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Review

Ecosystem-Based Practices for Smallholders' Adaptation to Climate Extremes: Evidence of Benefits and Knowledge Gaps in Latin America

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Abstract: Agricultural practices of smallholder farming systems of Latin America can play an important role in reducing their exposure to the risks associated with climate extremes. To date, however, there is no systematic analysis of scientific evidence for the extent to which these practices can provide the multiple benefits needed for smallholders to adapt to climate extremes. In this paper, we searched scientific databases to review scientific evidence of the benefit provided by twenty-six practices in crops commonly farmed by smallholders in the region and highly relevant for their food and nutrition security; namely, coffee, maize and beans. We reviewed scientific documents ($n = 304$) published in the period 1953–2021 to register evidence of the practices' effects on fifty-five benefits. Our analysis of these documents found measurement records ($n = 924$) largely based on field experiments (85%). Our results show strong evidence of the multiple benefits that some ecosystem-based practices (e.g., tree-based practices for coffee and no tillage for maize) can provide to support the adaptation to climate extremes of smallholder farming systems and enhance a farm's natural assets (e.g., biodiversity, water, soil). We also found that the majority of research on practices in the region focused more on the socioeconomic dimension (54%) rather than on the capacity of practices to improve the natural assets of a smallholder farmers or reduce the impact of climate extremes. Given these knowledge gaps, we discuss the importance of a renovated investment in research to address existing knowledge gaps. Our concluding suggestions for future research include the need for systematizing existing knowledge from different sources (e.g., peer-reviewed, gray literature, farmers, extension agencies, etc.), and to assess the extent to which these practices can

provide multiple benefits for smallholder farming systems by improving their wellbeing, reducing their vulnerability to different hydroclimatic extremes while also contributing to ecosystem services provision at the landscape level.

Keywords: agricultural practices; climate change; coffee; maize; beans; farming systems; vulnerability; agroecology; water and soil conservation; agroforestry

1. Introduction

Smallholder farmers in developing countries are among the most vulnerable to climate extreme events as these affect their agricultural production and livelihoods [1–3]. These impacts are especially critical for the almost 60 million smallholders in Latin America whose farms (of less than 2 ha; [4]) are a key source of income, food production and security [5–8]. Over the 2010–2020 decade, the region has experienced more than twice as many floods, drought and landslides than the 1970–1999 and 2000–2005 periods [9]. Observed increases in the number and frequency of precipitation extremes [10,11], high temperatures and unpredictable rainfall [12–14] have significantly reduced their crop yields, and caused increasing soil erosion, pests and diseases. In spite of the increasing occurrence and intensity of climate extremes and associated impacts on smallholder agriculture, there is still only limited and scattered information on which agricultural practices can help farmers reduce their vulnerability to climate change [7,15].

To date, adaptation initiatives to support smallholders farming in the region cannot count on a systematic assessment of the benefits provided by agricultural practices in the face of extreme climate events [16]. For some practices, evidence only exists for their benefits in other crops and/or regions. For example, Wezel and colleagues [17] examined the effectiveness of agricultural practices in Mediterranean farming systems (e.g., wheat, olive trees, vegetables and legumes) in increasing food production and minimizing exposure to climate risks. Similarly, other authors [18] reviewed the impacts of conservation agricultural practices (e.g., use of zero tillage, mulch and crop rotation) on the yields of important staple crops (maize, rice, wheat, sorghum, millet, cassava and cow-pea) in Sub-Saharan Africa and South Asia, but did not consider how these practices might reduce climate risks. Kremen and colleagues [19] reviewed the existing evidence for the capacity of biologically diversified and conventional farming systems worldwide to provide ecosystem services also in relation to extreme weather events. In Central America, there is evidence that smallholder farmers are already perceiving the negative impacts of climate change and extreme weather events on their crop production and are changing their farming practices in response [7,20]. However, to our knowledge, there is no systematic review for the Latin American region on (i) the evidence of the benefits of agricultural practices in reducing the impacts of extreme weather events on smallholder farming systems and (ii) the critical knowledge gaps that merit greater attention in agricultural adaptation research programs.

In this paper, we contribute to fill this gap by reviewing research on agricultural practices from the region in search of evidence of their contribution to reduce smallholder farmers' vulnerability. For this, we examine scientific evidence of the climate change adaptation benefits of agricultural practices (particularly ecosystem-based adaptation practices) for coffee, maize and beans production in Latin America. Coffee, maize and beans are key crops in the region for a smallholders' income, food production and security [21–23]. Sixty percent of global coffee production comes from Latin America accounting for 20–25 million smallholder coffee farmers mainly located in Brazil, Colombia, Peru, Mexico, and Central American countries [24,25]. Maize provides almost half of the daily dietary energy needs for people in the Americas, and, together with beans, are the main staple crops providing food security for smallholders in both Central and South America [26,27]. Thus, climate impacts on smallholder maize and bean production systems affects not only the livelihood opportunities (e.g., to sell harvests), but also achieving the basic nutritional needs [20,28]

in producing countries, such as Brazil, Mexico, Colombia, and Central America [29–31]. These trends are expected to continue in the future due to ongoing increases in temperature and changing precipitation patterns [5,15,32]. The overall objectives of this study were to: (i) review the scientific evidence for how different agricultural practices reduce the impacts of climate extremes, (ii) to identify the socioeconomic and environmental benefits of these practices for farmers, and to (iii) identify main evidence gaps in the adaptation benefits of particular agricultural practices. We first explore the characteristics and relevance of ecosystem-based adaptation (EbA) practices for smallholders, i.e., practices based on the provision of ecosystem services that also take into consideration the needs and capacities of smallholders [33]. We also present the systematic review protocol implemented and the associated outcomes. We then summarize the scientific evidence through tables and diagrams that help visualize knowledge regarding the effects of agricultural practices on the climate change adaptation of coffee, beans and maize, and identify existing knowledge gaps. Finally, we examine the current state of evidence, identify promising EbA practices and suggest ideas for future research in the region and beyond.

