted RSI. Referring now exclusively to the equal weighted RSI results, the two largest effect sizes of the six factors were from "Land tenure and household size" (0.124, $p < 0.001$) and "Non-cocoa agricultural market access" (0.123, $p < 0.001$), followed by "Drought training and value chain integration" (0.104, $p < 0.001$), "Regional context" (0.068, $p < 0.01$), "Income generating capacity" (0.056, $p < 0.01$), and finally "Severe drought shock experience" (0.039, $p = 0.099$). The R squared value of 0.20 indicated that the model explains 20% of the variation in RSI between farmers (B7).

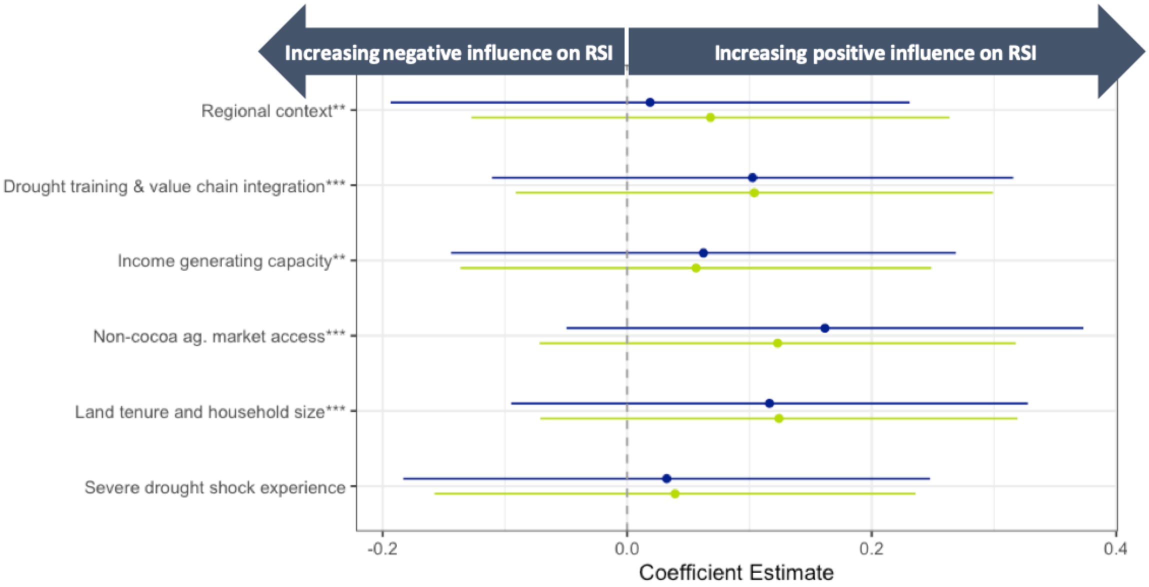

Figure 5 Factors influencing climate resilience strategy adoption. *Based on logit-fractional regression of factors influencing the Resilience Strategy Index. Estimates are presented for both unequal weighted (uRSI, blue) and equal weighted (RSI, green) indices. Dots show the value of the coefficient estimate and whiskers show the 95% confidence interval. Stars indicate significance (for RSI only) with *** $P<0.001$, ** $P<0.01$, *$p<0.05$.*

3.4 Discussion

The adoption of climate resilience strategies by smallholder farmers will be critical to limiting the impacts of extreme weather events, such as drought, and worsening stressors, such as increasing maximum temperatures. Here, we measured and explained the adoption of such strategies by smallholder cocoa farmers using a climate resilience strategy index (RSI). Overall, we find a large variation in climate resilience strategy adoption between the farmers in our survey, with RSI scores ranging from "very low adoption" ($RSI < 0.2$) to "high adoption" ($0.6 < RSI < 0.8$), with the majority having "low adoption" RSI scores ($0.2 < RSI < 0.4$). This showed that even though the majority of farmers reported suffering from the impacts of several droughts in the last 10 years, many did not adopt a climate resilience enhancing strategy. The variation in RSI, across the farmers sampled, reflects both macro and micro level differences in agroecological (wetter region with higher RSI), socioeconomic (larger households with higher RSI) and institutional contexts (certified farmers with higher RSI). We identified several factors that positively determine resilience strategy adoption (Figure 5); namely, we found positive effects of increased "Non-cocoa Agricultural market access", "Income generating capacity", "Drought training and value chain integration", and "Land tenure and household size". The regional agricultural and socio-economic context also significantly influenced resilience strategy adoption.

3.4.1 Access to domestic markets for alternative agricultural products is key to developing climate resilient multifunctional agricultural systems

Our finding, that increased market access for alternative agricultural products enhanced smallholder adoption of a climate resilience strategy (Figure 5), provides new evidence to suggest the critical role that domestic markets (for secondary crops) can play in enhancing the livelihoods of farmers with export oriented agricultural systems. In terms of mechanisms by which market access enhances the adoption of resilience strategy, we suggest that farmers with multiple agricultural income streams are more incentivised to actively manage their cocoa and mixed cocoa agroforests, which we see reflected in significant correlations between the number of agricultural income streams and, both, pruning and irrigation behaviour. This incentive for higher management intensity may reflect higher profitability of intercropped areas and lower risk exposure via diversification (Tittonell et al. 2007). The value of diverse income generating agricultural production to climate resilience is also supported by Kumar et al. (2020) who found income generating farm diversity to reduce impacts of climate shocks in India.

3.4.2 Cocoa income and, by extension, cocoa price, constrains climate resilience strategy adoption

Our finding that increasing income generating capacity (linked to household income, farm size and number of cocoa plots, Figure 5, Table 3) increases climate resilience strategy utilisation shows the critical role that livelihood resources, and in particular financial capital, play in the adoption of a climate resilience strategy. This supports the findings of Mutabazi et al. (2015) who highlight the need to enhance the financial capital of smallholders to enable them to undertake climate adaptive strategies. In the context of Ghanaian cocoa, financial capital is a persistent constraint to technology adoption in general (Abunga Akudugu et al., 2012; Boahene et al., 1999). Our findings provide further evidence that a climate resilience transition, in the cocoa sector, is closely linked to income generation and therefore cocoa prices. Whilst, as highlighted earlier, alternative crops have an important role to play in building climate resilience, cocoa makes up on average 78% of the income of famers we surveyed. There has been a recent push to establish a "living income" for cocoa farmers in West Africa, which has, however, met resistance from several sectors in the industry (Munshi and Terazono, 2020). Nevertheless, beyond moral arguments, a virtuous circle can be established by providing a higher cocoa price that enables farmers to invest in climate resilience strategies that also enhance productivity and secure the stability of supply (Wongnaa and Babu, 2020).

3.4.3 Targeted training can prevent smaller scale farmers from being left behind as climate pressures increase

The finding that smaller scale farmers (in terms of farm size and income) are less likely to adopt a climate resilience enhancing strategy (Figure 4, Figure 5), is concerning because it raises the prospect that these smaller scale farmers may be "left behind" as climate impacts widen the livelihood gap between those with "medium" scale farms. This is an important issue given the rise of "medium-scale" farmers and their increasing influence on agriculture on the African continent and in Ghana specifically (Jayne et al., 2016). This result is not surprising since several studies have found farm size to influence agricultural technology adoption (Bryan et al., 2013; Fisher et al., 2015; Hassan and Nhemachena, 2008). Therefore, special attention will need to be paid by decision makers to target the smallest scale farmers (i.e. farmers with small farm size and low income) in the design of new climate resilience policies and programmes. In particular, our study highlights the importance of value chain integration (in the form of certification and forward sale agreements – often linked to agronomic support and input supply) and training as two important mechanisms that can be employed to enhance resilience strategy adoption (Table 3, Figure 5). The role of training in agricultural technology adoption has been established in several contexts (Moser and Barrett, 2006; Nakano et al., 2018); here, we present new evidence that it is a critical driver of the adoption of strategies to enhance climate resilience.

Our findings regarding the role of farm size and training, suggest specific targeting of extension and training programmes to reach particular segments of producers will be critical to enhancing the climate resilience of the smallest scale farmers. This supports the findings of Williams et al. (2020) that programmes should strive to reduce the inequitable distribution of benefits relating to resilience enhancement strategies. Beyond ensuring training is delivered to specific underserved segments of producers, our findings suggest that the specificity (to dealing with drought), in addition to the frequency, of that training is a key factor for resilience strategy adoption. This supports the work of Noltze et al. (2012) who found that specificity of training is critical in promoting adoption of production strategies by smallholder farmers. Therefore, we suggest whilst expanding agricultural extension to farmers is important in enhancing climate resilience it is not sufficient, and thus training should be highly tailored (e.g. water and soil management, intercrop selection, canopy management) for the climate challenges faced by producers if it is to promote climate resilience strategy adoption.

3.4.4 Land tenure and regionality

Our finding that farm ownership is a key factor in the adoption of resilience strategy by cocoa farmers provides further insight into the crucial, yet nuanced, role of land tenure in improving the livelihoods of smallholder farmers (Asaaga et al., 2020). Several indicators of the climate resilience strategy index require a long-term view to rationalise their adoption, for example fire belt construction and irrigation. To be able to take such a long-term view for a particular parcel of land requires certainty over future access (Antwi-Agyei et al., 2015). Across several other types of technological adoption, not directly linked to climate resilience, this factor has also been found to be critical (Lawin and Tamini, 2019; Zeng et al., 2018). Our findings add to this literature by highlighting that for the adoption of climate resilience strateies land tenure is also important. In the context of cocoa production in Ghana, there are complex land-tenure relations between farm owners and those that cultivate the land, in particular through the common share cropping systems "abunu" (1:1 share of crops between farmer and land owner) and "abusa" (2:1 share of crops between farmer and land owner) (Benneh, 1988). For both of these share cropping systems, we find farmers had lower levels of resilience strategy adoption compared to owner-cultivators. The ability to catalyse climate resilience transformation must therefore be taken into account in the ongoing development of land tenure policies related to cocoa landscapes.

In the context of our study, we see a large regional disparity in the proportion of farmers that own the land they are cultivating (Eastern Region has 40% ownership and Western Region has 85%). Beyond ownership, our results show that regional differences exert a strong influence on climate resilience strategy. This is a consequence of multiple factors, including climatic (rainfall), ecological (shade cover) and socio-economic (household size). These differences are shaped by the socioeconomic history of Ghana, with the expansion of the agricultural frontier from East to West in the 20th and 21st centuries. In Western Region, primary forest still remains and cocoa production takes place on the forest frontier, as opposed to in Eastern Region where the forest transition has long since taken place and cocoa production takes place in a rural-peri-urban-agricultural mosaic (Knudsen and Agergaard, 2015). These different contexts lead to, for example, differences in the availability of off-farm and on-farm employment and hence endow farmers with different capacities and incentives to adopt climate resilience strategy. Thus, our findings provide further support to calls for attempts to enhance the uptake of climate resilience strategy to adapt to sub-national contexts, so as to maximise their adoption and potential impact.

3.4.5 Bundling the right mixtures of measures and practices to encourage uptake and enhance resilience

We find that several indicators (measures and practices) of climate resilience strategy show strong correlations between them in their rate of adoption with other indicators, suggesting a facilitating, symbiotic or incremental role in the adoption of these strategy subcomponents. Examples of strong positive correlations between indicators include, water harvesting and responsive irrigation, as well as diversity of non-agricultural income and owning a bank account. This supports the hypothesis that for the transformation of livelihood strategies, bundles of multiple innovations or technologies may be required (Christopher B. Barrett et al., 2020). However, we also find negative correlations between certain resilience practices such as those farmers that adopt hybrid cocoa varieties having lower secondary vegetation area on their farms. Therefore, the right combinations of measures must be promoted in a way to minimise trade offs between their adoption and maximise their utility (Makate et al., 2019). Our results show this bundling approach, in terms of innovations, will be critical for the adoption of climate resilience strategies but also for the optimisation of their use.

3.4.6 Evaluation and limitations of resilience strategy index approach

Overall, our approach has enabled us to take stakeholder identified climate resilience strategy subcomponents and synthesise them into an index that allows us to compare strategy utilisation between different types of farmers and elicit factors that determine the adoptions of such strategies. This approach has allowed us to make comparisons across diverse agroecological, socioeconomic and institutional contexts, whilst still applying a standardised metric for comparison. There are, however, some constraints to this approach. In particular, the construction of the index is subject to two key limitations. Firstly, the choice of indicators to include in the resilience strategy index, is constrained by the existing knowledge and experience of the workshop participants. This, in some ways, is a "double-edged sword" as the index benefits from strong local experience and long familiarity of the climate related challenges faced in Ghana but it means that potential strategy elements that are currently not commonly adopted or currently utilised in this context are excluded from the index. This is, nevertheless, partly mitigated by the presence of cross-sectoral workshop participants, such as insurers, government and scientists, with familiarity of resilience strategies across a range of value chains. However, in the end, this may lead to an over-estimation of climate resilience strategy adoption, given the rate of utilisation of this subset of indicators is higher than if a wider set of indicators were used. The second key limitation of the index is in the choice of weighting between indicators. Here we took two approaches unequal weighting, via PCA, and equal weighting. This provides some robustness to our results (with the similar effect sizes found for 5 out of the 6 factors with both indices) but future studies could enhance this by including further weighting approaches, such as stakeholder rankings, as highlighted by Najera Catalan (2019).

In terms of explaining adoption of climate resilience enhancing strategies, our model, based on the six extracted factors, explained a modest 20% of the variation in the index. However, given that the dependent variable (RSI) synthesises 12 individual (but linked) strategic adoption decisions that are made in highly multifactorial socio-ecological systems, by diverse individuals, these insights remain valuable. Beyond this, our study focuses on on-farm strategies and does not consider the wider landscape in which these producers operate. Future research could also explore the interaction between farmer strategies at a landscape level, such as the cumulative role of fallow or agroforest areas regulating climate at a landscape scale.

3.5 Conclusion

In conclusion, we find that several diverse factors influence the uptake of climate resilience strategies by smallholder cocoa producers in Ghana. These factors are both modifiable, i.e., related to the integration of farmers into the cocoa and alternative crop value chains, their exposure to training and land tenure, as well as non-modifiable (or less easily modifiable), i.e., factors such as farm scale and regional context. These findings, therefore, suggest that interventions to enhance the adoption of climate resilience strategies of smallholder farmers should focus on both pathways to enhance adoption, particularly alternative crop domestic market development, improving farmgate cocoa prices, as well as focusing on improved targeting of interventions to ensure that the entire spectrum of farmers, particularly the smallest scale, benefit from such training and market interventions. In addition, this study points to the interactions between different subcomponents of a resilience strategy and how certain components act symbiotically to promote the adoption of others. These interactions should be considered carefully in the design of strategies to promote bundles of climate resilience enhancing innovations. Finally, this study emphasises the location-specific nature of resilience strategy adoption and the need to tailor interventions to regional and sub-regional contexts.

4.0

Racing to Recover: Smallholder Climate Resilience in a Global Food Value Chain

This chapter will be submitted to Nature Food as: Thompson, W. [1], Varma, V.[2]*, Joerin, J.[1,3], Bonilla-Duarte, S.[4], Bebber, D.[2], Blaser-Hart, W.[1,5], Kopainsky, B.[6], Spaeth, L.[1], Six, J.[1], Krütli, P.[1], Racing to Recover: Smallholder Climate Resilience in a Global Food Value Chain. *These authors are joint lead authors.*

Prologue: *This paper synthesises multiple activities of the banana GFVC case study relating to the hurricane shocks of 2017. A collaboration was established with the Bebber Lab at the University of Exeter, which allowed the scaling up of farm level findings to the regional and national context using remote sensing. These remote sensing aspects were led by Dr Varun Varma.*

Abstract

Extreme weather events have severe impacts on food systems, especially for vulnerable smallholders embedded in global food value chains (GFVCs). Combining remote sensing and household surveys, we investigate the impact of two consecutive hurricane events in 2017 on smallholders in the Dominican Republic, engaged in the banana GFVC, and determinants of their recovery. Hurricane damage affected 11.4% of banana production area. With little power to mitigate flooding, farmers experienced "all-or-nothing" damage, where 75% of flooded farmers experienced >90% production losses. Recovery of regional production took ca. 450 days. However, farm-level recovery-times were very variable, with increases in damage and drainage times slowing recovery, while farm-livelihood specialisation and training quickened recovery. Furthermore, engaging in a GFVC impeded recovery via the "double exposure" of production loss, followed by losing market access as result of traders switching sourcing. These findings suggest critical opportunities, including trader loyalty, basin-scale collaboration and recovery-focused training, to enhance smallholder resilience in the banana GFVC.

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4.1 Introduction

As the climate changes, smallholder farmers in tropical regions are increasingly vulnerable to extreme weather events, such as droughts, hurricanes and flooding (Cottrell et al., 2019; Dixon and Stringer, 2015a; Harvey et al., 2014), which can cause loss of income, food insecurity and exacerbate environmental pressures (Morton, 2007). These impacts on smallholder farmers are often transmitted to downstream food systems, causing, for example food price volatility and reducing food availability (Beer, 2018; Holden and Shiferaw, 2004). Hence, understanding how extreme weather events impact smallholder farmers, and what determines their recovery is crucial for building more resilient food systems.

Increasingly, many smallholder farmers are embedded in global food value chains (GFVCs), producing crops for export, including commodities (e.g. cocoa), fruit (e.g. bananas) and vegetables (e.g. beans) (Swinnen, 2007). GFVCs are international networks of actors that interact at the various stages (production, processing, distribution, retailing and consumption) of the food system (Ericksen, 2008). However, little is understood about how farmers engaged in GFVCs are affected by climate shocks and how the impact is influenced by their participation in a GFVC (Donatti et al., 2018). Farmers participating in GFVCs may enhance their resilience with easier access to insurance (Isakson, 2015), cooperative formation and price premiums (Sellare et al., 2020) but conversely, could lose from price exposure (Kaplinsky, 2004) and crop quality pressures (Handschuch et al., 2013). Participation in GFVCs has also been suggested to create a double exposure to both climate and global market shocks (Castellanos et al., 2013; Laube et al., 2012; O'Brien and Leichenko, 2000).

As awareness of the future risks that extreme weather events pose to smallholder farmers and our food system has grown, "climate resilience" has emerged as a theoretical, governance and management approach, to understand and reduce the impact of such shocks (Dixon and Stringer, 2015a; Tendall et al., 2015). In general, resilience is the ability of a system to maintain function, recover and (even) improve in the face of a shock (Folke, 2006; Holling, 1973a) (Figure 1).