1.1. Ecosystem-Based Agricultural Practices for Smallholder Farmer Adaptation

Many governments, NGOs and private companies are supporting the adoption and implementation of farming practices that reduce the impacts of climate extremes on crop production [34]. A range of agricultural practices are already available to farmers (e.g., [35]) and/or promoted by those initiatives. The extent to which these practices are actually apt for smallholder production contexts can depend on their contribution to the economic benefits, access to inputs (e.g., credit, technical assistance, etc.) and the extent of labor required [36]. Conventional practices for climate change adaptation can be technology-intensive such as drought- or heat-tolerant transgenic varieties, agrochemical fertilizers and pesticides [37,38], or investments in irrigation schemes [39]. Although these practices may reduce specific impacts of extreme events (e.g., tolerate water stress, eliminate pathogens), they can also expose farmers to additional risks. For example, irrigation schemes might promote over-exploitation of groundwater and thus increase exposure to dry extremes in the long run. Similarly, the use of agrochemicals can increase a smallholders' dependence on external inputs from highly volatile markets (as shown by the recent increase in prices caused by COVID-19 market distribution failures; [40]).

Some adaptation practices can provide a wider range of co-benefits which are essential to maintain a smallholders' ability to adapt while reducing their exposure to additional risks. According to [41], climate-smart agricultural (CSA) practices should be sustainable and tailored to the farmers context, provide adaptation benefits and food security while also reducing greenhouse gases emissions [41]. A recent global review of the benefits provided by climate-smart agricultural practices to smallholders found that ecosystem-based practices (e.g., conservation tillage, cereal-legume diversification, manure management) have the potential to provide economic and environmental benefits depending on the site conditions, farms' characteristics (e.g., tenure, size, topography, etc.) and inputs required [36]. This is also stressed by authors highlighting the multiple benefits provided by ecosystem-based adaptation (EbA) practices [16,33,42] as they can contribute to three important elements of a smallholders' production contexts; namely, (i) reduce the impacts of extreme weather events, (ii) rely on and promote the conservation of farms' natural assets, (iii) are tailored to smallholder farmers production context being easy to adopt while reducing dependency on external inputs [33]. In other words, EbA practices can reduce the impacts of extreme weather events while relying on the use of biodiversity and ecosystem resources and processes that can be available in smallholder production contexts [33,42]. A concrete example of such multi-benefit practices is the use of trees in agroforestry systems which can enhance water use, storage and efficiency, soil overall fertility, pest and disease control, microclimate and habitat for favorable species while improving farms' profit and income opportunities and stability [43,44].

In addition, many EbA practices (e.g., mulching, trees, native cultivars, etc.) that are already part of the local knowledge [45,46] have already been widely promoted by international and national initiatives [47,48] and are already being used by many coffee, maize and beans smallholders in the region [35]. In this article, we examined a suite of adaptation practices available to smallholder farmers in Latin America, including both EbA practices and conventional practices (e.g., transgenic hybrids, technified irrigation, etc.).

2. Materials and Methods

Our methodology included four steps; namely, search for documents, create a list of practices and benefits to be registered, review documents to register evidence, and synthesize results. In Appendix A we provide the PRISMA flow diagram of the systematic process followed to identify scientific documents while in the following sections we provide more details on each step and present their associated outputs.

2.1. Document Search

For the selection of research documents, we used Boolean operators to combine terms related to climate impacts (e.g., storm, drought, hurricane, etc.), agricultural practices (e.g., mulching, weed management, pest control, etc.), and effects of practices (e.g., on productivity, costs, phenology, disease, etc.). We included keywords (Appendix B) regarding the crop species, i.e., Latin and common names of coffee, bean and maize and the names of countries in the region. We searched Web of Knowledge (WOK), the Scientific Electronic Library Online (SciELO), the Alliance of Agricultural Information Services (SIDALC) and Scopus to include peer-reviewed and gray literature (i.e., thesis, conference papers, technical reports and books) published in English, Spanish and Portuguese spanning from no pre-defined beginning date until 2021. After eliminating documents from unrelated domains (e.g., medicine, astronomy, etc.), we reviewed the abstracts of documents to select only those which used field experiments and expert opinions (i.e., we excluded modelling studies or literature reviews).

We retrieved and reviewed the abstracts of 5233 documents from which we selected 304 documents which we reviewed in depth (Appendix C). As shown by Figure 1, the majority of the research documents were from Brazil and Mexico, followed (especially for beans and coffee) by Costa Rica and Panama.



Figure 1. Number and geographical distribution across Latin America of the research documents analyzed for coffee $n = 120$, maize $n = 99$ and beans $n = 85$.

The documents we reviewed were published in English (141), Spanish (126), Portuguese (35) and French (2) and covered the period of 1953–2021. The most common publications were journal articles (244) followed by theses (23), conference proceedings (19) and books (18). A large majority of the documents reported findings from field experiments (85%) followed by surveys (7%) and in a much lesser proportion laboratory experiments

(2%) or observations (3%). Evidence came from a variety of environmental conditions in terms of altitude (up to 2200 m), soil types, slopes and Holdridge life zones.