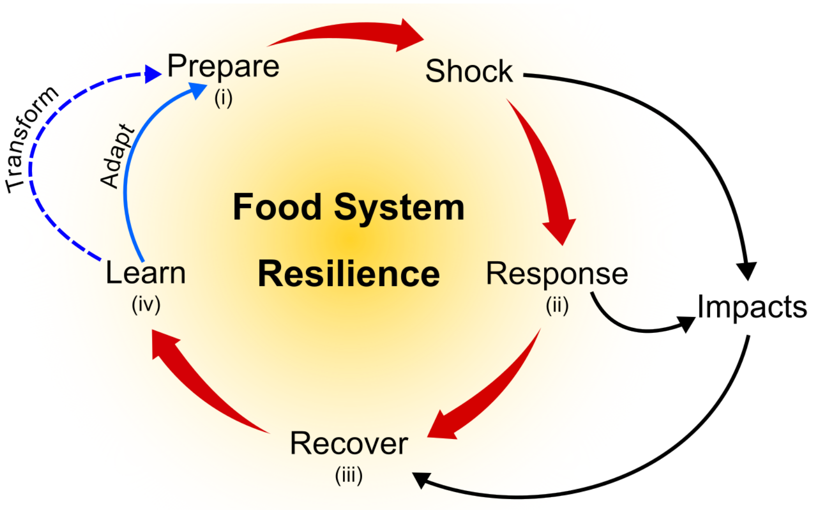


Figure 1 ***Food system resilience framework*** *For our study, we developed an action orientated framework, focused on four sequential stages undertaken by actors, reducing impacts by i) preparing for or ii) responding to a shock, iii) recovering from that shock and then iv) learning to improve future outcomes, by incrementally adapting or radically transforming the system.*

We focused on recovery, the process of restoring livelihood systems to a normal or new functional state post-shock (UNISDR, 2017). Recovery has been highlighted as critical in response to extreme weather events (Campbell and Beckford, 2009; Cottrell et al., 2019) because faster recoveries reduce the overall impact of shocks by restoring income generating assets and thus catalysing replenishment of non-productive assets (Carter et al., 2007). There has been limited research into the determinants of recovery for smallholder farmers from extreme weather events, with farm diversity and landscape topography suggested as potential factors (Alhassan, 2020; Philpott et al., 2008; Rosset et al., 2011). Understanding the determinants of recovery in smallholder agricultural settings is critical to designing appropriate climate resilience enhancing interventions.

In this study, we ask: What determines the resilience of smallholder farmers embedded in GFVCs to extreme weather events? We take the case of smallholder banana farmers engaged in the Dominican Republic–UK banana value chain that were exposed to flood damage caused by hurricanes Irma and Maria, which struck the Dominican Republic within a week of each other in September 2017. This case is globally relevant as the banana value chain typifies the challenges of smallholder GFVCs (Bebber, 2019; Castillo et al., 2000; Riisgaard and Hammer, 2011; Vagneron and Roquigny, 2011a; Varma and Bebber, 2019), and specifically because the Dominican Republic has a high dependence on agricultural exports, significant smallholder production (Vagneron and Roquigny, 2011a) and severe climate change exposure (Eckstein et al., 2019). Employing a transdisciplinary approach, involving multi-stakeholder workshops, focus groups, value-chain-actor interviews, farmer surveys and remote sensing, we address four specific research questions; i) How are smallholder farmers impacted by hurricane induced flooding? ii) What actions or strategies do the actors of this GFVC adopt to enhance their climate resilience? iii) How quickly did production recover? and iv) What determines recovery rates?

4.2 Results and Discussion

4.2.1 Diverse strategies by GFVC actors to reduce hurricane impact

In September 2017 Hurricane Irma, a category 5 hurricane on the Saffir-Simpson scale, passed the north west coast of the DR at a distance of 96 km. Windspeeds of up to 286 km h^{-1} and heavy rain caused severe damage to farms. The heavy rain led to severe flooding in the Yaque del Norte drainage basin, the key banana producing region. Just seven days later a second hurricane, Maria, also grazed the North West coast as a category 3, bringing further flooding (Blake, 2018). During workshops and interviews, 18 months after these events, DR-UK Banana value chain stakeholders, including smallholder farmers, importers, exporters and the DR government, reported taking a variety of actions in preparation for, response to and recovery from the hurricane induced flooding (Table 1). In terms of preparation, smallholder banana farmers reported having a limited range of actions to reduce the direct impact of the flooding on their farms, with reinforcing containing walls being of low efficacy. Importers and exporters took less direct action related to their activities and performed more co-ordinating actions in terms of preparation. This included avoiding purchasing from high-risk farmers and, but in contrast, also working with farmers to reduce flood risks by supporting the establishment of buffer zones near water sources. The Ministries of the Environment and Natural Resources reported taking two key actions in preparation for a hurricane in relation to the banana value chain: preparation of a disaster response plan and consequently damage limitation activities involving relocating people from vulnerable areas and dam venting. Responses following the start of flooding in September 2017 were enacted by these GFVC actors at multiple scales, including farm, watershed, nationally and internationally. Farmers reported taking key damage limitation actions including rescue operations for people and livestock as well as communicating loss of production to buyers. Importers and exporters took two key types of action “switching sourcing location” and “communication” to inform buyers. Government responses focussed on saving lives through rescue operations and provision of shelters.

The adoption of resilience enhancing strategies was relatively uniform across farmers that directly experienced flooding in 2017 versus those that did not (C1). These included crop diversification (mean number of crops farmed =2), intercropping (40% practicing), income diversification (41%), training in flood damage prevention (56%) and insurance (23%). Insurance was the only strategy for which there was a significant difference between flooded and non-flooded farmers, with 36% flooded farmers adopting versus 9% non-flooded (Chi-squared 21.217, $p<0.01$). However, insurance adoption of 36% amongst flooded farmers is still relatively low, with farmers citing cost and trust in the scheme as the main concerns. This compares with 63% of export banana farmers adopting weather insurance in the Windward Islands (Carballo and Reis, 2013).

***Table 1 Dominican Republic – UK banana value chain actor resilience actions** (preparation, response and recovery) in relation to hurricane induced flooding as reported by actors during participatory activities at a value chain stakeholder workshop.*

	Farmers	Importers and Exporters	Government
Preparation	Remove irrigation equipment from rivers	Identify suppliers from low-risk areas	Activating the early warning system
	Remove packaging material and inputs from warehouses	Work with farmers to reduce the risks (buffer zone, soils)	Emergency committee meeting
	Remove the animals	Focus on soil flooding, to prepare the crop to face and resist flooding	Emergency operational plan
	Remove people living in the dangerous zone	Supporting preventive measures on farms	Relocation of people from vulnerable areas
	Open the floodgates	Continuous monitoring of climatic conditions	Dam venting
	Reinforce the walls of containment	Contact various suppliers	
	Pre-cut the fruit so as not to lose exports	Request permission to buy in another country	
Response	Manipulate water and drain	Contact other suppliers	Attention to shelters
	Rescue operations for people and animals	Change date of harvest	Medical workers
	Speak to the government	Inform customers	Evaluation of damage
	Inform buyers		Rescue operation for personnel and animals
Recovery	Try to get the water out of the farm	Assess damage	Damage assessment and needs analysis
	Observe/evaluate damage – damage report	Contact other suppliers	Pest control
	Clean the farm	Support suppliers with recovery measures	Cleaning of drains and canals
	Funding management	Renegotiation with suppliers and buyers	Epidemiological alert
	Managing plant material		
	Repair infrastructure and access roads		
	Agricultural insurance notification		

4.2.2 "All-or-nothing" damage makes recovery key to resilience

Export banana production in the DR is concentrated in the regions of Valverde, Monte Cristi and, to a lesser extent, in Santiago (Supp. Mat. 2) and accounted for 21,561 ha of production area (Figure 2). The region is dominated by the drainage basin of the Yaque del Norte River that has suffered from severe deforestation over the past decades (Sambrook et al., 1999), affecting the hydrological regime, and exacerbating the scale of floods at time of heavy rain. Analyses of Synthetic Aperture Radar (SAR) imagery revealed that 2,447 ha, or 11.4% of banana production area in the three regions were affected by hurricane related damage, and largely concentrated around the Yaque del Norte river (Figure 2.). This estimate includes damage caused by open-water flooding in the immediate aftermath of the hurricanes, as well as more protracted storm damage over a period of three months since the hurricanes. In our survey of 158 banana farmers, 80 (51%) reported being directly impacted by the hurricanes (Figure 3a). Of these flooded farmers, 75% (60 farmers reported 90% of their production area flooded. This suggests an 'all-or-nothing' nature of storm damage, i.e. when farms are affected, damage is complete and catastrophic. This stands in stark contrast to the more incremental impacts of other extreme weather events, such as droughts (Harvey et al., 2018b). Additionally, with the initial direct physical impacts of flooding being largely unpreventable by smallholders and individuals, recovery becomes the key phase in which farmer actions could differentiate their outcomes.

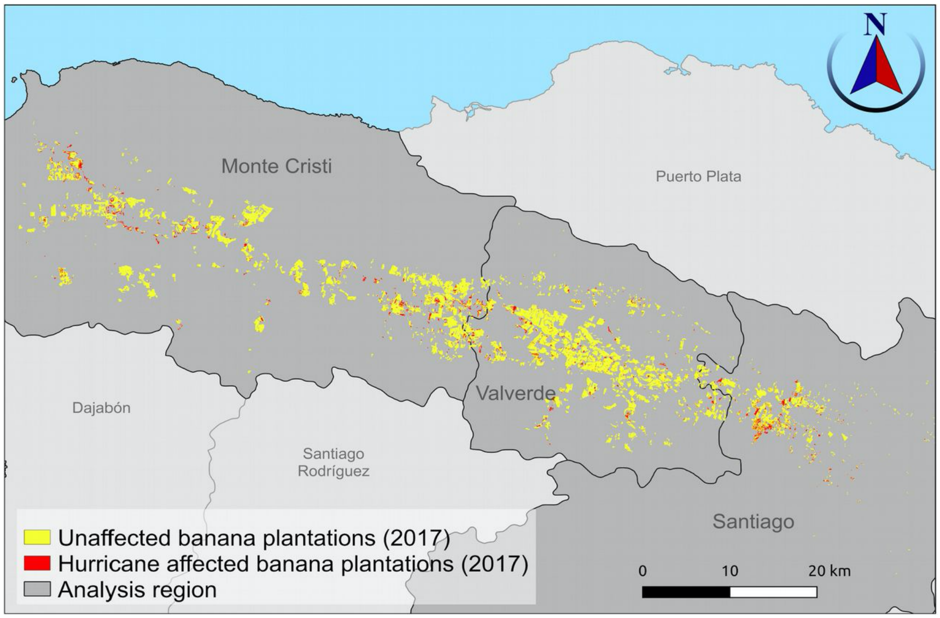
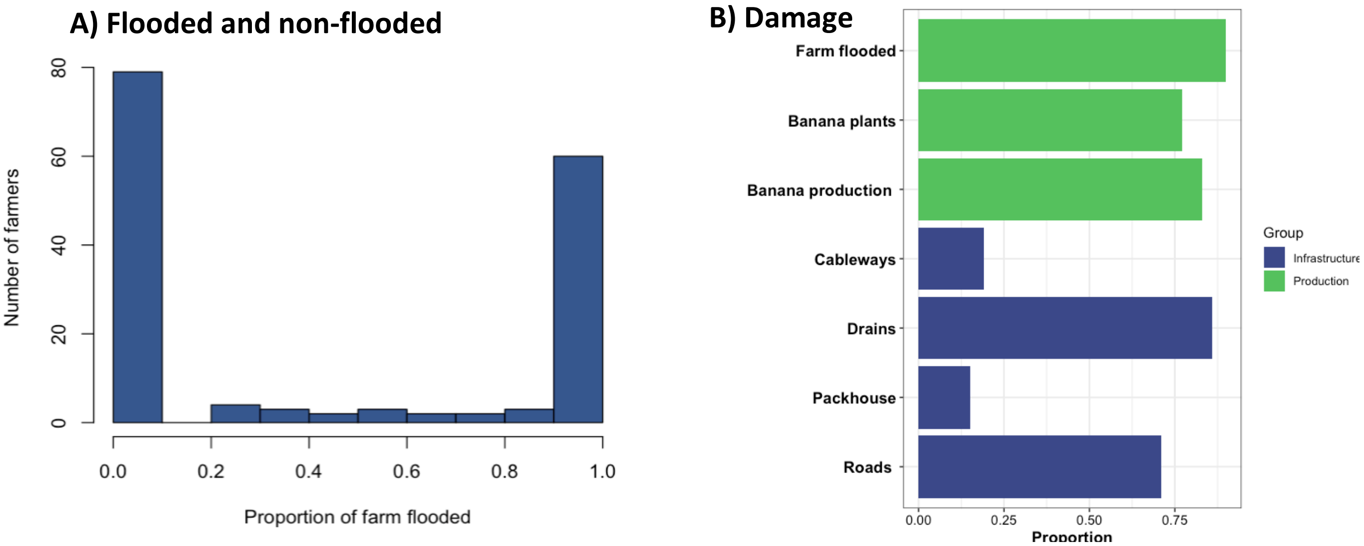


Figure 2 Map identifying locations in the study region where banana farms in 2017 were affected by flooding *induced by hurricanes Maria and Irma (September 2017). On overlaying the hurricane damage and banana farms maps for 2017 (Figure 4), we estimate 2,447 ha of farms were likely to have experienced damage. This accounts for 11.4% of area under cultivation before the hurricanes struck the Dominican Republic.*

The flood waters (Figure 3c) caused the destruction of fruit that was already growing on the plants. For surveyed flooded farmers, on average 83% of ongoing production was destroyed. The majority (77%) of banana plants in flooded areas were destroyed during the inundation with water and subsequent submersion period. Observations from surveys are also reflected in our regional-scale remote sensing analyses, where the canopy signature of flooded banana plantation pixels showed a sharp deviation away from values for non-flooded banana plantation pixels immediately after the hurricanes (Figure 4a), indicating a rapid change in the canopy structure of flooded plantations. Based on the productive farm index (PFI) – a surrogate for the proportion of productive banana plantation pixels – we observed losses of production area continuing till mid-December 2017 (Figure 4b) before any signs of production capacity recovery were detectable. This suggests that the true extent of production area loss is not immediately apparent after the initial hurricane shock, but, accumulated up to three months after the event. Beyond the damage to banana plants there was also significant infrastructure damage, with 18% of farmers experiencing cable ways being destroyed, 15% with packhouse damage, 68% with drainage canals destroyed and 71% having roads on their farms destroyed (Figure 3b). This damage beyond crop losses demonstrates an increased vulnerability to an extreme weather event as a result of making investments to enable access to GFVCs, such as for packhouses that meet retailer standards.


A) Flooded and non-flooded

B) Damage


C) Flood waters in 2017

D) Damage to banana plants

Figure 3 Flooding impacts to banana farmers *A) Histogram of the fraction of the banana farm flooded after Hurricane Maria in September 2017. B) Fraction of flooded farmers experiencing different types of damage (infrastructure is proportion of farmers reporting incident, production is mean proportion of land of production destroyed. C) Extent of flood waters on banana farm in Valverde province 2017. D) Damage to banana plants after flood water receded.*

4.2.3 Recovery time is highly variable between farmers

After flooding, there are a key set of activities that farmers reported performing to return banana production to full capacity (C2). These are moderated by natural processes after the flood event, such as the drainage of flood waters and soil aeration. Following this, the farmers and labourers cultivated the field using traction, prepared drains and paths and planted seed material. After the replanting phase, there was a nine-month growth phase before fruits were harvestable and saleable. Importers' and exporters' recovery process involved assessing losses from existing contracted farmers and then switching their sourcing to other locations not hit by the hurricane within the DR, as well as abroad. Coordination with other suppliers to fill gaps in order fulfilment was also performed by importers and exporters. The government response involved repairing damage to major infrastructure, as well as the provision of financial support to farmers and the purchasing of fruit from farmers that have lost market access.

At the household scale, we found a large variation in recovery times between farmers (Figure 5). Recovery times, reported by farmers and considered from an agricultural perspective (marketing aspects are covered in section 2.4, below), covering the time between fields draining and completion of replanting, ranged from two weeks to more than 11 months (min. = 14 days, max. = 343 days, mean = 99 days), with the difference between the slowest quartile and fastest quartile recovery being 91 days. This has large consequences in terms of production, cash flow and income but also shows there is an opportunity to level up these differences between farmers. This speed of recovery becomes increasingly important when shocks are of a high frequency and there is limited time to replenish assets that are critical as coping mechanisms to future shocks.

While farmer surveys capture recovery in terms of the time required to prepare and then replant farms, remote sensing analyses gave us a clearer picture with respect to time to recovery of regional productive capacity. Based on banana canopy backscatter values from SAR data, and using lenient criteria to define recovery, we observed that production recovery completed, at the earliest, by June 2018 (Figure 4a). However, canopy signatures of flooded plantations began tracking that of non-flooded plantations more closely only by late September 2018 – approximately 380 days after the first hurricane (Figure 4a). Applying more stringent criteria using the PFI, we estimate that productive capacity returned to pre-hurricane levels by the beginning of December 2018, approximately 450 days after the first hurricane (Figure 4b). Hence, DR's banana production system is likely to have seen below capacity production for a period of 15 months due to hurricanes Irma and Maria.

The dynamics of the recovery process were significantly affected by delays (Figure 5a), the time between when farmers judged fields were ready to cultivate and when they were effectively able to start. Fifty-three percent of farmers that were flooded (42 farmers) experienced delays in replanting. These delays vary between 1 and 36 weeks, with a mean delay of 5 weeks. For farmers that experience delays, it on average increased the overall recovery time by 96% and therefore significantly inhibited the recovery process. Farmers reported this equating to continued reduction in cashflow and income. At a cooperative level this delay exacerbated market access challenges, while at a national level thousands of tonnes of export production were lost during the recovery period. These significant consequences to farmer livelihoods by slow recovery rates from hurricane events are also supported by Rakotobe et al. (2016) with regards to slow recovery affecting food security outcomes and by Perfecto et al. (2019) with regards to slow recovery reducing farm productivity.

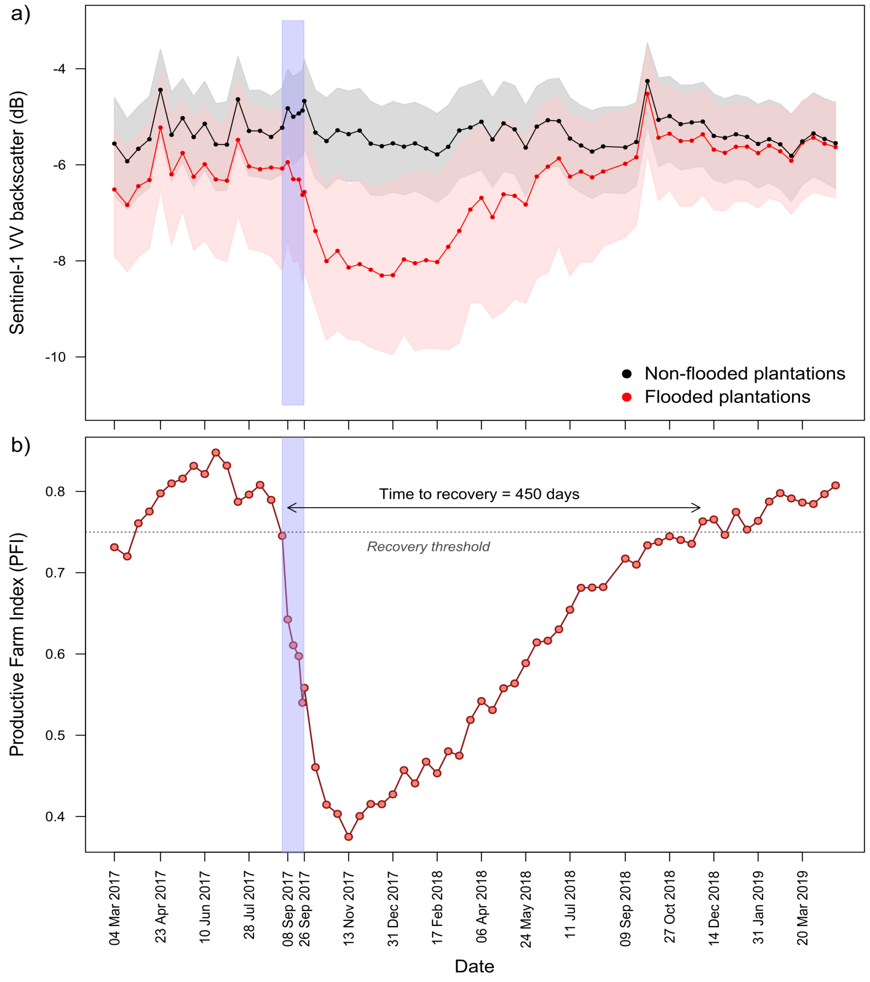


Figure 4. Impact and recovery assessment of banana production systems in the Dominican Republic using remote sensing. *(a) A timeline of banana plantation canopy structure as indexed by the Sentinel-1 VV polarisation band. The solid lines represent median VV backscatter values for flooded and non-flooded banana plantation pixels sampled in the study area. Shaded areas around the solid lines represent the bounds of the* 1^{st} *and* 3^{rd} *quartile. The*

blue shaded area indicates the date range when hurricanes Irma and Maria struck the Dominican Republic. (b) A timeline of the Productive Farm Index (PFI) for banana plantations from March 2017 to April 2019 in the study region. The blue shaded area indicates the date range when hurricanes Irma and Maria struck the Dominican Republic. The PFI represents the fraction of sampled banana pixels that were affected by hurricane damage with a Sentinel-1 VV polarisation backscatter value greater than, or equal to the 1st *quartile of backscatter values from unaffected banana plantation pixels. Recovery from the hurricanes is assumed to be completed when the PFI value is 0.75 or above. This method estimates production in hurricane affected pixels reached pre-hurricane capacity approximately 450 days after the hurricane events.*

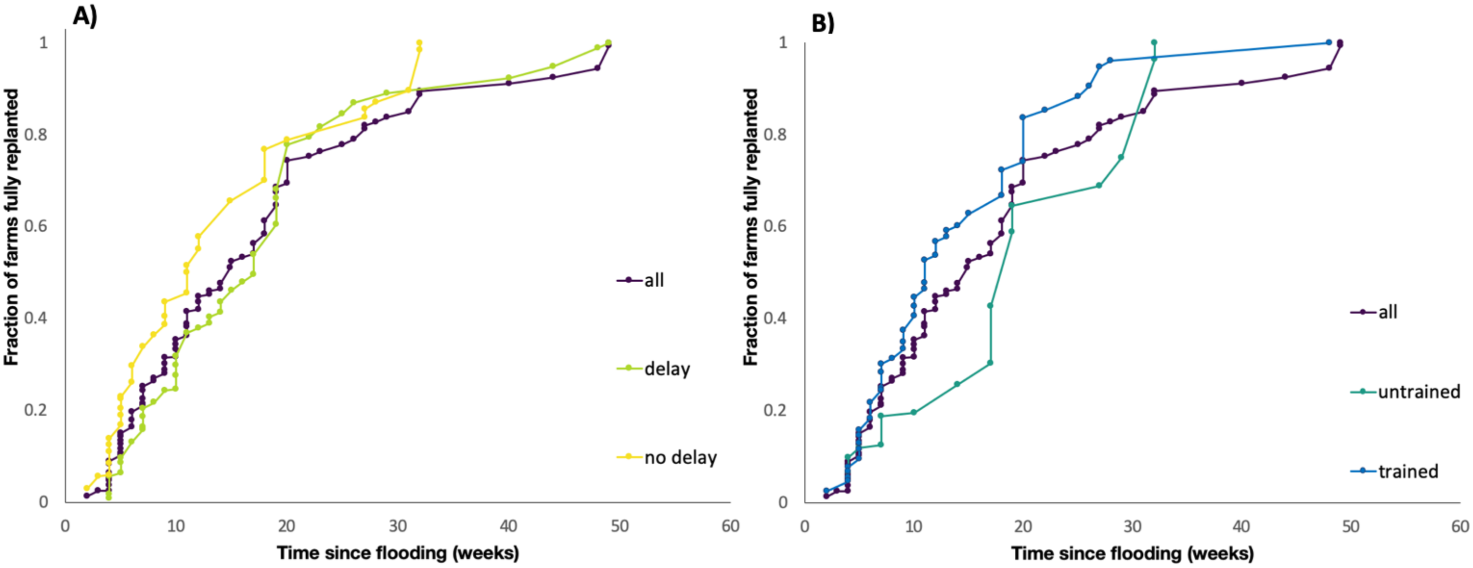


Figure 5 Agricultural recovery trajectories of flooded banana farmers *(n=80) based on recall of key events in 2017 and 2018 after hurricane induced flooding. A) Farmers with delays to starting versus farmers without. B) Farmers with flood recovery training versus farmers without. The x axis represents time since inundation in weeks and the y axis represents the cumulative fraction of the banana production area that is planted. Each point represents the completion of replanting for one farmer in the sample.*

4.2.4 Multiple factors cause heterogeneity in hurricane recovery

Recovery, both agronomically and from a market perspective, from the impacts of the flooding varied between farmers as a result of multiple diverse factors. Cooperatives and farmers cited flood water drainage, availability of finance to purchase materials and labour for cultivation and replanting, as well as the availability of planting material as major constraints to recovery. Farmers were supported in several ways, including by the cooperatives, who reported having to take out bank loans using their offices as collateral. This supports the claim that cooperatives can play a key role in enhancing smallholder farmers livelihoods (Bacon et al., 2014), in this case via contributions to climate resilience. However, cooperatives suggested that such a strategy would not be feasible should another significant shock occur in the near future.

Our analyses found four factors that influence smallholder recovery times (Figure 6. , C4). Scale of flooding (based on: Flooded area, Replanted area, Total banana farm size, beta = 0.262, $t = 2.12$, $p < 0.05$), farm and livelihood diversity (Agricultural crop diversity, Non-agricultural income diversity, Banana income dependency, beta= 0.240, $t = 2.21$; $p < 0.05$) and drainage time (beta= 0.298, $t = 2.99$; $p < 0.01$) all had a negative effect on recovery time, i.e. slowed recovery. In contrast, farmer flood training (Flood protection training, Flood recovery training, beta = -0.256, $t = -2.65$; $p < 0.01$, Figure 5b) made recovery quicker. The direction of effects of these factors on recovery time was as expected (C3), except for "Farm and livelihood diversity" (higher diversity increased recovery time). Previous research has suggested that increased diversity enhances farmer's resilience to climate shocks (Abson et al., 2013; Aguilar-Støen et al., 2009; Melvani et al., 2020). However, in the case of smallholder recovery from hurricane induced flooding in the DR, our findings suggest that increased specialisation, low income diversity and low crop diversity, reduces recovery time. In follow up interviews and focus groups, farmers explained their key motivation to diversify was to meet certification requirements and that income was limited from secondary crops. This highlighted the challenge of having "useful" diversity that can provide additional benefits to a livelihood strategy, such as additional income or nutrition. We suggest that whilst diversification is encouraged and to some extents implemented (e.g. intercrops and boundary crops), often this diversity does not modify the farmer's resilience as they do not provide significant alternative income.

Topographical elements that drive flood risk exposure, captured by factors "scale of damage" and "drainage", highlight how important risk-based spatial planning is in land-use-decision-making in flood prone areas. Highlighting that production sites that are both flood prone and difficult to drain should be avoided when possible. This supports Philpott et al.'s (2008) findings that topographical factors dominate agricultural management factors in terms of their effect on hurricane damage. The scale of damage is often out of the control of the farmer but the site choice for banana production can be better informed if flood risk and drainage potential are taken into account, from both a damage and recovery perspective.

Training farmers in specific flood damage prevention and flood recovery strategies is shown to be influential in reducing their recovery time. This highlights a key mechanism that has been used widely to improve farmer agronomic strategies but not widely within resilience enhancement strategies (Stewart et al., 2015). Given that risk exposure is clearly identifiable based on distance to river and previous hurricane events, expanding training to all farmers in "risk zones" would enhance both individual recovery outcomes but also regional scale economic responses post-event.

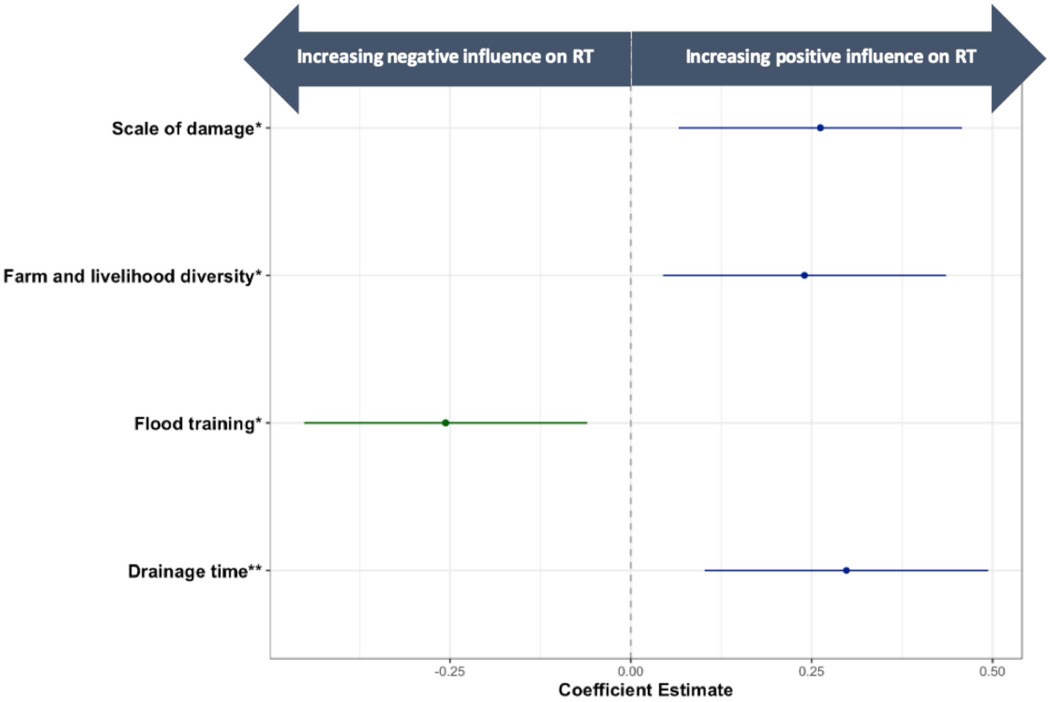


Figure 6 Key factors affecting smallholder recovery time (RT) post-hurricane induced flooding. *This presents the coefficient estimates from the multiple linear regression where the response variable is recovery time. The dot shows the value of the coefficient and the whiskers span the 95% confidence interval. Variables with negative coefficients speed up recovery, while those with positive values slow down recovery. The model explained 24% of the variation in recovery time (p<0.0001)*

4.2.5 Market responses also determine farmer recovery

Recovery is determined by both farmers replanting their crop, and the ability to sell their produce. This in turn is influenced by responses of the downstream value chain. Interviewed importers reported switching sourcing to other countries, e.g. Mexico – an emerging region for organic banana production – in the aftermath of the hurricanes. Consequently, 43% of interviewed farmers in the Dominican Republic reported, market inaccessibility in the following year, which impacted both flooded (40%) and non-flooded (45%) farmers. However, on average, flooded farmers saw greater reductions in the proportion of production sold to the export market (30%) compared to non-flooded farmers (21%).These findings show that farmers in a global food value chain experiencing a flood shock face a double exposure, with weather-driven production losses and simultaneously market access loss. This provides evidence to support the notion that climate change and globalisation will act together to disrupt vulnerable populations (O'Brien and Leichenko, 2000). This market exposure increases the scope of those that are impacted by the shock to non-flooded farmers. Even though 95% of sampled farmers are Fairtrade certified, market responses after a production shock are not fully covered by the scope of existing Fairtrade farmer-buyer agreements and results in buyers abandoning farmers at their most vulnerable moment. This provides further evidence for the need for longer-term relationships between farmers and buyers (Ola and Menapace, 2020).

4.3 Conclusion

Here, we have shown that the impacts of hurricanes Irma and Maria on the banana production system in the Dominican Republic were substantial and immediate. However, the process of recovering to pre-hurricane production capacity was protracted, taking up to 15 months, with consequences for farmers' cashflow, overall income and national exports. The smallholder farmers had very limited power to mitigate hurricane induced flood damage. Consequently, the shock had an "all-or-nothing" nature. Therefore, recovery becomes a critical phase in determining the system's resilience. Our analyses show that increased farm and livelihood specialisation as well as flood training quickened recovery and that increased scale of flood damage and drainage time slowed recovery. Beyond this, by engaging in a GFVC, farm recovery was impacted by a "double exposure" from production and market loss; the latter affecting both flooded and non-flooded farmers alike.

These findings have several implications for future research and the design of supply chain initiatives to support smallholder farmers. Firstly, given the "all or nothing" nature of flood shock experiences, to enable smallholders to reduce their exposure to such hazards, collaborations between farmers and or co-operatives at a drainage basin scale should be facilitated. Stakeholders highlighted potential approaches including; landscape management to increase forestation in drainage basins, as well participatory planning with government, water boards and farmers to optimise zoning of agricultural land and the location of flood defences. Secondly, recovery training should be refined and expanded to more farmers. Thirdly, mechanisms should be designed that allow farmers engaged in GFVCs to maintain market access after production shocks, so as to avoid a "double exposure". Overall, this study demonstrates the high interdependence of actors in smallholder GFVCs with regards to resilience to extreme weather events and that collaborations should be enhanced to protect against the negative impacts of such events.

4.4 Methods

To answer the research questions we adopted an overall transdisciplinary approach with three stages presented here: i) co-defining climate risks through semi-structured interviews and focus groups ii) hurricane shock characterisation for the banana value chain and system mapping through a value chain stakeholder workshop iii) resilience assessment through a survey of smallholder banana farmers and analysed with factor and regression analysis iv) remote sensing of regional flood damage and recovery patterns.

4.4.1 Co-defining climate challenges in the banana value chain

Whilst climate modelling has shown that there is an increasing risk of drought in the Dominican Republic (DR) (Spinoni et al., 2020) and also an increasing risk of high intensity hurricanes (Biasutti et al., 2012), it was important to collaboratively define the specific challenges that the stakeholders in the banana value chain face when these events strike. The purpose of this was to allow the value chain actors to guide the key focus of the study, thereby making it more relevant to their needs and avoiding preconceived conceptions of how a resilience approach could benefit them. Transdisciplinary research involves the co-defining of problems and co-generation of knowledge between scientists and stakeholders (Lang et al., 2012; Pohl et al., 2017; Pohl and Hirsch Hadorn, 2007). To do this we convened a platform of stakeholders, that are key actors in the DR-UK banana value chain, that would participate in the various research activities of the study. This included the DR government (Ministry of Environment and Natural Resources), regional water boards, NGOs, certifiers, farmers, exporters, importers, farmer cooperatives, academia and a UK retailer. These actors were chosen as they experience the challenges of climate risk in the banana value chain but also because they have the power to enact resilience enhancing strategies.

To identify the full contingent of stakeholders for the study and climate related challenges in the value chain, we organised a series of semi-structured interviews with actors from the banana value chain, including retailers (n=1), importers (n=2), exporters (n=2) and banana farmer organisations (n = 4). Following this, we also arranged as series of focus groups with banana farmers in the DR (5 groups of between 5 and 8 farmers) to understand how climate shocks affect their livelihoods and to decide which aspects would become the focus of the study. Through this process with the stakeholders, hurricane induced flooding was identified as a major threat to the banana value chain to investigate, the knowledge gained from this process also informed the questionnaire for the resilience assessment.

4.4.2 Hurricane shock characterisation for the banana value chain

In February 2019, we held a workshop with the identified stakeholders of the banana value chain in Mao, DR. The workshop had two key aims i) to characterise the systemic structure of the banana value chain to understand how shocks are transmitted and feedback within the system and ii) to characterise the actions that actors take to enhance their resilience to such shocks. To jointly characterise the systemic structure of the banana value chain, we conducted a group system dynamic model building exercise, with each of the actors identifying key variables in their systems and connecting the variables that influence each other (Luna-Reyes et al., 2006). To understand the options available to different actors to enhance their resilience to flood shocks, we introduced the resilience framework that we developed based on Tendall et al. (2015) (Figure 1). In activity specific groups, (farmers, banana exporters (DR) and banana importers (International), government) value chain actors were asked to describe what options are available to them in terms of preparation, response and recovery to a flood shock. This information also served as the basis for designing the resilience assessment questionnaire.

4.4.3 Resilience assessment

4.4.3.1 Questionnaire

To understand how farmers are impacted by the hurricane induced flooding, how they recover from this shock, as well as what factors enhance or disrupt these processes we conducted a survey of smallholder banana farmers in February and March 2019, using a resilience assessment questionnaire based on the workshop outcomes and refined in focus groups with banana farmers, cooperatives and scientists. The digitised resilience assessment questionnaire contained six sections including: household, agronomy, marketing, preparation, impacts, response and recovery. Recovery was based on farmers recall of events the previous season. We focussed in particular on the dynamics of recovery time, using farmer recall of the period post inundation in 2017. We assessed: field drainage time post flood, time until ready to replant, delay in replanting and time until fully replanted. The survey data was supplemented with value chain data on prices and volumes, collected from exporters and importers as well as the DR government. Semi-structured follow up interviews with farmers were conducted in January 2020 to validate the results of the analysis (n=12).