2.2. List of Practices and Benefits

The list of practices ($n = 26$), the majority of which ($n = 20$) were based on the use of biodiversity and ecosystem processes, was based on the knowledge of experts on those crops from the region familiar with smallholder farming practices and related literature (Table 1). For three of the remaining practices the research documents did not specify the technology used so that they can be considered ‘ecosystem-based’ depending on the technology used, for example, biological control can rely on locally available predators, grafting can be applied to native species, improved cultivars can refer to selecting better-performing landraces. The rest of the three practices can be defined as a non-ecosystem-based practice as they are often based on high technical agrochemical and biological processes (i.e., inorganic fertilizers) and use hybrids or infrastructure technology (i.e., irrigation). The majority of documents focused on coffee ($n = 120$), followed by maize ($n = 99$) and beans ($n = 85$). Practices focusing on shaded coffee systems (e.g., multi-use shade trees, N-Fixing trees and timber-shade trees) accounted for more of the research documents (26% of documents).

Table 1. Total number of documents retrieved and analyzed by practice and crop system.

Practices	Description	Number of Documents			Total
		Coffee	Maize	Beans	
Multi-use shade trees *	Include mix of planted species with different uses	40			40
N-fixing shade trees *	Use N-fixing trees as shade	31			31
Improved cultivars **	Use unspecified genetically improved varieties		8	22	30
No tillage *	No disturbance of soil superficial structures		24		24
Multi-species cropping *	Use mix annual crops in structured systems	3	11	8	22
Land races varieties *	Use seeds from landraces		12	9	21
Mulching *	Cover soil with vegetation biomass residues		9	11	20
Cover crop *	Use leguminous crops as vegetation cover	1	7	3	11
Inorganic fertilization	Use inorganic fertilizers	3	3	4	10
Irrigation	Provide water in stress periods	3	2	5	10
Timber shade trees *	Include comercial wood tree species	10			10
Pruning *	Cut non-productive tissue	9			9
Biological Control **	Use of natural predators	7	1		8
ConservationTillage *	Minimize intensity and/or frequency of tillage		2	5	7
Sowing date *	Adjust sowing date	1		6	7
Density of plants *	Increase crop plant density	2	3	2	7
Rotation *	Alternate crops		5	1	6
Grafting **	Improve cultivar by grafting	4		1	5
Hybrids	Use hybrid varieties		5		5
Mychorrize *	Inoculate N-fixing organisms in roots		1	4	5
Alley Cropping *	Combine rows of trees/shrubs with crops	1	1	2	4
Weeding *	Manually eliminate undesired vegetation	1	1	2	4
Organic fertilization *	Apply organic fertilization	2	1		3
Change Crop *	Change cultivated crop	2			2
Live barriers *	Plants in plot borders and/or on contour lines		2		2
Agro-silvopastoral *	Use a mix of crops, trees and grasses		1		1
	Total	120	99	85	304

* Ecosystem-based practices. ** Practices that can be ecosystem-based depending on the technology used.

The list of benefits identified included fifty-five benefits based on the literature on smallholder farming practices. As shown in Table 2, we conceptually grouped benefits in the three dimensions (i.e., first column) relevant to smallholder production systems mentioned in Section 1.1; namely, adaptation benefits to extreme events, enhancement of farms’ natural assets (to increase farms capacity to withstand environmental stress) and socioeconomic feasibility of their adoption in a smallholders’ production context (e.g., enhancing income opportunities, reducing costs, etc.). Under these dimensions we highlighted twelve sub-dimensions (column 2) which further specify the benefits provided to smallholder production systems. Finally, under each sub-dimension in Table 2, we identified the specific variables measured in the reviewed research, registered as either positive or negative evidence as illustrated in Section 2.3.

Table 2. List of the benefits and evidence, and the number of records registered regarding the positive (Pos) and negative (Neg) effects of coffee, maize and beans agricultural practices on smallholders in Latin America. In parentheses next to each variable description we included a reference to the literature* supporting the inclusion of benefit in the list.

Dimension	Sub-Dimension	Variables	Code	Pos	Neg	Tot	
Adaptation benefits	Buffers extremes	Buffering temperature extremes (min) (a)	BufMaxT	25	0	25	
		Buffering temperature extremes (max) (a)	BufMinT	24	0	24	
		Buffering physical impacts of heavy rainfall on crops (a)	BufRain	8	0	8	
		Reducing excessive radiation (a)	RedRad	16	0	16	
		Protecting against strong winds (a)	ProStrWin	10	0	10	
		Reducing competition for light (b)	RedLightC	1	2	3	
				84	2	86	
	Genetic tolerance	Providing genetic tolerance to drought (a)	GenTolDro	33	0	33	
		Providing genetic tolerance to extreme rainfall (a)	GenTolRai	2	0	2	
		Providing genetic tolerance to high temperatures (a)	GenTolHig	9	0	9	
		Providing genetic tolerance to low temperatures (a)	GenTolLow	8	0	8	
		Providing genetic tolerance to strong winds (a)	GenTolWin	1	0	1	
		Providing genetic tolerance to climate change (a)	GenTolCC	3	0	3	
				56	0	56	
	Decrease incidence of crop disease	Acting as a barrier for disease dispersal (c)	BarDecDis	1	1	2	
		Providing genetic tolerance or resistance to disease (a)	TolCroDD	6	0	6	
		Improving beneficial biodiversity habitats (c)	HabDecDis	3	0	3	
		Improving soil physical properties (c)	SoilDecDis	3	1	4	
		Regulating microclimate conditions to control disease (c)	MicDecDis	3	6	9	
					16	8	24
		Decrease incidence of crop pests	Acting as a barrier for pest dispersal (c)	BarDecPes	4	0	4
			Promoting biological control of pests (c)	BioConDP	11	0	11
			Providing genetic tolerance or resistance to pests (d)	TolCroDP	1	0	1
			Improving beneficial biodiversity habitats (c)	HabDecPes	12	1	13
	Improving chemo-physical soil quality to control pests (c)		SoilDecPes	3	1	4	
	Improving microclimate conditions to minimize pests (c)		MicDecPes	4	2	6	
	Reducing alternative hosts of pest bearer (c)		RedHosDP	0	1	1	
				35	5	40	
	Crop phenology	Homogenizing flowering seasonality (e)	StanFlo	2	1	3	
		Extending longevity of perennial crops (f)	ExtCofLiv	2	0	2	
Reducing the crop life cycle period (c)		ShortCroCyc	19	1	20		
			23	2	25		
Total records of Adaptation benefits				214	17	231	