4.4.3.2 Study site

The DR is the Caribbean's largest banana exporter (FAOSTAT, 2021) and the world's largest organic banana exporter (Willer and Lernoud, 2019). In addition, the DR faces several severe climate threats, including reoccurring droughts and tropical cyclones that cause significant damage through: heavy rainfall, flooding, strong winds, as well as sea surges (IISD, 2013).

Export banana production in the DR is concentrated in the North West Line regions of Valverde and Monte Cristi (C5). The provinces are dominated by the drainage basin of the Yaque del Norte River which runs through the Cibao valley. The river's flood plains are a key agricultural area for the DR. The river provides water for irrigation for key export crops, including rice and banana. The drainage basin has suffered from severe deforestation over the past decades (Sambrook et al., 1999). This has affected the hydrological regime, further exacerbating the scale of floods at time of heavy rain and reducing water availability during times of drought (Brandimarte et al., 2009).

4.4.3.3 Sampling and sample

In the Yaque del Norte drainage basin we sampled the farmers from four farmer cooperatives that supply two major exporters in the region, making up 28% of DR banana exports (Vagneron and Roquigny, 2011b). To understand the impact of the shock, we preferentially sampled farmers with farms in proximity to rivers. We did this using GPS data shared by farmer cooperatives. Using a zone generated from a rivers layer on GIS software, we included farms within 1.5 km of a waterway to make up 60% of the sample (QGIS, 2021). Using the lists generated from this analysis of farmer cooperative data, we randomly sampled farmers from the list of farmers in the buffer zone and a list of farmers whose farms are outside the buffer zone (40%).

The sample consisted of 158 smallholder banana farmers engaged in the international export value chain (C6). According to their responses, farmers were subsequently categorised based on whether they were flooded or not flooded as a result of the 2017 hurricanes. The majority of farmers were male (89%) aged on average 50 years. The mean total farm area, including crops other than banana, was 6.0 ha and the mean banana farm area was 5.2 ha. The majority of farms were certified organic (78%) and almost all were Fairtrade (95%). 47% of the farms were triple certified with Rainforest Alliance certification in addition to Organic and Fairtrade. This reflects the high levels of certification nationally with 60% of exports certified (Vagneron and Roquigny, 2011b). On average farms had one type of intercrop and banana was the primary source of income, making up 61% of the household income on average. There were no significant differences in pre-existing socio-economic characteristics between farmers that were affected by flooding in 2017 and those that were not, with the exception that flooded farmers were situated significantly closer to the river (1.1km vs 2.2km, $p<0.01$).

4.4.4 Data analysis

4.4.4.1 Variable selection

To explain what influences the recovery time (Replanting time plus any delay experienced before this) of smallholder farmers after a hurricane shock has occurred, we analysed the data collected in the household survey using descriptive statistics, exploratory factor analysis and multiple linear regression. We identified potential explanatory variable, a priori, from the existing literature on smallholder resilience, focus groups with farmers and the workshop held with banana value chain stakeholders (C3).

4.4.4.2 Exploratory factor analysis

Using these variables, we conducted an exploratory factor analysis, following Fabrigar and Wegener (2011). First, to test issues with multiple collinearity in the explanatory variables, we conducted a correlation analysis using Pearson's correlation coefficient on the 80 flooded households. Variables related to recovery time (and its subcomponents delay and replanting time) were selected based on significant correlation coefficients. Bartlett's test of sphericity was conducted to determine whether factor analysis was suitable with regards to the relatedness of the variables. The Kaiser-Meyer Olkin (KMO) approach was used to determine sampling adequacy, based on common variance. Variables not meeting this criterion were discarded. Following this, an initial un-rotated principal component analysis (PCA) was conducted with these variables. The Kaiser criterion (>1) was used to determine the number of factors to extract based on the eigenvalues of the unrotated components. These components were thus extracted and their axis rotated using varimax technique. We then used multiple linear regression to assess the influence of these factors on recovery time. The analysis was carried out using the *psych* package with R statistical software (Revelle, 2017).

For the exploratory factor analysis, the correlation analysis revealed nine explanatory variables significantly correlated with recovery time (including subcomponents replanting time and delay time) from the 22 tested (C7). Income diversity was replaced by non-agricultural diversity (income diversity – ag. diversity) as its correlation with ag. diversity was above 0.9. These nine variables met the KMO measure of sampling adequacy to be included in the factor analysis (>= 0.5). The overall KMO with these nine variables was 0.58. A Bartlett's test of sphericity on these variables (Chi squared = 329.97, p<0.01) indicated that there was sufficient correlation between the variables to conduct factor analysis. The initial PCA generated four components with eigenvalues greater than one. Therefore, four components, explaining 79% of the variation, were extracted and rotated (C8).

4.4.4.3 Multiple regression analysis

These four components were explored as drivers of recovery time with multiple linear regression using the factor scores of the four derived components. The following model was therefore formulated using the PCA components:

$$Recovery\ time = \beta_0 + \beta_1 Scale\ of\ damage + \beta_2 Farm\ and\ livelihood\ diversity + \beta_3 Flood\ training + \beta_4 Drainage + \varepsilon$$

4.4.5 Remote sensing

See Appendix C9.

5.0

Findings, Limitations and Outlook

In this chapter, I synthesise the findings from the three previous chapters in the context of the overall objectives of this thesis (5.1). Following this, I evaluate the approach that was taken and its limitations (5.2). Finally, I suggest opportunities for future research identified from this study (5.3).

5.1 Research findings

There were three key objectives of this thesis for which the two case studies were conducted:

Objective 1: Co-define, with stakeholders, "climate resilience" of smallholder farmers in global food value chains.

Objective 2: Assess the climate resilience of smallholder farmers and its determinants in global food value chains.

Objective 3: Assess and explore different opportunities to enhance climate resilience of smallholders in global food value chains.

5.1.1 The nature of climate resilience strategies in smallholder driven GFVCs

The three chapters across the banana and cocoa case studies revealed a variety of insights relating to the nature of climate resilience strategies for smallholders in global food value chains (Objective 1).

Finding 1.1 ***Climate resilience strategies need to be generalisable across diverse threats whilst incorporating specificity versus key hazards***

The characteristics of the different shocks (hurricane induced flooding versus drought) and the value chain contexts gave insights into how generalised resilience strategies (resilience strategies versus multiple, diverse, even unforeseen shocks) will be critical to reducing the impacts of extreme weather events. Conversely, the cross-case comparison suggests, given that there are several predictable, reoccurring (and worsening) high impact hazards (e.g. drought and hurricane events), with highly particular resilience related idiosyncrasies, that incorporating specificity into a resilience strategy is also necessary. The finding that recovery is critical in terms of resilience to hurricane shocks emphasises this point, when contrasted with the critical roles of preparatory (e.g. hybrid varieties) and responsive (e.g. pruning) measures to the drought shock, experienced by Ghanaian cocoa farmers. This finding supports the role of integrating specialised and generalised resilience strategies, in reference to the ongoing debate that often frames them as opposing options (Anderies et al., 2010; Carpenter et al., 2001; Folke et al., 2010).

Finding 1.2 ***Farmer agency relating to resilience strategy utilisation is scale-limited***

Resilience is not just determined at the farm scale but at multiple scales beyond this (e.g. community, landscape, drainage basin, value chain). However, smallholder farmers' power to act beyond the farm scale is incredibly limited. In the banana case, this is clearly shown by the "all or nothing" scale of the flooding impacts on smallholder production from Hurricanes Irma and Maria. Here farm scale defences were largely ineffective against the hurricane induced flooding and damage limitation can only be implemented at a drainage basin scale (e.g. reforestation, dam modifications). In terms of drought shocks, impacts can be mediated at a farm scale but there are also actions that would benefit the farmers at a community scale (e.g. reduction of fire use in dry periods) and landscape scale **(**e.g. reforestation**).** In addition, local climate patterns continue to be impacted by local and regional scale deforestation outside the control of individual farmers (Lawrence and Vandecar, 2015). The ability to respond to this has been established in some instances via smallholder led landscape management boards in Juabeso Bia, Ghana, for example. This supports findings on the need for facilitating greater participation by smallholder farmers and other stakeholders in landscape scale governance (Ros-Tonen et al., 2015; Speelman et al., 2014). However, it remains unclear how successful these landscape governance interventions are at facilitating farmers to implement climate resilience strategies at this scale .

Finding 1.3 ***Resilience strategies are more than just the sum of their parts and therefore interactions must be considered in their design and promotion***

Resilience strategies are more than the sum of their subcomponents (measures, practices, sub-strategies). There are multiple, both beneficial and negative, interactions between these parts in terms of adoption, utilisation and resilience outcomes generated by them. In the cocoa case study, the subcomponents of a climate resilience strategy, that were co-defined with stakeholders, included several that are synergistic in terms of their use, such as pruning and crop diversification, as well as some that are antagonistic in their uptake, such as hybrid varieties and firebelts (farmers using hybrids were less likely to have firebelts). Additionally, I find that certain measures of the stakeholder co-defined resilience strategies are more likely to be adopted in pairs or bundles than others, such as water harvesting and irrigation. In the banana case study, I find that there are hierarchical interactions between elements that dominate resilience strategies implementation, with adaptability subcomponents, such as access to finance, moderating the use of other subcomponents, such as choice of available recovery strategies. This supports the assertion of Barrett et al (2020) that innovations will have to be consciously bundled to create positive transformation of the agri-food system. This finding has implications in terms of the prioritisation of measures to enhance resilience, suggesting that "keystone measures" (e.g. water harvesting or access to finance) that enable the utilisation or uptake of other measures should be prioritised.

Finding 1.4 ***Resilience strategies are not, by default, benevolent and important inter-actor trade-offs occur***

Both the banana and cocoa studies show, that it matters significantly whose perspective is taken in terms of the commonly asked, in the context of resilience assessment, question "resilience for whom?"**.** I find that actors working to maximise their own resilience often do so at the expense of other actors or the function of the value chain itself. By extension the resilience of the global value chain as a whole and its function is often antagonistic to the resilience of one regional or national subset (e.g. as a result of switching sourcing by banana importers). In both cocoa and banana value chains, I find that strategies taken by different actors often have negative trade-offs for other actors in the value chain, such as exporters choosing to work only with "flood safe" banana producers thereby reducing the resilience of "flood-risk" producers via decreased access to market. However, I also find evidence for co-operation and collaboration on issues of climate resilience. For example, banana exporters helping farmers they purchase from to create buffer zones between water sources and their farms to reduce flooding impacts and cocoa traders supporting the planting of shade trees on cocoa farms via seedling distribution. On balance, the scale of this assistance is relatively limited compared to the large impact of the importer strategy of switching sourcing to non-climate impacted countries after a shock has occurred. Sustainability initiatives would deliver greater benefits to farmers if they were able to enhance trader loyalty, particularly in the aftermath of shocks.

5.1.2 Determinants of resilience strategy utilisation

The two case studies elicited several factors that influence the adoption and utilisation of resilience enhancing strategies by smallholder farmers in GFVCs.

Finding 2.1 ***Access to markets for alternative agricultural products is key to developing climate resilient multifunctional agricultural systems***

The stakeholder co-defined vision for a climate resilience strategy in both banana and cocoa value chains focuses heavily on the multifunctional nature of an agricultural system (e.g. crop diversity). In particular, the potential for crop diversity to create redundancies in income streams and for this to allow modularity that enables post-shock recovery. In the cocoa case study, I find that access to diverse agricultural markets is critical to enabling producers to adopt such multifunctionality. In the banana case study, I find that the crop diversity that is currently included on farms does not benefit banana producers in their recovery from the hurricane shock. Farmers reported that this is because of a lack of markets for these secondary products. This leads me to suggest further development the concept of "useful" agricultural diversity and how to identify it (See *Box 1* in section *5.3.3*). I conclude that there is a necessity to enhance diversity on farms and that this can have resilience benefits, but this should not just be promoted for diversity's sake but for its functional benefit and that this will require related market interventions as well.

Finding 2.2 *Participating in GFVCs is a "double-edged sword" for smallholders' climate resilience*

The relationship between smallholder farmers and the global value chains they supply determines their resilience to extreme weather events. I find smallholder participation in GFVCs has a strong influence on their climate resilience, both positively via value chain integration (e.g. producer group membership, forward sales contracts, access to extension) and negatively via international market exposure (e.g. sourcing switching, persistent low prices). In the banana case study, I find that double exposure, losing export markets in addition to hurricane impacts, reduces a farmer's ability to recover from a climate shock. In addition, in the cocoa case study I find that "income generating capacity" significantly limits ability to adopt resilience enhancing strategies. This is influenced by the low cocoa price paid by upstream value chain actors (72% below a living income threshold based on author calculations of studied farms versus 328 USD per month for a family of 5 (Richard and Anker, 2020)). However, there are benefits of greater integration in a GFVC, including cocoa group memberships and increased access to climate relevant training, as well as (small) price premiums. Together the two studies show the importance of fair and "intelligent" trading arrangements between downstream value chain actors and farmers, if there is going to be a transition to a more climate resilient mode of production. This supports concerns, highlighted by O'Brien and Leichenko (2000), regarding the double exposure faced by smallholders, as well as adding to the existing literature on the benefits and drawbacks of farmer participation in GFVCs (Maertens and Swinnen, 2009; Swinnen, 2007), from a climate resilience perspective. These findings suggest that in the interests of smallholders, as well as the wider value chain and food systems, longer term more "climate-smart" (protecting producers in the event of shocks) relationships between suppliers and buyers should be established (Ola and Menapace, 2020).

Finding 2.3 The *sub-national regional context strongly moderates climate resilience strategy adoption and extreme weather shock-outcomes*

Smallholder climate resilience strategy adoption and outcomes after an extreme weather event are not just determined by their value chain interactions. I find strong regional differences in strategy adoption and shock impacts driven by both socio-economic and ecological context. For instance, in the cocoa case study, I find Eastern Region cocoa farmer livelihoods are characterised by the post-forest frontier agricultural mosaic, diversification, intermediate cocoa reliance, and more livestock, while Western Region livelihoods are shaped by the forest-frontier; high cocoa reliance, younger and larger farms. Our study allowed us to identify a link between these different livelihood structures and the resilience of producers to shocks. For example, livestock ownership providing more options in terms of recovery mechanisms (via sales), as well as greater natural capital (e.g. fallow land) providing more options in terms of adaptability. This shows that resilience is highly interconnected with the regional context, supporting findings from Shinbrot et al. (2019) and the importance of contextual factors in mediating intervention outcomes as highlighted by Garrett et al. (2021). These findings suggest the need for locally specified interventions to support the adoption of climate resilience strategies, furthermore, agro-climatic zoning for policy implementation (Bunn et al., 2019b) should be augmented with resilience linked socio-economic indicators.

5.1.3 Mechanisms to enhance the climate resilience of smallholders in GFVCs

This thesis evaluated existing mechanisms (principally sustainability certification in the cocoa case) to enhance the climate resilience of smallholder farmers participating in GFVCs, as well as identifying additional mechanisms. This gave insights into Objective 3 and identified opportunities to improve engagement with smallholders in GFVCs.

Finding 3.1 ***Certification has the potential to modify smallholder climate resilience but underperforms on the uptake of complex versus simple measures***

Our findings show that certification such as Organic, Rainforest Alliance, UTZ and Fairtrade has the potential to enhance the climate resilience of smallholders (via producer group memberships, climate specific training, price premiums, improved access to inputs). I find that in the cocoa case, certification is associated with enhancement of some aspects of robustness, (e.g. changes in agronomic practices) but does not lead to more substantive climate resilience enhancement (e.g. diversification of crop production and income) as proposed in the certification standards. In addition, in the banana case, despite farmers being certified by Fairtrade, there was limited protection from the double exposure of a market shock. However, there were benefits from strong producer co-operatives, supported via the Fairtrade premium, that funded producer recovery after the hurricane induced flooding. I suggest that broader contributions to improved resilience are limited by the commodity-focus of existing certifications. This commodity focus conflicts with imperatives to diversify farming systems to reduce vulnerability to climate and market shocks and the need to develop alternative crop markets to support this diversification.

Finding 3.2 ***Climate specific training enhances climate resilience strategy uptake but targeting is key to avoid smaller scale farmers being left behind***

Across the two case studies, training, in particular training specific to the demands of climate shocks, had a strong influence on the uptake of resilience enhancing strategies. I find that training was key to both the uptake of climate resilience strategies (in the case of cocoa) and to resilience related outcomes, such as recovery time (in the banana study). Training can be targeted to different types of farmers, for example, farmers with high hazard exposure (e.g. flood exposure near rivers) or smaller scale farmers that I find have lower levels of resilience strategy adoption. Training should take into account local specificity in terms of preferences for particular components of a resilience strategy and the varying utility of different measures in different places, as highlighted above. These findings find support in other contexts relating to training specificity and strategy adoption by smallholder farmers, such as with the System of Rice Intensification (Noltze et al., 2012).

Finding 3.3 ***Spatial planning at a landscape scale can enhance climate resilience***
Drought and hurricane shocks occur relatively regularly in the GFVCs and production regions I studied (Burn and Palmer 2015; Shanahan et al. 2009). In addition, these climate related shocks can, increasingly, be predicted spatially (e.g. rainfall patterns and flood areas). The two case studies highlight that this spatial information can be combined with other findings (e.g. benefit of training and insurance uptake) for planning purposes in terms of farm establishment, construction of buffer zones, as well as targeting of training and service provision. Our finding that after the 2017 hurricanes the replanted area of banana production in flood zones was higher than prior to the hurricane, increasing the risk exposure of farmers and the value chain, suggests remote sensing data could be a vital tool in such spatial planning efforts. In addition, only a fraction of farmers in flood risk areas had received flood relevant training or had taken out weather insurance**.** Together the two studies show that spatial planning in land use and service provision has the potential to enhance the resilience of smallholder farmers.

5.2 Limitations

My attempts to evaluate smallholder climate resilience in GFVCs; its nature, determinants and mechanisms to enhance it; had several limitations. These limitations were both; **(*i*) conceptual**, relating to **a)** smallholder driven value chains and **(b)** climate resilience, and **(*ii*) methodological**, relating to **(a)** co-producing knowledge with stakeholders, **(b**) measuring resilience of smallholders and **(c)** assessing the impacts of certification on climate resilience.