Table 2. Cont.

Dimension	Sub-Dimension	Variables	Code	Pos	Neg	Tot	
Farms' natural assets	Soil conservation	Reducing soil erosion (20)	RedEro	19	2	21	
		Reducing gully formation (g)	RedGully	2	0	2	
		Reducing soil nutrients leaching (c)	RedLeach	3	0	3	
		Reducing competition for nutrients (c)	RedNutC	0	1	1	
		Increasing organic carbon within the soil (c)	IncSOC	19	3	22	
		Improving soil fertility (c)	ImpSoilFer	37	2	39	
			Improving soil structure (h)	ImpSoilStr	22	2	24
					102	10	112
	Water conservation		Increasing water infiltration into soil (c)	IncWatInf	8	0	8
			Increasing water retention in soil (c)	IncWatRet	32	3	35
			Increasing water-use efficiency (i)	IncWUE	14	1	15
					54	4	58
	Biodiversity conservation		Increasing pollinator health (j)	FavBenBio	6	0	6
			Favoring beneficial microorganisms in the soil (c)	FavBenMic	14	2	16
					20	2	22
			Total records of Farms' natural assets benefits		176	16	192
	Crop performance/Increase Crop		Increasing crop quality (k)	IncProQua	22	0	22
			Increasing the system's overall biomass production (l)	IncSysBio	25	1	26
			Increasing crop yield (m)	IncCroYld	128	38	166
		Increasing crop biomass production (r)	IncCroBio	38	7	45	
		Increasing the number of crop cycles per year (l)	IncCroCyc	1	0	1	
		Increasing the number of chances to harvest (m)	IncHarOdd	4	0	4	
				218	46	264	
Socioeconomic support	Economy/Costs	Increasing household income (n)	IncHowInc	33	2	35	
		Diversifying household income (n, o)	DivHouInc	55	1	56	
		Reducing the management costs of the practice (n)	RedCostMP	13	27	40	
		Reducing investment costs (p)	ShoRturn	10	0	10	
					111	30	141
	Adoption		Reducing the requirement for structural changes (q)	FewChaReq	1	1	2
			Reducing the need for technical assistance (r)	FewInfUpg	0	1	1
					1	2	3
	Reduce external inputs		Reducing weed abundance (u)	RedWedAbu	26	2	28
			Reducing the use of chemical fertilizers (t)	RedFert	12	11	23
		Reducing labour requirements (n)	RedLabReq	6	20	26	
		Reducing the use of chemical pesticides (v)	RedPest	8	8	16	
				52	41	93	
		Total records of Socioeconomic support benefits		382	119	501	
			Total	772	152	924	

* a = [49]; b = [50]; c = [42]; d = [51]; e = [52]; f = [53]; g = [54]; h = [55]; i = [56]; j = [13]; k = [57]; l = [58]; m = [59]; n = [60]; o = [61]; p = [62]; q = [17]; r = [63]; s = [64]; t = [65]; u = [66]; v = [67].

2.3. Review of Evidence

For each document, we revised the research evidence for the effects of the agricultural practice on one or more of the above listed benefits (Table 2). Evidence refers to the specific measurement records reported in each document on the effect of a practice for the benefits we listed. Since most documents measured the effects on more than one benefit, the total number of benefits registered as evidence ($n = 924$) was higher than the number of documents revised ($n = 304$). We registered whether the effects were positive or negative. We considered an effect to be “positive” when there was evidence that the practice provided specific benefits among those listed. We considered an effect to be “negative”

when the results suggested that the practice actually reduced or worsened the achievement of a specific benefit (e.g., reduce yields, increase exposure to climate extremes, increase dependency on external inputs, etc.). As shown in our result section, for some practices, we found evidence indicating a positive effect on a specific benefit in one document and a negative effect in another.

Of all the measurement records registered, more than eighty percent confirm positive effects of the practices (Table 2). The dimension concerning socioeconomic feasibility for smallholder farming systems was the most studied dimension (i.e., 54% of all records). Within this dimension, a large part of the research evidence (52%) focused on the benefits of practices in increasing yields, reducing economic production costs (28%) and the dependency on external inputs 18%. While evidence of the ease of adoption for smallholders was the least researched (less than 1%).

The second largest number of records focused on the adaptation benefits (AB, $n = 231$) of practices in reducing the impacts on crops by extreme weather conditions ($n = 86$), genetic tolerance ($n = 56$) and to a lesser extent on controlling pests ($n = 40$) and diseases ($n = 20$). In the benefit dimension regarding the farm's natural assets (FNA), more records were found on the sub-dimensions of soil ($n = 112$) and water ($n = 58$) conservation than on biodiversity ($n = 22$).

2.4. Results Synthesis

To synthesize and communicate the results of our review, we used two visualizations for each of the cropping systems. The first was a table summarizing the evidence that a given practice confers a particular benefit. We used a darker green to indicate when we found at least two measurement records confirming that practice A provides a positive effect for benefit B. Lighter green indicates that we could only find one record of that positive effect while white cell indicates that no evidence was found. We also show in the same table records of negative effects following the same principle but using two stars where at least two records of a negative effect were found and one for only one such record found.

We also created a new table summarizing the list of practices for which we registered two or more reports evidencing positive effects (i.e., the darker green cells) in any of the benefit variables. In this way, only the most promising practices (i.e., those counting with several records of positive effects) were included in the table. To further improve visual clarity, we also combined benefit variables to show them at the level of the sub-dimensions of smallholder farming adaptations (e.g., buffer extremes, genetic tolerance, disease control, water conservation, etc.; see Table 2 above). Each cell of the Sankey table reports the sum of the number of measurement records of positive effects (including only those with two or more records) that each practice has on each benefit sub-dimension. In order to identify which variables comprised each of the links between practices and the specific sub-dimensions, the reader can see which cells in the accompanying evidence table are highlighted in darker green. The lines in the Sankey diagram link agricultural practices on the left to the sub-dimensions of benefits (on the right). The lines in the diagram only show evidence of the positive effects; the thickness of the lines reflects the proportion of the total records (n reported with each practice) that confirm that positive effect. This diagram allows readers to easily visualize the extent to which evidence can confirm the multiple benefits provided by a practice and identify which practices might be promising for a smallholders' production contexts.

3. Results

In the following section, we present the evidence and knowledge gaps regarding the benefits each practice can provide to support smallholder adaptation in coffee, maize and bean production systems in Latin America. For each crop, we group practices based on the strength of the evidence (i.e., number of measurement records) showing the extent to which they can provide multiple benefits across the three dimensions of a smallholders' adaptation;

namely, adaptation benefits (AB), farms' natural assets (FNA) and socioeconomic feasibility of their adoption (SEA).

3.1. Effects of Coffee Farming Practices

The first group of practices highlighted in green in Figure 2a included EbA practices using trees for shade (i.e., multi-use shade trees, N-fixing trees, timber-shade trees), whose contribution to all three dimensions of the adaptation benefits improve farms' natural assets and socioeconomic feasibility of their adoption, supported by strong evidence, i.e., two or more measurement records (Figure 2a). While all of these EbA practices can contribute to buffer the impacts of climate extremes (i.e., extreme temperature, rainfall, radiation, winds), shaded polycultures and the use of N-fixing tree species can also create biodiverse habitats for pest control, improve water retention, soil structure and organic matter, as well as reduce erosion. All the three EbA practices, in addition, can provide several benefits in the SEA dimension as they can help diversify household incomes and increase production quality (*IncProQua*). We found contradictory evidence for the case of Multi-use shade trees where we registered more than two records of negative effects on soil organic matter and erosion reduction. Similarly, for Timber-shade trees we found records in different research documents of both their positive and negative effects on crop yields.

The second group of practices (highlighted in blue) included only biological control for which we found strong evidence for (i.e., two or more measurement records), suggesting that it can reduce the dependency on external inputs, and be an effective means in controlling pests. For this practice there is a large knowledge gap regarding its contribution to buffer climate extremes, controlling diseases, and providing benefits in any of the benefits in the socioeconomic dimension of smallholder farmers (SEA dimension).

The third group of practices (highlighted in orange) included those for which we only found strong evidence of their benefits for one of the three dimensions of a smallholders' adaptation to climate change. Here, the literature showed that inorganic fertilization and pruning in shaded coffee systems can increase yields, changing crops can help diversify a household's income and that intercropping can help reduce weeds. Among these practices, we found weak evidence that pruning can extend the life of perennial crops (*ExtCoLiv*), increase soil organic matter and favor beneficial biodiversity.

The fourth group included the rest of practices, such as organic fertilization, alley cropping, legume cover crops, cultivars, irrigation, weeding, managing sowing density and changing sowing dates. For these, we found only weak evidence (i.e., one record) of the benefits they can provide. More specifically, cultivars can provide genetic tolerance to water scarcity conditions and help control disease (AB dimension), increase water-use efficiency (FNA), increase yields and reduce practice management costs (SEA dimension). Irrigation can reduce the risk of pests, regulate crop phenology (AB), increase crop yields and biomass production (SEA).

The visual synthesis in the Sankey diagram (Figure 2b; $n = 168$) confirms tree-based EbA practices associated with shaded coffee systems (i.e., multi-use shade trees, N-fixing trees, timber-shade trees) provide multiple benefits in different dimensions relevant for a smallholders' adaptation to climate change. More specifically, polyculture and use of N-fixing species contribute positively to buffering many impacts of extreme events and, though with lower number of records (i.e., thinner line), reducing costs and dependence on external inputs. There is also evidence that these practices can increase productivity in some cases; however, there were also reports that these practices could reduce yields.