5.2.1 Conceptual limitations

5.2.1.1 Food systems, GFVCs, smallholder livelihoods

Smallholder driven GFVCs are complex systems that are nested entirely, and partially, within other complex systems, such as the global food system and national economies. Therefore, it was necessary to draw boundaries for the study from the start. This introduced the first set of boundary limitations. In both the cocoa and banana case studies the value chain (the vertical cascade of interacting actors from producer to consumer) was taken as the "unit' of study. As has been remarked upon previously in the literature (Gereffi, Humphrey, and Sturgeon, 2005), value chains are, in reality, more like networks, with multiple actors outside of the vertical chain interacting to support this vertical activity. In an attempt to capture the entire network of actors involved in the cocoa and banana systems, I also included actors not directly participating in the vertical chain of supply (e.g. government, NGOs, water boards, scientists etc). However, this did not fully capture the extent of the network of key actors, such as input companies, financial institutions, other local land users (e.g. agriculture, mining, forestry). This meant that interactions between cocoa and banana value chain actors and these secondary "network" actors were not fully considered in this study.

In addition, several actors in the studied value chains also act beyond the chain (i.e. cocoa or banana is not their only or even main activity). This was most significant for the smallholder producers and the retailers. For smallholder farmers, even highly specialised producers (mean 78% cocoa, 62% banana income dependency), they have other agricultural income sources, nutritional sources and non-agricultural incomes that make up their livelihood systems. While I attempted to include this as much as possible, by asking farmers about their other income generating activities, the depth of information that was collected about alternative crops or off-farm income sources was relatively shallow. Equally, for other keystone actors in the value chain, such as retailers, understanding their economic interests beyond cocoa and banana (and therefore their decision making related to this) was beyond the boundary of this thesis but nevertheless, likely, plays some role in their interactions with banana and cocoa producers. An example of this worth highlighting is the UK retail price wars that have led to certain key commodities, including bananas and milk, having their prices driven down to unsustainable levels (Moberg, 2005).

Another boundary limitation of this study is the temporal boundary that was chosen. Studies of climate resilience benefit from being able to investigate actual shocks that have occurred (clearly researchers would prefer these events never happened), in this case the 2015/2016 El Niño Drought in West Africa and the 2017 twin hurricane events of Irma and Maria in the Caribbean. However, I was restricted in terms of the time period of the study in which measurements could reasonably be made. In the Ghanaian case, interactions with cocoa value chain stakeholders begun in 2017 and the survey was conducted in 2018, one year and a half after the climatic drought period subsided. In the case of banana, interactions with value chain actors started in 2017 and the survey was conducted in 2019, also one and a half years after the hurricane shock. This had benefits such as familiarity with the relatively recent shock event and the ability to recall actions before it but did not allow time for complete manifestations of impacts to be felt. For example, Dercon (2004) shows that even 15 years after a severe drought shock in Ethiopia contractions in household consumption are still seen. In addition, this meant that in both cases baseline data on production and marketing was based on recall over several years.

5.2.1.2 Conceptualisation of resilience for food systems, value chains and smallholders

Beyond the cocoa and banana system boundaries, the conceptualisation of climate resilience in these contexts was also a limitation to the study. Multiple attempts have been made to conceptualise and operationalise resilience in food systems and their sub-components. This has led to diverse definitions in the literature (Meuwissen et al., 2019; Tendall et al., 2015). Several interlinked concepts are often presented under the umbrella of resilience (e.g. transformability and adaptability), with often overlapping concepts present. This makes measurement and communication complex, particularly beyond the scientific sphere to value chain stakeholders. To simplify this process, I attempted to develop a model of smallholder climate resilience that would be easy to communicate with farmers and stakeholders and allow for clear measurement of different subcomponents. This led to taking an "action orientated approach" to the conceptualisation of resilience and taking four key temporally consecutive time steps in the cycle of shock experience (before - preparing, during - response, after - recovery, and following this – learning (adaptability and transformability)).

The "action orientated framework" proved to be very useful for communication to stakeholders, who quickly grasped the overall concept and the four sub-components, as well as being able to relate this to their own experiences of climate shocks. However, operationalising the climate resilience concept in this way came with a loss of complexity in some respects, such as temporal separation of preparation, response and recovery, when in reality the activities to enhance outcomes of these phases may happen concurrently. In addition, there were limitations regarding aspects of livelihood strategies that do not fit cleanly into these temporal steps (e.g. in the cocoa case, ascribing cocoa group membership to the learning phase only).

Finally, regarding the conceptualisation of resilience, there were limitations in conceptualising more radical forms of learning (i.e. transformation versus adaptation). These aspects were difficult to co-define with stakeholders as the majority had not experienced system transformation or participated in the process actively. Given the multiple problems the current food system faces, it is clear that transformation is necessary at multiple scales. Indicators that can predict this or support this are hard to empirically test without prior transformations occurring and often remain in the theoretical domain.

5.2.2 Methodological limitations

Across the three chapters, I used multiple methods (Table 1) to approach the three research objectives and answer the specific research questions that were generated. Each of these individual approaches had their own limitations, here I focus on limitations of **i)** the overall transdisciplinary approach, **ii)** measuring resilience and resilience strategy adoption and **iii)** impact assessment of sustainability certification on smallholders' resilience.

Table 1 Methods utilised in the three chapters *(Yellow – overall approach, Green – data collection, Blue – analysis)*

Study	Td	Value chain interviews	Focus groups	Workshop	Household survey	On-farm biophysical data collection	Remote sensing	Value chain sales data	Coarsened Exact Matching	Factor analysis	Index Generation
Cocoa 1	✓	✓	✓	✓	✓	✓	✓		✓		
Cocoa 2	✓	✓	✓	✓	✓					✓	✓
Banana	✓	✓	✓	✓	✓		✓	✓		✓	✓

5.2.2.1 Transdisciplinary Research

Overall, I adopted a transdisciplinary research approach. The three phases i) problem framing, ii) knowledge co-generation, iii) effecting change (Lang et al., 2012) were utilised to varying extents in the two case studies of banana and cocoa (with phase iii – being only implemented to a very limited extent). In the cocoa case study, I focused on phases i) problem framing and ii) knowledge co-generation (with phase iii) being initiated as part of a masters thesis in which cocoa value chain stakeholders co-designed new financing pathways for agroforestry adoption). In the banana case study, it was possible to focus on the first two phases, with (phase iii) seeds of change being planted via specific recommendations to smallholder co-operatives, banana importers and the UK retailer. Adopting the transdisciplinary research approach was critical to delivering the objectives of this thesis, as it was stakeholder orientated and without the co-framing of problems or co-generation of knowledge, it would have been impossible to get the stakeholder buy-in to support the activities of the study. There were, however, several key limitations to the transdisciplinary approach, which I will discuss here.

One key challenge in using a transdisciplinary approach was the selection of actors to participate in the study process. This was biased, to some extent, by the initial partners that I was engaging with in each value chain (Ghanaian research institution and a UK retailer). This led to a "snowball" style selection of actors to participate in the transdisciplinary workshops. I moderated this by also selecting several additional value chain actors directly, not via the initial partners. For some of the actors that were recruited to the process via other value chain actors, this may have influenced the way that dependent upstream partners (e.g. farmers on coops and coops on exporters) acted or responded to interviews. This dependency reflects power dynamics which can be extremely unbalanced in GFVCs (particularly from a North -South perspective). To this end, I tried to create a "safe space" atmosphere, so that all actors were comfortable discussing their challenges.

Co-defining resilience challenges and strategies had a huge benefit to the project, as it allowed the least heard (smallholder) point of view to be adopted. However, given the lack of information (e.g. climate forecast information) on future production risks available to farmers, it impeded their ability to consider low frequency hazards that had not recently occurred. For example, banana farmers wanted to focus on hurricanes as a key hazard in the first interactions. In the following interaction, a few months later, a moderate-severe drought was ongoing, so this became the priority. Whilst I tried to mediate this by collecting data on both types of shocks, I perceived the present crisis to affect the relative importance that was, understandably, given to other aspects of the study.

5.2.2.2 Measuring resilience

Operationalising the resilience framework that I developed required multiple types of measurement. I had three types of measurement; these were **i)** measurement of resilience strategy adoption (measures and strategies, indicators of adaptability) **ii)** measurement of moderating outcomes (e.g. soil carbon and nitrogen) and **iii)** measurement of resilience linked outcomes (e.g. change in yield, recovery time, marketable sales).

In terms of measurement of resilience strategy adoption, in Chapter 2 I looked at individual climate resilience measures, sub-strategies and variation in the adoption of each of these subcomponents. This was effective as, for many sub-components, it was easy for a farmer to recall their use of a particular measure, giving a binary outcome (e.g. firebelt - yes or no?). For some indicators, I was able to assess the intensity of use, e.g. shade cover was measured on a subset of 70 plots using satellite remote sensing (percentage cover) and the amount of training received in the last year (count variable). Therefore, for these indicators, intensity was possible to assess, although the quality of the data varied with recall being less accurate than direct measurement. In addition, there were several variables that intensity-of-use would have been an interesting data point but I was unable to have a reasonably accurate way of assessing this, for example fertiliser use per hectare.

In terms of outcomes that I could measure relating to a farmers' climate resilience, I measured change in yield, recovery time, coping mechanisms and marketable sales. These were also a mixture of binary variables (e.g. use of coping mechanisms) and continuous (e.g. change in yield). There were also accuracy issues with these, for example recall of yield being increasingly unreliable for older seasons. I tried to mediate this through the use of government issue pass books. However, these types of record were not available for non-cocoa or banana production. This left gaps in terms of changes in secondary sources of income and productivity of other agricultural crops.

5.2.2.3 Impact assessment of sustainability certification on smallholders' resilience

One key limitation in measuring the impact of certification on smallholders' climate resilience was having to resort to the use of a quasi-experimental methodology, as opposed to a truly experimental approach. A key challenge in evaluating the impact of certification schemes on smallholder farmer outcomes, in general, is the non-random nature of farmer participation in such schemes. This therefore creates a selection bias in our sample, which can be due to both observed and non-observed characteristics. To overcome this there are several options; one approach is to conduct a randomised control trial (RCT) in which farmers are randomly assigned to a treatment (certification) groups or a control group (no-certification). However, such designs are difficult to implement and would require working with groups of farmers that have not had the opportunity to be certified previously, which is not possible in the Ghanaian context. An alternative method is to use an instrumental variable approach, where an instrument (variable) is utilised that is correlated with certification but has no direct effect on outcome variables of interest. I investigated the potential to use this approach however no valid instruments were identified. A third option is to use a matching approach. This involves matching certified sampled farmers to non-certified farmers using observable characteristics. Given the existing extent of certification and resources of the project a quasi-experimental design, using this matching approach, was the next best option (Barrett et al. 2012).

5.3 Research outlook

Throughout the process of conducting this study, the multiple perspectives shared and gained from conversations, field visits, meetings, interviews, analysis and evaluation of the findings, have led to the identification of some potential avenues for future research. I have classified these as **(*i*) conceptual** relating to smallholder food value chains and resilience, **(*iii*) methodological** relating to the assessment of resilience of smallholders and, finally, **(*iii*) topical** relating to climate resilience of smallholder agricultural systems in the tropics.

5.3.1 Conceptual studies

The following suggestions for conceptual studies related to the resilience of smallholders in GFVCs have been identified:

Conceptual Study 1: ***Conceptualising GFVCs as networks for resilience assessment***

Research related to global food value chains is often conducted with the "chain" concept front of mind. However, in reality these systems operate much more like an ecosystem of actors and therefore a network approach to their study would be more warranted. For example, looking at network configuration and network interactions and the impact of removals from the network, as in ecological science (E.g. Dunne et al. (2002) and as proposed for socio-ecological systems in general by Janssen (2006)). Therefore, in the context of GFVCs and climate resilience, network analysis could be conducted on particular food systems. For example, at a national scale for Dominican Republic to explore the effects of changing different resilience-linked outcomes (e.g. recovery time, sales lost) and how these relate to overall network function and persistence.

Conceptual Study 2: ***Exploring indicators of transformability in smallholder GFVCs***

In the resilience framework utilised in this study, the learning elements that relate to transformability remain largely untested. Using our resilience framework, I was able to co-define indicators of preparation and response (robustness), recovery and adaptability. It was harder, to find in the literature and from stakeholders, indicators of transformability of a system. A gap remains to identify indicators that show traits of smallholder systems that facilitate transformation. Therefore, a potential research question would be: What indicators describe the ability of smallholder agriculture systems to successfully transform to a more resilient state in the face of climate shocks and stressors? This could be achieved by seeking case studies where successful transformations have occurred and conducting surveys of farmers to see what common attributes helped this transformation (a prominent case would be Green Revolution rice production in Asia but finding heterogeneous levels of transformation would be key). This research would provide a building block to introduce more transformability indicators into future resilience assessments.

Conceptual Study 3: ***Defining generalised resilience strategies for smallholders***

In this thesis, I focused on climate shocks, however, given the findings on the importance of generalised resilience strategies, it would be beneficial to conduct further research with a more general resilience focus. However, it would be useful to still maintain some specific shock focus, so as to account for key risks**.** Therefore, key shocks as well as resilience attributes for unknown or unpredictable shocks could be assessed and the outcomes integrated to inform a generalised resilience strategy. A transdisciplinary approach could be conducted, with actors that have multi-shock experience. As in Chapter 3, empirical validation of the indicator framework could be performed versus key resilience outcomes.

5.3.2 Methodological approaches

In this thesis I utilised multiple methodologies to measure resilience attributes, strategies and outcomes for smallholder farmers. These experiences have led me to identify the following potential methodological approaches to studying climate resilience of smallholder farmers:

Methodological Approach 1: ***Network analysis of resilience strategies***

In order to understand the interactions in terms of adoption, utilisation and impact on producers resilience-linked outcomes, a network analysis of the components in farmers' agricultural and livelihood strategy could be conducted to understand further the key interactions (Figure 1). This would allow the identification of facilitating attributes or technologies that also drive the adoption of other climate resilience measures. In addition, this network analysis could identify and characterise trade-offs between particular sub-components of a resilience strategy. The configuration of "strategy and measure networks" is likely to be more revealing than comparing linear variables of adoption, such as fertiliser use intensity.

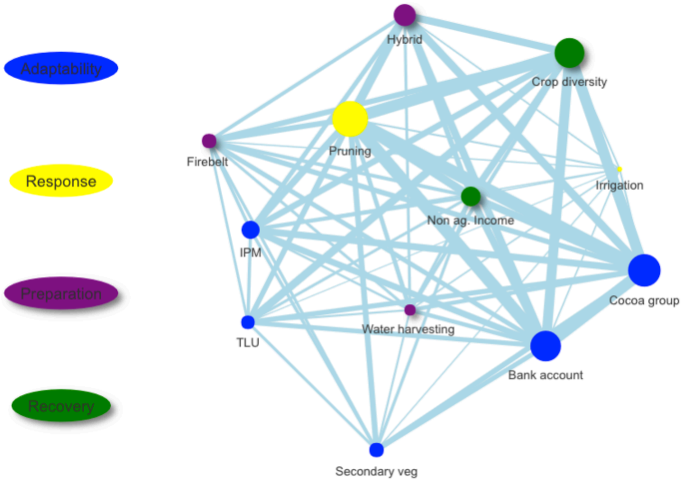


***Figure 1 Network representation of smallholder cocoa strategies**: The size of the node indicates the number of farmers adopting. The width of the blue lines connecting the nodes is proportional to the number of farmers adopting the measure at both nodes. The layout is driven by Fruchterman-Reingold algorithm, with related nodes closer together.*

Methodological Approach 2: ***Integrating satellite and big data with smallholder surveys.***

"Farming is undergoing a digital revolution" (Bronson and Knezevic, 2016). Sources of big data for agriculture and food systems are rapidly materialising, these include high resolution satellite data on weather and productivity. These data sets will allow the evaluation of the impact of shocks, such as drought, on selected outcomes in food systems and therefore identify channels in food systems that display higher levels of resilience relative to others. For example, shock outcomes can be observed at a high resolution across large areas using satellite remote sensing (as in the banana case study). Potential outcomes that can be observed include drought impacts on crop production, via NDVI or synthetic measures of crop health based on computer image interpretation. These outcomes can then be linked with smallholder household survey data to understand how management and value chain engagement influences production outcomes. This approach was piloted as part of this project with a masters thesis (led by Megan Morrow).

Methodological Approach 3: ***Using indexes to integrate multiple types of resilience strategy indicator***

Indexes using subcomponents co-defined by stakeholders can be powerful for spatially comparing resilience or resilience strategy adoption between different contexts (e.g. institutional or ecological). The indicators generated through this study could be collected across large areas when linked to large-scale surveying efforts, such as the agricultural census being conducted by the Ghanaian government. Mapping and spatial statistics can then be used to investigate sub-national patterns of index scores.

Methodological approach 4: ***Panel studies against the temporal boundary limitation***

Finally, from a methodological perspective, I suggest that resilience studies should increasingly adopt panel data approaches. As baseline resilience assessments become increasingly widespread, follow up studies at annual or larger intervals after climate shocks could assess outcomes over a greater temporal scale. This would allow the assessment of the long-term impacts for different farm scale strategies or interventions.

5.3.3 Topical studies

In terms of specific topics that arose that would make potential avenues for future research, I propose further investigation of **i)** specific attributes of a resilience strategy, **ii)** mechanisms to influence the uptake of resilience strategies at different scales, **iii)** the consequences of deficiencies in resilience at a farm, landscape and value chain scale **iv)** designing tools to support the enhancement of smallholder climate resilience.

5.3.3.1 Resilience strategy evaluation

Topical Study 1 ***Designing a new metric of "useful" on-farm diversity***

All three of the chapters making up this thesis identify the extent of on farm diversification, or specialisation, as critical to the climate resilience of smallholders. Diversity at a farm and livelihood scale is often dealt with in a crude way and I suggest that this can be improved by designing a more nuanced metric of diversity, e.g. extending Functional Agricultural Biodiversity (FAB, see Box 1) (Bianchi et al., 2013). To improve such a metric, a participatory approach could be used to co-define indicators and weightings could be validated against performance metrics, such as productivity, income or even resilience outcomes. Such a metric could be used to answer research questions regarding drivers of diversity adoption and also as a metric to plan farm or landscape scale modifications.

Box 1: Extending the Functional Agricultural Biodiversity (FAB) concept: Beyond diversity for diversity's sake, to useful diversity – adding a resilience perspective

- Diversity of crop types produced on a farm that play a role ecologically but also economically (and socially).
- These crops may provide redundancy in income generation during shocks to production of other crops in the system. This redundancy may be a result of shock-susceptibility differences or spatial or temporal redundancies (even recovery speed differences after a shock).
- In addition, these crops may provide shock-related functions by providing wind, flood or sun protection.
- There are also diversity benefits in non-shock contexts (e.g. smooth cash flow maintenance or pest management).

This enhanced FAB metric allows the assessment of functional diversity relative to what is already present on a farm (therefore it could be a useful planning metric) Example of potential sub-components of the metric:

1. Number of crop species
2. Number of crop species varietals
3. Ratio of species types – biodiversity metric
4. Income generated from each species
5. Temporal diversity in management, harvest, yield, income
6. Spatial diversity
7. Structural diversity
8. Key shock susceptibility
9. Market diversity (availability of local market, scale of local market)
10. Input diversity
11. Dependency ratio from each crop
12. Landscape presence (e.g. really rare =no info/inputs, common =disease risk)

5.3.3.2 Mechanisms to enhance resilience

Topical Study 2: ***Assessment of landscape scale interventions on smallholder climate resilience***

The studies conducted as part of this thesis focus on the household and farm scale in terms of climate resilience and interventions to enhance climate resilience. However, in both study contexts, it was highlighted (for banana in particular) that actions taken at a landscape scale have the potential to influence smallholder and value chain resilience. Therefore, the following research questions could be asked: What impact do jurisdictional approaches have on smallholder climate resilience? To answer these questions a quasi-experimental study design could be used (See Figure 2). Matching could be conducted at both a landscape scale and a household scale. This approach is proposed as part of the new Sustain-Cocoa project at ETH Zurich.

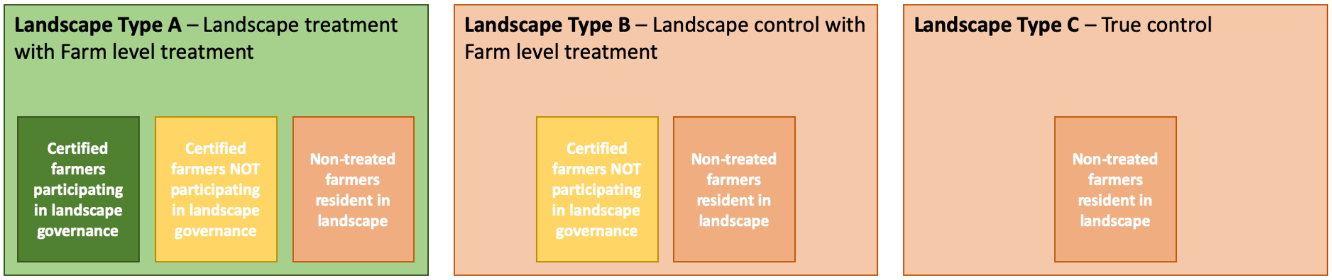


Figure 2 Quasi-experimental design to assess landscape intervention impact on smallholder resilience

5.3.3.3 Consequences of climate resilience deficits

Topical study 3: Climate resilience and deforestation

It has been suggested that commodity driven deforestation may be exacerbated by shocks to smallholder livelihood systems. Indeed, multiple farmers reported removing large shade trees from their farms as a source of extra income after the 2015-16 drought. To test the extent that a lack of climate resilience leads to exacerbation of smallholder-driven deforestation, I propose a study that integrates remote sensing and household surveys. Using existing remote sensing deforestation products, such as those from Global Forest Watch and more recent cocoa maps developed by the EcoVision Lab (ETH Zurich), a pixel by pixel (e.g. 1 km by 1 km) analysis could be conducted that evaluates the likelihood that a primary or secondary forest pixel adjacent to a pixel with cocoa present, that experiences severe drought (e.g. utilising the self-calibrating Palmer Drought Severity Index) undergoes deforestation and then cocoa production follows in a subsequent satellite image (likely several years after given tree growth time). This process could be automated over Ghana. Then areas that indicate a high density of cocoa-linked deforestation pixels could be targeted for household surveys to understand the context that leads to deforestation and the decision making that underpins this. This would add to the existing literature in terms of specific drivers of deforestation and also provide further specification to the societal costs of resilience deficits.

5.3.3.4 Designing solutions to enhance climate resilience

Topical Study 4: ***Designing decision making tools to guide climate resilience jurisdictional interventions***
Making decisions about how to guide the management of complex systems is inherently difficult, as changing one part of a system may have unintended consequences to other parts of the system. Decision support tools that capture the complexity of multifunctional agricultural systems can be used to evaluate what the best options are for farmers, landscape managers and governments (for example using goal programming (Gosling et al., 2020)) and will be critical to help improve decision making in relation to enhancing climate resilience. To test and design such tools, an overall transdisciplinary process with the multiple actors involved in a landscape intervention could be conducted, first to define their needs (and therefore criteria) in terms of decision making (e.g. resilience related needs), then to explore what interventions are available and then to refine and test modified versions of these interventions. An example would be a tool to assess the optimal configuration of agroforestry and reforestation interventions (e.g. types of agroforestry, patch enhancement, natural recovery, wind breaks) to enhance a landscape community's climate resilience.

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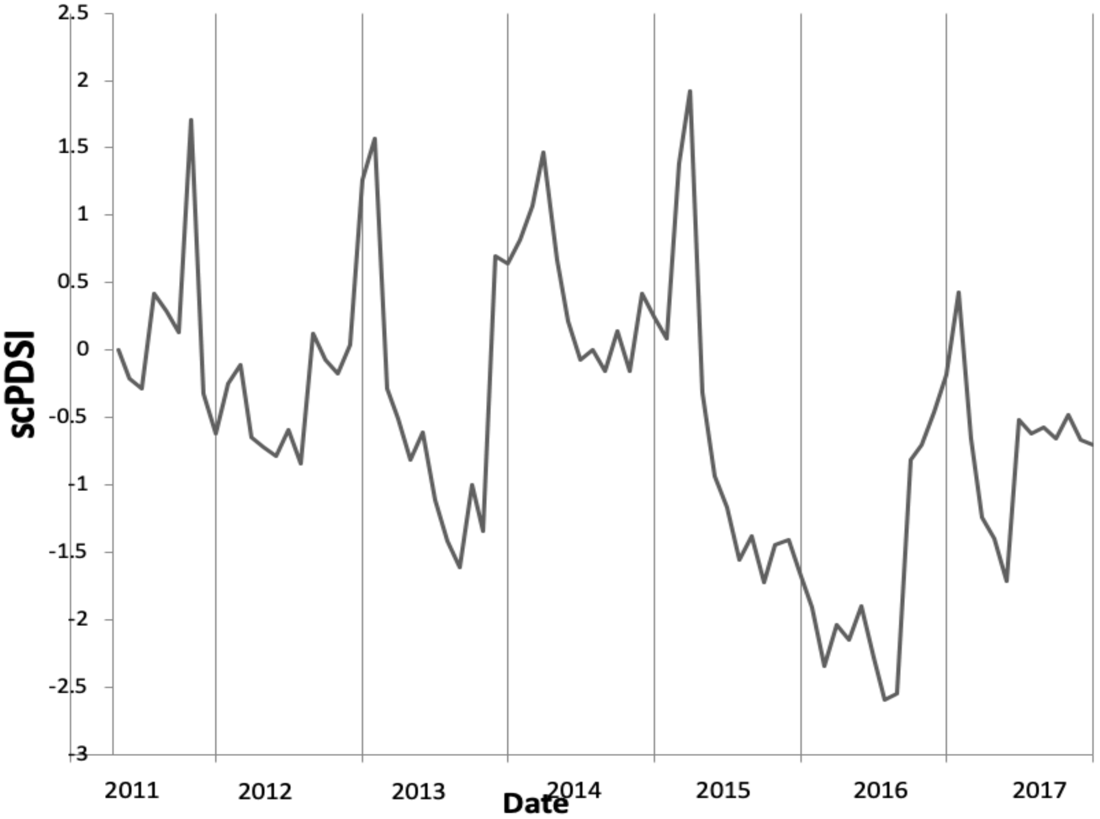
Appendix A - Supplementary Material – Chapter 2

A1: Self-Calibrating Palmer Drought Severity Index (scPDSI) averaged over all study locations from 2011 -2017. Author analysis using scPDSI data from Osborn et al., 2018 and GPS locations of communities in the study. + 5 extremely wet to - 5 extremely dry.



A2: List of variables and units in Household Survey.

Variable name	Description	Unit
Production_system	Organic, Non-certified East, Non-certified West, UTZ or RA	
Gender	Female farm lead decision maker	% of sample
Age	Of lead decision maker	Years
Education	Years in education	Years
Household	Number of members in immediate household	People
Ownership	Does the respondent own the farm	% of sample
Tropical_Livestock_Units	The Food and Agriculture Organization's Tropical Livestock Unit is based on the weight of the animal raised to the power of 0.75, compared with the equivalent figure for a "tropical cow" of 250 kg. e.g., a goat is 0.1 TLU	TLU
Cocoa_income_proportion	Percentage of total income that is from cocoa	%
Total_farm_size	Area of all agricultural land farmed by respondent	ha
Forest	Percentage of Total farm size that is primary forest	%
Secondary_vegetation	Percentage of Total farm size that is secondary vegetation i.e. uncultivated land that has been recolonized by native species	%
Cocoa_area	Area of cocoa production	ha
Cocoa_farms	Number of separate cocoa plots	plots
Tree_age	Average age of cocoa trees on all plots	years
Hybrid	Does farmer use hybrid cocoa tree varieties	% of sample
Crop_diversity	Number of crops other than cocoa on farm	crops
Modify_pruning	Farmer modifies pruning strategy in the face of drought	% of sample
Modify_weeding	Farmer modifies pruning strategy in the face of drought	% of sample
Yield_17_18	Volume of cocoa produced in the 2017/18 minor and major seasons	kg
Years_certified	Number of years certified	years
Mineral_fertiliser	Proportion of the sample using mineral fertilizer	% of sample
Liquid_fertiliser	Proportion of the sample using liquid fertilizer	% of sample
Organic_fertiliser	Proportion of the sample using organic fertilizer	% of sample
Herbicide	Proportion of the sample using herbicide	% of sample
Insecticides	Proportion of the sample using insecticide	% of sample
Fungicide	Proportion of the sample using fungicide	% of sample
Organic_Insecticide	Proportion of the sample using organic insecticide	% of sample
Firebelt	Dummy firebelt present	% of sample
Water_harvesting	Dummy use water harvesting	% of sample
Irrigation	Irrigation on cocoa farm	% of sample
Hybrid	Dummy use Hybrid varieties	% of sample
IPM	Dummy use Integrated Pest Management	% of sample
Diversity_alt_ag_income	Number of alternative agriculture income sources	integer
Diversity_non_ag_income	Number of non-agricultural income sources	integer
Crop_diversity	Number of crops other than cocoa grown on farm	integer
Yield_17_18	Cocoa yield 2017/18 season	kg ha-1
Cocoa_income_proportion	Percentage of total income from cocoa	%
Yield_change	Change in yield between 2016/17 and 2017/18	%
Fire_tree_death	Dummy experience tree death due to fire	% of sample
Tree_death	Dummy experience tree death	% of sample
Disease_exasperated	Multiple sources to measure yes or no disease exasperated	% of sample
Mitigate_ag_work	Dummy use this coping method	% of sample
Mitigate_non_ag	Dummy use this coping method	% of sample
Sell_livestock	Dummy use this coping method	% of sample
Sell_ag_items	Dummy use this coping method	% of sample
Cut_expenditure	Dummy use this coping method	% of sample
Use_savings	Dummy use this coping method	% of sample
Coping_diversity	Number of coping methods used	integer
Training_intensity	Number of training sessions in last 5 years	integer
Drought_training	Dummy received specific drought training	% of sample
Secondary_vegetation	% of plot secondary vegetation	%
Ability_raise_capital	Can the farmer raise GHC in week before harvest if required	% of sample
Bank	Farmer has a bank account	% of sample
Agricultural_network	Number of people the farmer regularly discusses cocoa production with	Integer
Cocoa_group_membership	Membership of a cocoa producers group	% of sample
Other_ag_groups	Membership of a non-cocoa producers group	% of sample
Contract_agreement	Farmer has a forward contract with LBC to purchase their cocoa	% of sample

A3: List of variables in biophysical assessments

Variable name	Description	Unit
Cocoa density	Number of cocoa trees per hectare	Trees ha^{-1}
Shade_density	Number of shade trees per hectare	Trees ha^{-1}
Shade cover	Percentage of plot covered by shade tree canopy	%
Shade_species_richness	Number of shade tree species in plot	Richness
Soil carbon	Total Carbon content of soil	%
Soil nitrogen	Total Nitrogen content of soil	%

A4: Strata boundaries for CEM

Variable name	Strata boundary 1	Strata boundary 2	Strata boundary 3
Education	1	12	na
Household	3	12	na
Farm size	1	11	21
Age	26	60	na

A5: Matching outcomes from Coarsened Exact Matching

Treatment	Matching	Treatment	Control	Total
Organic	All	104	80	184
	Matched	86	71	157
	Unmatched	18	9	27
	Share matched	82.7%	88.8%	85.3%
UTZ	All	60	104	164
	Matched	54	65	119
	Unmatched	6	15	21
	Share matched	90.0%	62.5%	72.6%
Rainforest Alliance	All	108	105	213
	Matched	100	91	191
	Unmatched	8	14	22
	Share matched	92.6%	86.7%	89.7%

A6: Estimated effect of certification on Robustness indicators after matching using CEM: Average treatment effect on the treated (ATT), standard errors in brackets. Significance * p < 0.10, ** p < 0.05, ***p < 0.01. The unmatched sample mean is presented (RA, ORG, UTZ), stars denote significant t-test difference from non-certified sample. Significant regional differences, t-tests between non-certified samples, are denoted by stars.

Measure or strategy	**Total sample**	**Non-cert. West**	**RA**	**RA ATT (SE)**	**Non-cert. East**	**ORG**	**ORG ATT (SE)**	**UTZ**	**UTZ ATT (SE)**	**Regional diff.**
Sample size (Matched)	457	105	108	(191)	80	104	(157)	60	(119)	
Preparation										
Mineral fertilizer	12%	12%	20%	**0.117** * **(0.032)**	15%	**2.9%** ***	**-0.149** *** **(0.052)**	**5.0%** **	**-0.101** * **(0.051)**	
Liquid fertilizer	46%	70%	74%	-0.023 (0.047)	45%	**14%** ***	**-0.205** *** **(0.066)**	**13%** ***	**-0.316** *** **(0.065)**	***
Organic fertilizer	14%	1.00%	0%	-0.009 (0.010)	1.20%	**35%** ***	**0.333** *** **(0.010)**	**43%** ***	**0.441** *** **(0.009)**	
Hybrid	46%	37%	38%	-0.005 (0.053)	54%	58%	0.061 (0.062)	43%	-0.074 (0.062)	**
Shade tree cover	3.58 (3.23)	2.82 (3.50)	3.66 (3.17)	1.376 (0.677)	4.04 (2.86)	4.86 (3.48)	-1.044 (1.704)	2.72 (3.14)	-1.489 (1.034)	
Water harvesting	21%	29%	27%	0.043 (0.047)	10%	19%	0.093 (0.034)	12%	0.049 (0.035)	**
Fire belt	28%	20%	20%	0.032 (0.037)	35%	**37%** *	0.028 (0.066)	35%	0.09 (0.063)	***
Crop diversity	3.10 (1.61)	2.62 (1.64)	2.66 (1.65)	0.229 (0.163)	3.26 (1.48)	**3.72 (1.44)** **	**0.593** * **(0.172)**	3.43 (1.50)	0.129 (0.186)	***
Shade tree sp. richness	2.26 (1.92)	0.67 (1.05)	1.31 (1.08)	**1.049** ** **(0.236)**	3.08 (1.56)	3.69 (1.38)	0 (1.112)	3.30 (2.58)	-0.171 (0.795)	***
Diversity alt. ag. income	1.83 (1.17)	1.75 (1.25)	1.56 (1.26)	-0.146 (0.136)	2.09 (1.03)	1.87 (1.10)	-0.231 (0.139)	2.02 (1.03)	-0.042 (0.143)	**
Response										
Response irrigation	4.80%	5.70%	5.60%	0.001 (0.026)	5.00%	4.80%	0.022 (0.017)	1.70%	-0.012 (0.023)	
Modify pruning	82%	90%	90%	-0.038 (0.028)	79%	**67%** *	**-0.165** * **(0.051)**	82%	-0.027 (0.053)	*
Modify weeding	54%	34%	42%	0.003 (0.052)	66%	63%	-0.068 (0.057)	78%	0.112 (0.062)	***
Impacts										
Tree death	82%	85%	83%	0.004 (0.037)	86%	**75%** *	-0.08 (0.052)	82%	-0.079 (0.046)	
Fire damage	7.40%	10%	**3.7%** *	-0.044 (0.030)	10%	7.70%	-0.018 (0.043)	5.00%	-0.04 (0.043)	
Disease exasperated	48%	55%	**41%** **	**-0.159** * **(0.05)**	46%	46%	-0.001 (0.064)	52%	0.05 (0.066)	
Yield loss	0.13 (0.46)	0.09 (0.47)	0.12 (0.44)	0.019 (0.054)	0.08 (0.44)	0.18 (0.51)	0.016 (0.065)	0.21 (0.40)	0.065 (0.066)	
Yield change kg	-69.9	-60.1	-88.2	-24.2 (28.4)	-54.3	-57.1	3.46 (21.1)	-81.9	-29.3 (19.5)	
Yield 2017/18	407	540	591	58.2 (50.6)	304	238	**-59.4** ** **(28.3)**	272	-49.2 (31.8)	***

A7: Estimated effect of certification on Recovery indicators after matching using CEM*:* Average treatment effect on the treated (ATT), standard errors in brackets. Significance denoted by * p < 0.10, ** p < 0.05, ***p < 0.01. The unmatched sample mean is presented (ORG, UTZ, RA), stars denote significant t-test difference from non-certified sample. Significant regional differences, t-tests between noncertified samples, are denoted by stars.