3.2. Effects of Maize Farming Practices

For maize we identified three groups of practices. In the first group, among the practices (highlighted in green) that can provide benefits across the three dimensions relevant for smallholder adaptation, we only found strong evidence for no tillage. The registered records found for this practice suggest that it can reduce the impacts of low temperatures, promote pest control (AB dimension), improve soil structure and fertility,

efficiency of water use, and mulching can reduce soil erosion. The use of leguminous cover crops can improve soil fertility and also increase crop and farm biomass.

In the third group, we found strong evidence for the benefits on only one dimension. While we found that the three practices comprising this group (i.e., live barriers, inorganic fertilization and sowing density) can contribute to the socioeconomic dimension of smallholders, we found very limited research records of their contribution to the other benefits dimensions. More specifically, both sowing density and live barriers can contribute to increasing household income. Strong evidence also suggests that the former together with inorganic fertilization can also increase crop yields. Interestingly, for an ecosystem-based practice such as live barriers there was also weak evidence for its contribution to the other two dimensions. One record was found reporting its benefit in reducing pests by providing habitats for biodiversity, its ability to reduce soil erosion and increase water retention on the farm plot.

The final group included practices (i.e., agro-silvopastoral, conservation tillage, mycorrhiza, alley cropping, biological control, organic fertilization, weeding) for which we could not find strong evidence of their contribution to any of the 55 benefits. Among these, we found that research in the region analyzed a broader spectrum of benefits for mycorrhiza, weeding and agro-silvo-pastoral practices. This small number of records suggest that the former can contribute to improve soil fertility and soil biodiversity (FNA), increase crop biomass (SEA), while weeding can help control pests and increase yields (SEA), and agro-silvo-pastoral practices can contribute to buffer the impacts of different climate extremes and help control diseases (AB). Finally, mycorrhiza can contribute positively to improve soil fertility, support beneficial biodiversity and increase crop biomass.

The Sankey diagram (Figure 3b) highlights the multiple benefits that no tillage and native cultivars can provide to smallholders. More specifically, there is strong evidence that no tillage can contribute to soil and water conservation, reduce the impacts of extreme climate events and reduce costs. The use of landraces can provide genetic tolerance, regulate crop phenology and increase yields. However, there was no evidence that these practices can benefit soil or water conservation or other socioeconomic aspects of smallholder adaptation.

3.3. Effects of Bean Farming Practices

For all of the practices analyzed for bean farming systems we found strong evidence of their contribution across the three benefits dimensions relevant for a smallholders' adaptation. The first group highlighted in blue included seven practices (i.e., native and improved cultivars, alley cropping, mulching, mycorrhiza, sowing dates and irrigation) for which we found strong evidence of their benefits in only two of the three dimensions. For the first two (i.e., native and improved cultivars) strong evidence suggests they can provide both genetic tolerance to dry conditions and help regulate crop phenology by shortening the crop cycle. In addition, we also found strong evidence suggesting their contribution to increase yields; however, for improved cultivars, we also found that they can have negative effects on yields (Figure 4a).

For other practices of this first group (i.e., alley cropping, mulching, mycorrhiza, sowing dates and irrigation), we found strong evidence of their positive contribution to increase yields (except mycorrhiza for which we only found weak and contrasting evidence). Alley cropping, mulching and mycorrhiza can help increase soil fertility and crop biomass but the former, in addition, can also provide benefits in the socioeconomic dimension by reducing weed abundance and the dependency on external fertilizer inputs. Finally, we found strong evidence (i.e., two or more measurement records) that adjusting sowing dates and irrigation can help in shortening the crop cycle and increase water-use efficiency.

The second group included six practices (highlighted in orange) (i.e., intercropping, conservation tillage, weeding, sowing density, legume cover crops and inorganic fertilization). For these we found strong evidence of their contribution to the benefit variables belonging to the socioeconomic dimension (SEA). All these practices can increase crop yields. In addition, intercropping can improve crop quality and conservation tillage can

Figure 4b shows that improved cultivars and native cultivars can increase productivity while also providing genetic tolerance to climate extremes, regulate phenology and control diseases. It is also evident from the figure that we found no strong evidence for the benefits to the socioeconomic dimension of a smallholders' adaptation that these two practices provide. Conversely, we found that intercropping and mulching can contribute to increasing productivity and reduce production costs and dependency on external inputs.

Overall, the findings across the three crops above showed that several dimensions of the adaptation of a smallholder farming system have been largely understudied. More specifically, we only found strong evidence from a few papers reporting the benefit variables under the adaptation benefits dimension. Except for a few practices presented above, for the majority of practices across the cropping systems little is known on their possible contribution to buffering extremes, decreasing pests and disease. For example, for only two of the nineteen practices in the case of maize farming (i.e., no tillage and intercropping), three of the sixteen for coffee farming (i.e., multi-use shade trees, N-fixing trees, timber-shade trees) and none for bean farming, we could only find strong evidence for the positive contribution to the sub-dimension, buffer extremes. Additionally, under the other sub-dimensions of adaptation benefits, the table and the diagram visualize contain similar gaps with only a few practices actually being tested by research in the region. In this dimension, we found strong evidence for the positive effects of genetic tolerance from cultivars to climate extremes for maize and bean farming systems and only one report for the coffee farming system (*IncTolDro*).

In relation to the benefits to a farm's natural assets, we found a larger number of practices with published evidence of their contribution to soil, water or biodiversity conservation. However, for more than eighty percent of practices ($n = 13$) in coffee systems, seventy percent in maize ($n = 14$) and beans ($n = 11$) systems, we found no strong evidence in the reviewed research of their contribution to a farm's natural assets. In the socioeconomic dimension (the most researched across all cropping systems), we found a larger knowledge gap for coffee and maize compared to bean production systems. More specifically, for nine of sixteen practices in coffee and seven of the nineteen in maize systems, we only found weak to no evidence of their socioeconomic benefits to smallholders, differently from beans systems where only two of fifteen practices are under studied in this dimension. In general, our review suggests that the least studied benefits are those concerned with the extent to which the practices do not require important significant changes in their crop production structure or continuous support from technical assistance.

4. Discussion

Our review of scientific evidence for the effectiveness of different agricultural practices in enhancing the adaptation of coffee, maize and bean cropping systems suggests that research in the region has investigated the multiple benefits of the adaptation practices in coffee system more thoroughly than in the maize and bean farming systems. Overall, due to the high diversity of Latin American biomes [68] and smallholder production contexts [69], the number of studies we reviewed might still be too small to provide conclusive recommendations on which practices might be promoted all over the region. However, our findings suggest that for each of these crops there is strong evidence for some promising practices which, though tested in the variety of site-specific conditions, have been shown to reduce the impacts of extreme climate events while providing multiple other benefits.

More specifically, our findings suggest that there is strong evidence that the use of tree-based practices for coffee systems (e.g., using trees for N-fixing or for timber) can contribute by buffering the impacts of extreme climate events while also conserving the natural assets of the farm and benefit smallholders' socioeconomic status. This suggests that these practices represent good example of ecosystem-based practices that can help these producers adapt to climatic extremes while protecting and/or enhancing the natural

assets of their farm and provide opportunities to use resources already available in those production contexts.

For the case of maize and beans we found some promising EbA practices but also large knowledge gaps. For maize, we found that EbA practices already known to producers (e.g., no tillage and use of native cultivars) can provide adaptation benefits, e.g., genetic tolerance, buffer temperature extremes while using local resources and protecting soil and water resources. However, we found none or weak evidence regarding the capability of many of these practices to reduce the impacts of different extreme hydroclimatic events (e.g., for mulching, sowing density, conservation tillage, mycorrhiza, live barriers, organic fertilization, weeding buffering hydroclimatic extremes, pests and disease control), their contribution to biodiversity or their implications in the socioeconomic status of smallholders (e.g., scarce evidence for costs, dependence on external inputs, etc.).

In the case of beans, our review found even more knowledge gaps as, for all practices, research in the region we reviewed assessed a more limited number of benefits. For example, we found a very limited number of records on the possible benefits of many ecosystem-based practices (i.e., crop rotation, legume cover crops, weeding, conservation tillage, sowing density and dates, alley cropping and cultivars) to buffer the impacts of hydroclimatic extremes. In this case, only for EbA practices as native cultivars, mulching and sowing dates had strong supporting evidence that they could reduce specific impacts of extreme weather events (e.g., tolerate dry conditions for native cultivars) and also benefit the socioeconomic status of a smallholders' adaptation by increasing crop yield.

As shown by the larger number of records found in our review, the socioeconomic dimensions has been at the center of research, possibly reflecting the need, underlined by many authors reviewing the use of practices by smallholders farms (e.g., [36,60,69–71]), to understand the extent to which their adoption is feasible in the context of smallholder production and whether they can help reduce the exposure to non-climatic risks (e.g., inputs and outputs markets). While attention to the socioeconomic benefits is very important due to the limited resources and risk-taking margins characterizing smallholder farming systems, the large knowledge gap regarding the adaptation benefits in the face of hydroclimatic extremes might be of special concern given their observed increasing frequency. However, we should consider that there might be two reasons for the lack of documented relationships between a practice and the benefits provided which does not necessarily mean that these relationships do not exist or are not known. First, the “file drawer” problem [72], as a common challenge for evidence systematization efforts, might suggest that negative or insignificant results are unpublished (i.e., kept in drawers), thus resulting in a possible analytical bias. Second, it might suggest that the research assessment of a practice's benefits have not been designed with an explicit objective to capture these adaptation benefits. This might highlight an unfortunate way of framing research questions that does not consider adaptation to extreme events. For example, many studies have been conducted on the genetic resistance of Arabica coffee plants to fungal diseases [73]. Some of these diseases will be exacerbated in the future due to a combination of climatic extremes and societal pressures on smallholders' production systems [74], but this situation is, according to our results, not taken into account in the breeding process when assessing coffee cultivars. Similarly, many studies have been conducted on drip and controlled irrigation to extend coffee cultivation in suboptimal and drier areas [75,76], but not in anticipation of worsening drought in optimal production areas.

Based on these findings, adaptation programs supporting smallholders in Latin America can currently count on either informal information sources, on studies from other regions or, as suggested by our findings, on incomplete knowledge as research in their region only covers a few of the benefit dimensions for each practice. This might limit the possibility to make informed and robust choices regarding which practices are worth promoting that benefit multiple dimensions of a smallholder's farm and adaptation. It might also run the risk of promoting practices that perform well in one dimension but expose smallholders to other unexpected risks or pressures. In addition, the lack of knowledge

on the multiple benefits of each practice might also limit the ability to grasp opportunities to valorize EbA practices beyond the farms' plots by, for example, conserving water, soil and biodiversity and thus enhancing the landscape's environmental performance. Similarly, while the existing evidence base supports the claim that many EbA practices can improve household wellbeing by diversifying income (e.g., tree-based practices in coffee, inter-cropping in beans) and increasing yields, there is need for more research to provide evidence that they can also help increase crop quality, reduce production costs and dependency on external inputs or require limited investments for implementing them. Possibly, the lack of records on these multi-dimensional adaptation benefits might also be due to the lack of explicit attention, in the design of the research reviewed, to test the performance of the practices during or after the occurrence of an hydroclimatic extreme.