Measure or strategy	**Total sample**	**Non-cert. West**	**RA**	**RA ATT (SE)**	**Non-cert. East**	**ORG**	**ORG ATT (SE)**	**UTZ**	**UTZ ATT (SE)**	**Regional diff.**
Sample size (Matched)	457	105	108	(191)	80	104	(157)	60	(119)	
Redundancy										
Cocoa income proportion	0.78 (0.20)	0.86 (0.17)	0.89 (0.15)	**0.025** * **(0.016)**	0.68 (0.19)	0.70 (0.21)	0 (0.026)	0.70 (0.20)	0.016 (0.024)	***
Diversity non-ag income	0.79 (1.13)	1.40 (1.36)	1.26 (1.32)	-0.194 (0.146)	0.34 (0.50)	0.34 (0.65)	0.036 (0.065)	0.28 (0.61)	-0.085 (0.071)	***
Coping										
Sell livestock	21%	8.60%	**20%** **	**0.135** ** **(0.037)**	25%	23%	0.012 (0.064)	37%	0.133 (0.067)	***
Sell ag equipment	41%	29%	37%	0.09 (0.037)	54%	45%	-0.047 (0.064)	48%	-0.046 (0.067)	***

A8: Estimated effect of certification on Adaptability indicators after matching using CEM: Average treatment effect on the treated (ATT), standard errors in brackets. Significance is denoted by * p < 0.10, ** p < 0.05, ***p < 0.01. The unmatched sample mean is presented (ORG, UTZ, RA), stars denote significant t-test difference from non-certified sample. Significant regional differences, t-tests between noncertified samples, are denoted by stars.

Measure or strategy	**Total sample**	**Non-cert. West**	**RA**	**RA ATT (SE)**	**Non-cert. East**	**ORG**	**ORG ATT (SE)**	**UTZ**	**UTZ ATT (SE)**	**Regional diff.**
Sample size (matched)	457	105	108	(191)	80	104	(157)	60	(119)	
Capitals										
Agricultural network size	5.05 (5.78)	4.35 (6.04)	4.59 (4.70)	0.95 (0.750)	5.12 (6.06)	5.30 (4.89)	0.746 (0.798)	6.53 (7.70)	**3.131** * **(0.750)**	
Cocoa group membership	73%	61%	**93%** ***	**0.353** *** **(0.073)**	59%	**78%** ***	**0.263** *** **(0.074)**	72%	0.137 (0.073)	
Training intensity	9.56 (6.57)	8.31 (6.58)	**11.49** **(6.58)** ***	**3.657** *** **(0.968)**	7.71 (6.82)	**10.04** **(6.03)** **	**2.792** * **(0.942)**	**9.88** **(6.16)** *	2.39 (0.968)	
Forest	0.01 (0.04)	0.01 (0.05)	0.01 (0.04)	-0.005 (0.003)	0.01 (0.02)	**0.02** **(0.06)** *	**0.016** * **(0.003)**	0.01 (0.02)	-0.002 (0.003)	
Secondary vegetation	0.05 (0.10)	0.03 (0.08)	0.05 (0.11)	0.022 (0.007)	0.02 (0.05)	**0.08** **(0.11)** ***	**0.07** *** **(0.006)**	**0.07** **(0.12)** **	**0.04** ** **(0.007)**	
Soil Carbon	1.56 (0.53)	1.55 (0.58)	1.46 (0.44)	-0.134 (0.038)	1.75 (0.62)	1.78 (0.56)	-0.111 (0.060)	**1.26** **(0.30)** **	**-0.666** ** **(0.049)**	
Ability to raise capital	81%	85%	82%	-0.037 (0.065)	82%	81%	0.011 (0.052)	72%	**0.107** * **(0.065)**	
Bank account	68%	78%	75%	-0.008 (0.067)	66%	**54%** *	-0.099 (0.068)	68%	0.002 (0.067)	*
TLU	0.58 (1.14)	0.41 (1.00)	0.46 (0.97)	0.157 (0.238)	0.92 (1.87)	**0.55** **(0.68)** *	**-0.359** * **(0.233)**	0.73 (0.91)	-0.273 (0.238)	**
Ability to raise capital	81%	85%	82%	-0.037 (0.065)	82%	81%	0.011 (0.052)	72%	**0.107** * **(0.065)**	
Agricultural group membership	16%	13%	20%	0.072 (0.053)	16%	16%	0.031 (0.054)	8.30%	-0.055 (0.053)	
Drought training	73%	67%	**81%** **	**0.239** *** **(0.073)**	62%	**76%** *	**0.217** * **(0.068)**	**77%** *	**0.261** * **(0.073)**	
Market integration	24%	25%	31%	0.112 (0.049)	20%	21%	-0.004 (0.051)	20%	0.053 (0.049)	

Appendix B - Supplementary Material – Chapter 3

B1 List of variables and their units in the household survey

Variable name	Description	Unit
Production_system	Organic, Non-certified East, Non-certified West, UTZ or RA	
Gender	Female farm lead decision maker	% of sample
Age	Of lead decision maker	Years
Education	Years of education	Years
Household	Number of members in immediate household	People
Ownership	Does the respondent own the farm	% of sample
Tropical_Livestock_Units	The Food and Agriculture Organization's Tropical Livestock Unit is based on the weight of the animal raised to the power of 0.75, compared with the equivalent figure for a "tropical cow" of 250 kg. e.g., a goat is 0.1 TLU	TLU
Cocoa_income_proportion	Percentage of total income derived from cocoa	%
Total_farm_size	Area of all agricultural land farmed by respondent	ha
Forest	Percentage of total farm size that is primary forest	%
Secondary_vegetation	Percentage of Total farm size that is secondary vegetation i.e. uncultivated land that has been recolonized by native species	%
Cocoa_area	Area of cocoa production	ha
Cocoa_farms	Number of separate cocoa plots	plots
Tree_age	Average age of cocoa trees on all plots	years
Hybrid	Does farmer use hybrid cocoa tree varieties	% of sample
Modify_pruning	Farmer modifies pruning strategy in the face of drought (increase cocoa pruning – decrease shade pruning)	% of sample
Modify_weeding	Farmer modifies weeding strategy in the face of drought (increase and leave residues)	% of sample
Years_certified	Number of years certified	years
Mineral_fertiliser	Percentage of the sample using mineral fertilizer	% of sample
Liquid_fertiliser	Percentage of the sample using liquid fertilizer	% of sample
Organic_fertiliser	Percentage of the sample using organic fertilizer	% of sample
Herbicide	Percentage of the sample using herbicide	% of sample
Insecticides	Percentage of the sample using insecticide	% of sample
Fungicide	Percentage of the sample using fungicide	% of sample
Organic_Insecticide	Percentage of the sample using organic insecticide	% of sample
Firebelt	Dummy firebelt present	% of sample
Water_harvesting	Dummy use water harvesting	% of sample
Irrigation	Irrigation on cocoa farm	% of sample
IPM	Dummy use Integrated Pest Management	% of sample
Diversity_alt_ag_income	Number of alternative agriculture income sources	Richness
Diversity_non_ag_income	Number of non-agricultural income sources	Richness
Crop_diversity	Number of crops other than cocoa grown on farm	Richness
Yield_17_18	Cocoa yield 2017/18 season	kg ha^{-1}
Cocoa_income_proportion	Percentage of total income from cocoa	%
Yield_change	Change in yield between 2016/17 and 2017/18	%
Fire_tree_death	Dummy experience tree death due to fire	% of sample
Tree_death	Dummy experience tree death	% of sample
Disease_exasperated	Multiple sources to measure yes or no disease exasperated	% of sample
Mitigate_ag_work	Dummy use this coping method	% of sample
Mitigate_non_ag	Dummy use this coping method	% of sample
Sell_livestock	Dummy use this coping method	% of sample
Sell_ag_items	Dummy use this coping method	% of sample
Cut_expenditure	Dummy use this coping method	% of sample
Use_savings	Dummy use this coping method	% of sample
Coping_diversity	Number of coping methods used	Richness
Training_intensity	Number of training sessions in last 5 years	Trainings
Drought_training	Dummy received specific drought training	% of sample
Ability_raise_capital	Can the farmer raise GHC in week before harvest if required	% of sample
Bank	Farmer has a bank account	% of sample
Agricultural_network	Number of people the farmer discussed production within last month	Contacts
Cocoa_group_membership	Membership of a cocoa producers group	% of sample
Other_ag_groups	Membership of a non-cocoa producers group	% of sample
Contract_agreement	Farmer has a forward contract with LBC to purchase their cocoa	% of sample

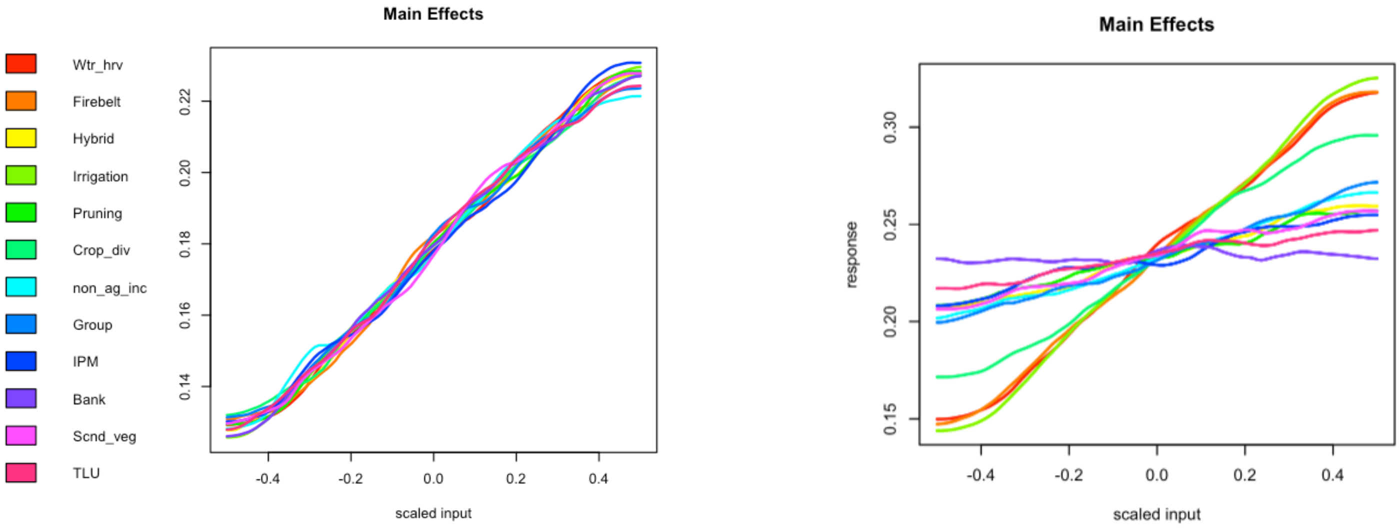
B2 Sample Overview

244 farmers from Eastern Region and 213 from Western Region. The mean age of the farmers was 51 years, with an education of 7 years and a mean household size of 7. Household heads were in general male (25% female). Farmers were generally highly dependent on cocoa production, with a mean of 78% cocoa income dependency. The majority of farmers (82%) had at least one other source of agricultural income and some (42%) at least one other source of non-agricultural income. 41% were non-certified, 23 % organic 13% UTZ and 24% Rainforest Alliance certified.

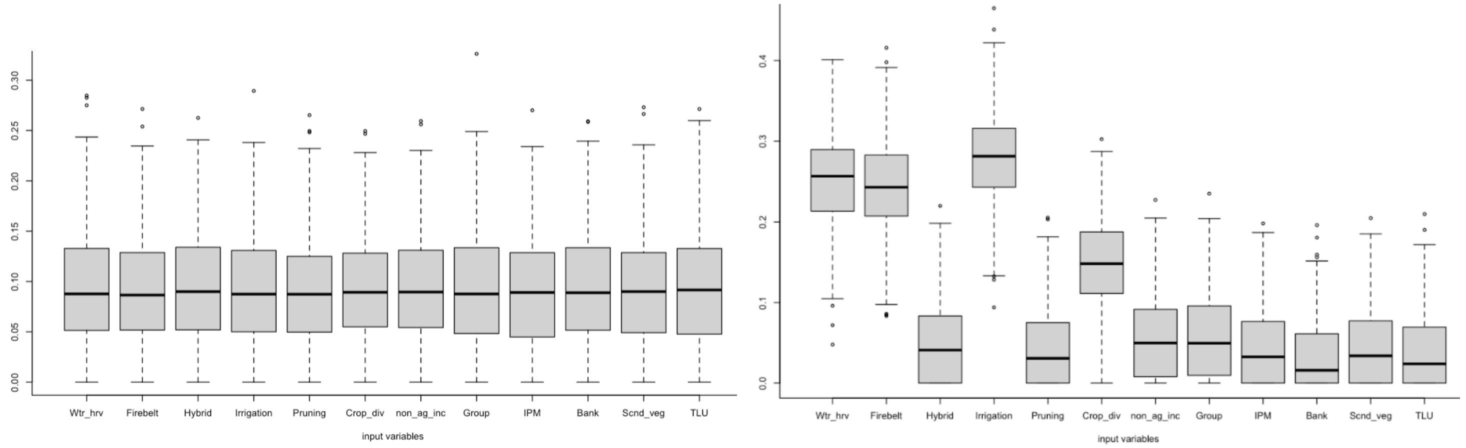
B3 Global sensitivity analysis of RSI and uRSI. A global sensitivity analysis was conducted for both RSI and uRSI. A treed Gaussian process model was implemented (using the tgp package in R) to explore how RSI responds to concurrently changing indictor values: **a)** shows how RSI and uRSI respond to changing values of all 12 indicators. For uRSI flat lines for several indicators suggest limited impact on the index with variation in these indicators. **b)** First order indices and **c)** Total indices are interpreted as the expected reduction in variance from fixing a specific indicator (first order: excluding interactions and total: including interactions).

RSI **uRSI**

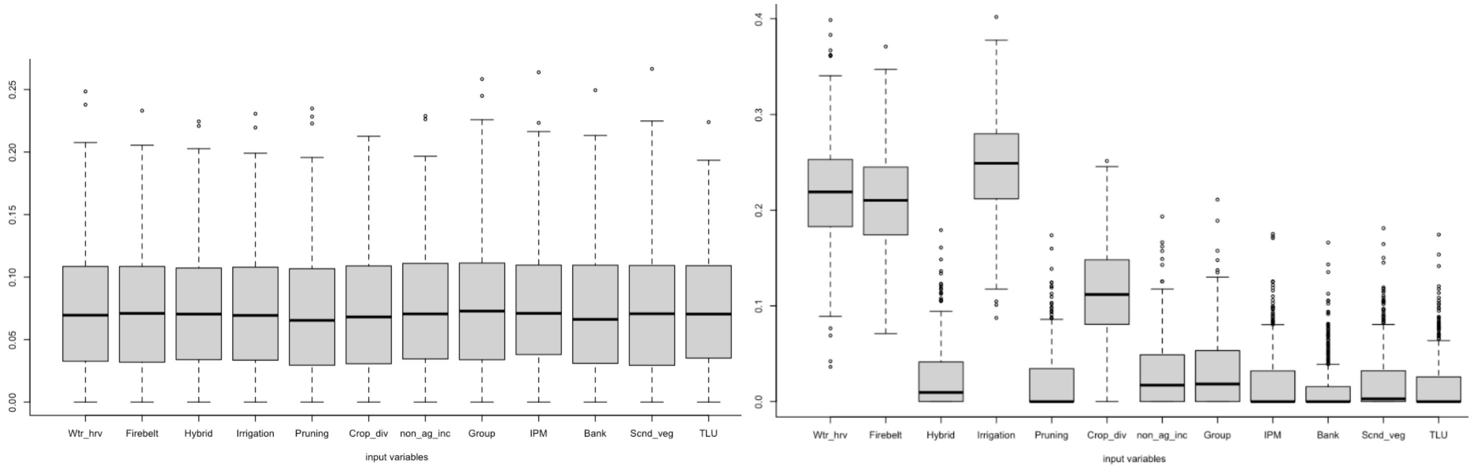
a) Main Effects



b) 1st Order Sensitivity Analysis



c) Total Effect Sensitivity Analysis



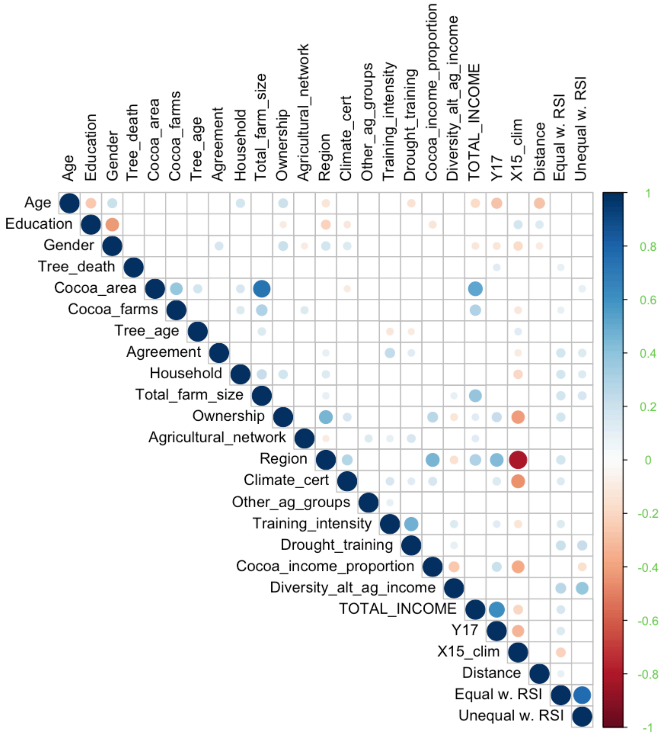
B4 Comparison of RSI and uRSI by household characteristics t-test outputs for RSI comparisons. Stars indicate significance *** P<0.001, ** P<0.01, *p<0.05.

Characteristic		Mean RSI	t value	Mean uRSI	t value
Gender	Female	0.366	-0.438	0.261	0.648
	Male	0.372		0.270	
Age	Above 50	0.377	1.209	0.275	1.212
	50 and below	0.363		0.269	
Household size	**Above 5**	0.379	**2.557****	**0.276**	**2.418***
	5 and below	0.344		**0.241**	
Education	Above 6 years	0.370	-0.270	0.265	0.639
	6 years and below	0.373		0.274	
Farm area	**Above 3 hectares**	**0.390**	**4.380*****	**0.285**	**3.789*****
	3 ha and below	**0.338**		**0.238**	
Region	**Eastern**	**0.350**	**-3.869*****	0.261	-1.077
	Western	**0.394**		0.275	
Ownership	**Farmer owned**	**0.388**	**-3.752*****	0.277	-1.842
	Not owned	**0.344**		0.253	

B5 Variables hypothesised to influence climate resilience strategy adoption

Variable	Description	Expected influence on resilience strategy adoption
Gender	Female household head	Negative (i.e. decreased RS index)
Age	Age of household head	Negative
Household size	Number of people in the household	Positive
Education	Years of completed formal education	Positive
Cocoa income dependency	Proportion of income from cocoa	Negative
Diversity of ag. income streams	Number of different ag. income sources	Positive
Total farm size	Total area of all farmed land in hectares	Positive
Farmer owned	Household owns the farm	Positive
Cocoa farms	Number of separate cocoa plots	Positive
Cocoa farm size	Area of cocoa farms in hectares	Positive
Cocoa tree age	Average age of cocoa trees	Negative
Agricultural network size	Number of other farmers that the farmer discusses cocoa production strategy with every month	Positive
Drought training	Farmer has received specific training on producing cocoa in drought conditions	Positive
Training intensity	Number of trainings received	Positive
Agricultural group memberships	No. of agricultural groups the farmer is engaged in	Positive
Certification	Farm is certified under RA or UTZ with climate adaptation module	Positive
Region	Farm is located in Eastern or Western Region	Neutral
Savings	Does the farmer have savings	Positive
Forward purchase agreement	Does the farmer have an agreement to sell the cocoa	Positive
Buyer richness	Number of buyers	Positive
Distance to market	Distance in km to market town	Negative
Total household income	HH Income from cocoa, and non-cocoa activities	Positive
Rainfall	Annual rainfall in mm	Positive
Tree death	Cocoa tree death experienced in 2015/16 drought	Positive

B6 Correlation plot of explanatory variables with RSI and uRSI Correlation plot showing significant correlations (Pearson's) between collected variables and Resilient Strategy Index (RSI) - unweighted (RSI) and weighted. Larger circles show stronger correlations. Blue indicates positive correlation and red indicates negative correlation.

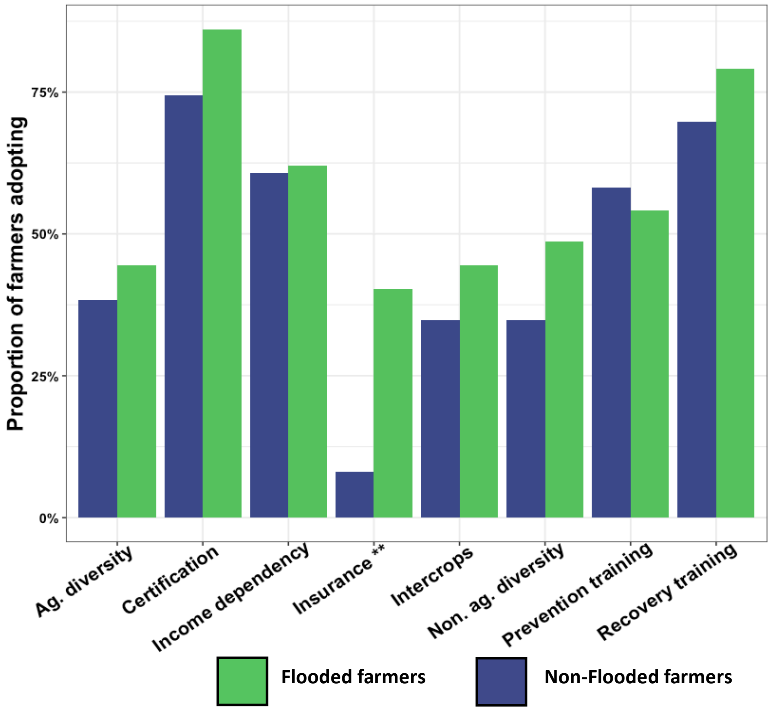


B7 Fractional regression results with Equal and Unequal weighted RSI Stars indicate significance *** P<0.001, ** P<0.01, *p<0.05. (13 observations were excluded due to incomplete data for at least one of the factors).

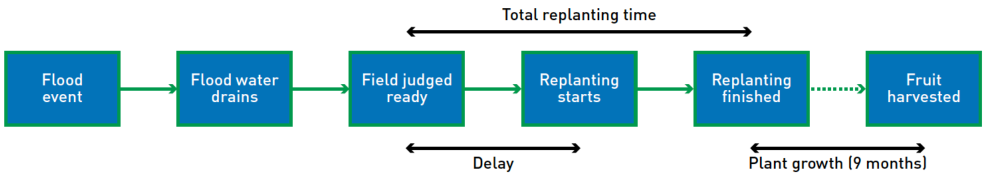
	Equal weighted RSI		Unequal weighted RSI	
Variables	**Estimate**	**Standard Error**	**Estimate**	**Standard Error**
(Intercept)	**-0.533*** **	**0.023**	**-1.101** **	**0.031**
Regional context	**0.068** **	**0.023**	**-0.019**	**0.031**
Drought training and value chain integration	**0.104*** **	**0.022**	**0.103*** **	**0.029**
Income generating capacity	**0.056** **	**0.020**	**0.062** **	**0.025**
Non-cocoa ag. market access	**0.123*** **	**0.022**	**0.162*** **	**0.030**
Land tenure and household size	**0.124*** **	**0.022**	**0.012*** **	**0.028**
Severe drought shock experience	0.039	0.024	0.030	0.030
R^2	0.20	No. observations 444	R^2 0.12	No. observations 444

Appendix C - Supplementary Material – Chapter 4

C1: Proportion of farmers utilising different strategies to enhance their resilience to a flooding event. Flooded farmers (green) and non-flooded farmers (blue) are segregated, with significant differences (Chi-squared test) shown ($p<0.01=$ **)



C2: Agricultural recovery process for smallholder banana farmers after flooding



C3: Variables hypothesised to determine farmers recovery from flooding event:

Name	Description	Expected influence on recovery time (RT)	Literature supporting variables role in climate resilience of smallholders
Gender	Female household head	Positive (i.e increased RT)	(Jost et al., 2016)
Age	Age of household head	Negative	(Tazeze et al., 2012)
Education	Number of years education	Negative	(Menike and Arachchi, 2016)
Banana income dependency	Proportion of income form bananas	Positive	
Non-agricultural income streams	Number of non-agricultural income sources	Negative	(Bellon et al., 2020)
Diversity of all income streams	Number of different income sources (ag./non-ag.)	Negative	(Antwi-Agyei et al., 2014)
Farmer owned	Household owns the farm	Negative	(Antwi-Agyei et al., 2015)
Banana farm size	Area of banana farms in hectares	Negative	(Harvey et al., 2014)
Distance from river	Distance from the river in metres	Negative	(Philpott et al., 2008)
Intercrops	Number of different crops integrated in banana production	Negative	(Lasco et al., 2014)
Farm diversity	Diversity of crops produced on the farm	Negative	(Lin, 2011)
Flooded area	Size of area flooded in September 2017	Positive	
Area replanted	Area of banana farm that was replanted after flooding	Positive	
Agricultural network size	Number of other farmers that the farmer discusses banana production strategy with every month	Negative	(Saint Ville et al., 2016)
Flood training	Farmer has received specific training on flood damage prevention	Negative	(Nor Diana et al., 2019)
Recovery training	Farmer has received specific training on replanting the farm after flooding	Negative	(Stewart et al., 2015)
Agricultural group memberships	No. of agricultural groups the farmer is engaged in	Negative	(Kangogo et al., 2020)
Certification	Farm is certified under Organic, RA or FT	Negative	
Financial sources	Number of financial sources the farmer has access to e.g. bank loans, credit groups	Negative	(Li et al., 2020)
Savings	Does the farmer have savings	Negative	(Oostendorp et al., 2019)
Insurance	Does the farmer have flood insurance	Negative	(Collier et al., 2009)
Drainage time	Days after initial flood water drained from farm	Positive	

C4: Standardized regression coefficients of the four determinants of the dependent variable recovery time (Significance: $p<0.01$ '**', $P<0.05$ '*') The model has an adjusted R squared value of 0.241, showing it explains 24% of the variation in recovery time. Recovery time= β_0+ β_1 Scale of damage + β_2 Farm and livelihood diversity+ β_3 Flood training+ β_4 Drainage+ ε

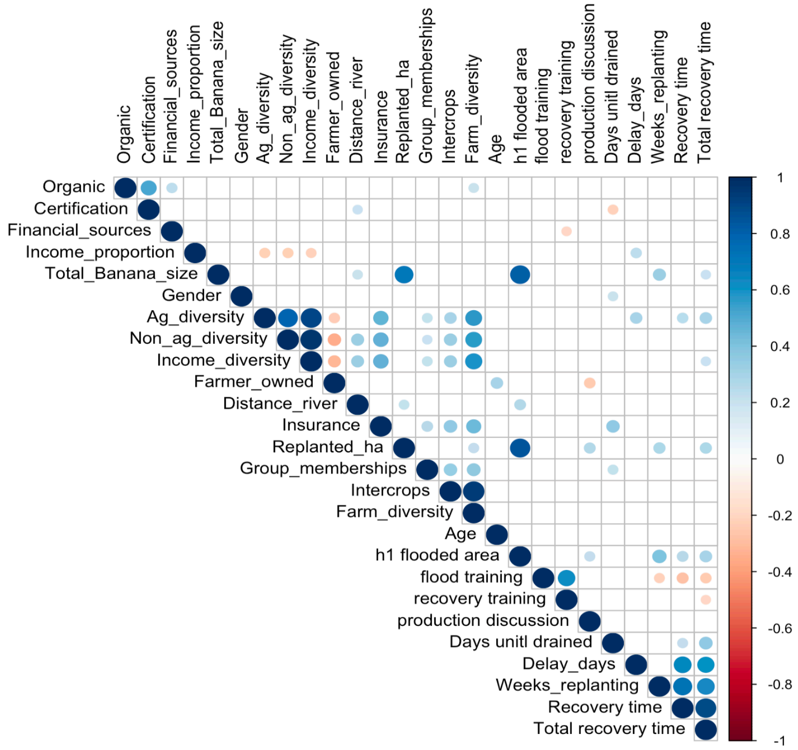
Variables	Standardised regression coefficients	Standard Error
(Intercept)	**1.233 ****	**0.0997**
Scale of damage	**0.262***	**0.0999**
Farm and livelihood diversity	**0.240***	**0.0998**
Flood training	**-0.256***	**0.0998**
Drainage	**0.298****	**0.1000**
Multiple R-squared: 0.2807, F-statistic: 7.026 on 4 and 72 DF.	Adjusted R-squared: 0.241 P <0.0001	

C5: Map of the Dominican Republic on the Island of Hispaniola with the study area marked in red in the provinces of Monte Cristi and Valverde. The River Yaque del Norte, the main source of flooding during the 2017 hurricane events is shown in blue.

C6: Characteristics of sampled banana farmers Means are presented with standard deviation in brackets for continuous and count variables. Differences are assessed using t-tests for continuous variables and Chi-squared for binary and count). Farmers were categorised based on whether they were flooded as a result of the 2017 hurricanes.

Characteristic	**Total sample, n = 158**	**Non-flooded, n = 78**	**Flooded in 2017 n = 80**	**P value**
Female	11%	8.10%	15%	0.248
Age	50 (13)	50 (14)	51 (12)	0.286
Number of farms	1 (1)	1 (1)	1 (1)	0.072
Farm size (ha)	5.2 (4.8)	5.1 (5.2)	5.2 (4.3)	0.176
Organic	78%	74%	83%	0.245
Fairtrade	95%	94%	96%	0.915
RA	47%	48%	46%	0.943
Intercrops	1 (1)	1 (1)	1 (1)	0.822
Crop types	2 (2)	2 (1)	2 (2)	0.725
Non ag. income diversity	0 (1)	0 (1)	0 (1)	0.600
Distance to river (m)	**1698 (2263)**	**2232 (2570)**	**1164 (1772)**	**0.007**
Banana income proportion	0.61 (0.31)	0.61 (0.31)	0.62 (0.32)	0.821

C7: Correlation matrix of the explanatory and dependant variables. Only significant correlations (p<0.05) are displayed. Circle size and colour intensity are proportional to the correlation coefficients (Pearson's) Blue circles indicate positive correlation and red circles indicate negative correlation. Recovery time (dependent variable) and its sub-components are on the right-hand side of the matrix.



C8: Factor loadings after rotation. Loadings greater than 0.3 are considered in the interpretation of the factors and highlighted in bold.

	Scale of damage	**Farm and livelihood diversity**	**Flood Training**	**Drainage**
Flooded area	**0.94**	0.01	-0.01	0.10
Replanted area	**0.87**	0.13	-0.01	-0.05
Total banana size	**0.91**	-0.05	-0.03	0.11
Agricultural diversity	0.05	**0.93**	0.09	0.04
Non. ag. diversity	0.02	**0.92**	-0.05	-0.03
Flood training	-0.08	-0.02	**0.90**	-0.10
Recovery training	0.04	0.05	**0.88**	0.18
Drainage	0.14	0.19	0.01	**0.82**
Income dependency	-0.03	**-0.40**	0.08	**0.57**
Eigen values	2.49	1.93	1.60	1.07

C9: Remote sensing methodology

a) Mapping banana production area and impact of hurricanes

For the three provinces of Monte Cristi, Valverde and Santiago, maps of banana plantation area in 2017 and 2019, as well as the extent of area affected by hurricanes Irma and Maria, were generated using remote sensing techniques detailed in Varma et al. (2020). In brief, banana plantations for 2019 were mapped by building a random forest classifier using a fusion of Synthetic Aperture Radar (SAR) data from the European Space Agency (ESA) Sentinel-1 satellite platform, multi-spectral data from ESA's Sentinel-2 platform, and terrain information from the 90m resolution Shuttle Radar Telemetry Mission (SRTM) Digital Elevation Model (DEM). Specifically, classification was run on a stack of rasters comprising the median VV polarisation backscatter for 2019 (i.e. January 2019 to December 2019), the standard deviation in VV backscatter for the same time period, the median red, green, blue and NDVI values for 2019, and slope derived from the DEM. The random forest classifier was trained using ground truth data from 100 banana plantation polygons, and a set of other land-cover classes that were manually digitised using imagery available from Google Earth. The classifier was used to produce a map of banana plantation area for 2019 (representing the post-hurricane recovered production area). Using a confusion matrix (Stehman, 1997) and a random sample of 500 test pixels generated from the banana plantation ground truth data, accuracy of classified banana plantations was estimated at 99.8%. The trained classifier was then used to produce a map for pre-hurricane banana plantations using one years worth of Sentinel-1 and Sentinel-2 data immediately preceding hurricane Irma (i.e. from September 2016 to August 2017).

The area affected by the hurricanes was mapped using ESA's Sentinel-1 data. Affected areas consisted of the spatial union of three components. First, the immediate impact of the hurricanes was identified as pixels with large reductions in VV polarisation backscatter immediately after the hurricane events, as reduced backscatter can be used as a signal for flooded pixels (Schumann and Di Baldassarre, 2010). The second component comprised a 100 meter buffer around the pixels identified in the first component. This accounted for areas that are likely to have experienced open water flooding (or at the very least, inundated soils) but which may have been obscured by vegetation features (e.g. banana plants, large trees, etc.). The third component, a legacy effect, was identified as pixels which during the three months after the hurricane events showed large negative deviations in average VV polarisation backscatter values relative to the distribution of values observed for the year preceding the hurricanes. This third component accounts for more protracted impacts of the hurricane, for example, banana plantation pixels that do not see immediate loss of plants after the hurricane. Spatially overlaying the pre-hurricane banana plantation area map (for 2017), the post-hurricane plantation map (for 2019) and the map of areas affected by hurricanes in the region, we identified (1) the location and spatial extent of banana plantation area in 2017 affected by the hurricane events, and (2) the turnover in plantation area between 2017 and 2019.

b) Quantifying recovery of banana plantations

Using the banana production area maps for 2017 and 2019 we identified pixels that were classified as banana plantations in both time periods (i.e. excluded areas that were lost or gained between 2017 and 2019). Overlaying the hurricane damage map we then grouped the selected pixels into hurricane affected and unaffected pixels (hereafter, flooded and non-flooded). A set of 6500 random sampling points were generated within each group, such that minimum spacing between points was 50m. Sentinel-1 VV polarisation backscatter values, averaged within a 50m x 50m window, were extracted at each sampling point from every Sentinel-1 image available from March 2017 to April 2018 (68 images). The spatial averaging in a 50m window was conducted to eliminate speckling artefacts that SAR data suffers from when working at fine spatial resolutions. Separately for the flooded and non-flooded pixels, we calculated the first quartile (Q1), median (Q2) and third quartile (Q3) of the VV backscatter values across the study region for every date that Sentinel-1 data were available for. These data (i.e. Q1, Q2 and Q3) were visualised as a function of date of image capture to illustrate the deviation in backscatter values in flooded pixels after the hurricane events relative to non-flooded pixels.

We estimated time to recovery using two criteria. For a more lenient criteria, recovery time was calculated as the number of days from the first hurricane till Q2 of flooded pixels was equal to, or greater than Q1 of non-flooded pixels for three consecutive dates of Sentinel-1 image capture (the third consecutive date was used as the end date for recovery). This method summarises the time taken for the flooded banana plantation canopy signature to resemble that of non-flooded plantations for the region as a whole.

The second, more stringent, criteria involved the calculation of a Productive Farm Index (PFI) for flooded pixels, which serves as a surrogate for the proportion of plantation area in a productive state. The rationale for this analysis is that for non-flooded pixels, by definition, 75% of pixel values should be greater than or equal to Q1 of all non-flooded pixel values. Prior to the hurricanes 75% of subsequently flooded pixels should also show values greater than or equal to Q1 of non-flooded pixels (i.e. Q1 of flooded pixels ≈ Q1 of non-flooded pixels). A loss of structural complexity following the hurricanes (through direct hurricane damage or clearing of affected plants after the hurricanes) leads to lower backscatter values in flooded pixels, which in turn results in less than 75% of pixels with values greater than or equal to Q1 of non-flooded pixels. The deviation in the fraction of flooded pixels which meet this criterion can be used as a proxy for the fraction of affected pixels that are not in a 'productive state'. As post-hurricane recovery of production area progresses and more affected area returns to a productive state, the fraction of flooded pixels with values greater than or equal to Q1 of non-flooded pixels will increase. This will continue until once again Q1 of flooded pixels ≈ Q1 of non-flooded pixels, and recovery is said to be completed. The PFI was obtained by first subsetting the sampled flooded pixels, such that only pixels whose VV backscatter values were greater than or equal to Q1 of non-flooded pixels for a minimum of eight out of the 15 image dates prior to the hurricane events were retained. This subsetting step minimised large fluctuations in backscatter values between consecutive images from having a disproportionate influence on the analysis and is primarily observed in pixels at plantation edges. In total, 3365 flooded pixels were retained for this analysis. Then, for each date, the proportion of flooded pixels with a backscatter value greater than or equal to Q1 of non-flooded pixels for the corresponding date were calculated. Recovery time was calculated from the onset of the first hurricane event till the date when at least 75% of flooded pixels first showed a backscatter value greater than or equal to Q1 of non-flooded pixels.