Our review supports the global call for investing in research to reduce the impacts of climate extremes on smallholder cropping systems [77]. Filling this knowledge gap could help reveal the large potential that many smallholder EbA adoptable practices have to not only reduce the impacts of climate extremes, but also to support the efforts in responding to the recent international calls from governments (e.g., [78–80]) for a transition to agroecology-based food production.

In this respect, strategic research to upscale adaptation programs could fill the knowledge gaps we found and provide evidence for the extent to which many of these EbA practices can provide ecosystem services and goods on- and off-site. For example, a large number of studies have shown the capacity of shaded coffee systems in providing on-site benefits to smallholders and off-site ecosystem services at the landscape scale by enhancing water cycles, reducing soil removal and sediment transport or favoring biological connectivity in the landscape [81,82]. Similarly, more research on smallholder cropping system practices could show that EbA practices, such as no tillage, could help conserve a farm's natural assets but also, as shown in other production context, provide ecosystem services at the landscape scale by conserving soil structure, water content and biodiversity [83]. The following section builds on the evidence we found and the knowledge gaps discussed above to suggest avenues of future research.

5. Conclusions

Based on the scientific evidence we reviewed, we found that ecosystem-based practices based on locally available biodiversity (e.g., trees species, local genetic resources) and low-impact soil management practices can provide a variety of benefits to different dimensions of coffee, maize and bean smallholder production systems. Interestingly, these practices are already adopted by smallholders in the region and can thus be considered relatively well adapted to their production contexts. However, we also found a significant knowledge gap regarding many positive or negative effects that many of the practices might have on smallholder farming systems. In this respect, in the remainder of this section we conclude with three recommendations for future research.

First, our findings suggest that more research is needed to assess the multiple benefits of specific practices that are largely understudied in one or multiple dimensions relevant to smallholder adaptation. This research might design experiments to assess the performance of practices in different biomes and production contexts on multiple specific benefits that are already known by researchers in Latin America or other regions. An example, in this respect, can be the use of weeding (largely understudied in coffee, maize and beans) which, as suggested by research on other crops in Africa [84], can increase natural farm assets (e.g., water and soil conservation) that can reduce the exposure to hydroclimatic extremes (e.g., dry spells or heavy rainfall). Similarly, except for maize and bean systems, there is a huge knowledge gap on the contribution of an ecosystem-based practice, such as legume cover crops, to the socioeconomic dimension of smallholder farming systems or to reducing the impacts of extreme climatic events, controlling pests and diseases, or conserving water.

Second, more national research efforts are needed to increase experimental evidence for the benefits provided by practices implemented in regionally important cropping systems,

and in response to common hydroclimatic extremes affecting smallholders in a variety of biomes and production contexts. This research might use standardized protocols to compile data from a variety of specific crop production locations across these different contexts and in response to specific climate extremes. This interchange might be facilitated by the use of the growing regional digital connectivity in rural areas of Latin America [85], thus facilitating the remote and real-time involvement of smallholders in observing practices effects on a variety of benefit dimensions.

Third, future research should consider similar regional systematization that not only looks into published evidence, but that taps into the rich yet-unpublished knowledge and experiences generated by technical assistance programs and the smallholders' farming efforts in the region. By directly engaging with farmers (e.g., exploiting the increased digital connectivity), this research could recompile real-time data and then systematically assess the bundle of practices implemented by smallholders and their perceived benefits.

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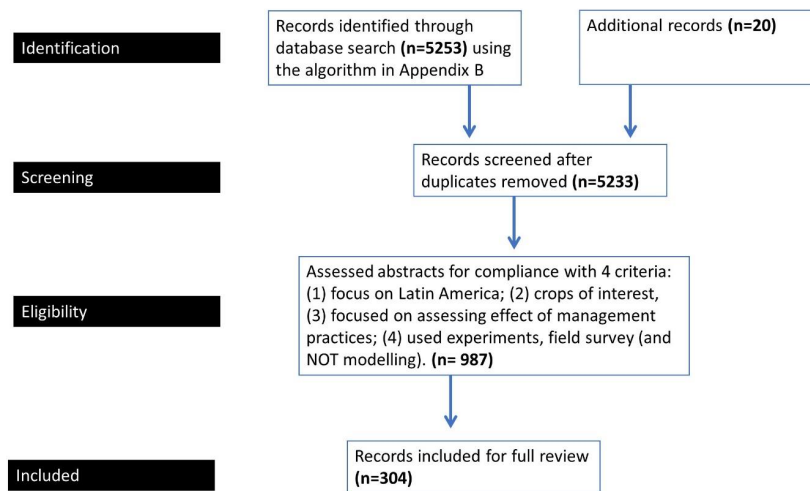
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Appendix A. PRISMA Diagram for the Selection of Scientific Documents for in-Depth Review of Evidence of Practices



Appendix B. List of Papers Retrieved for Search of Evidence for the Effects of Practices in Coffee, Maize and Beans Farming Systems

Section	Boolean Operator between Sections	Agroecosystem Elements	Boolean Operator within Sections	Terms Searched
I	OR	Climate	AND	((Climat * AND (Variability OR Extreme OR Drought OR Flood OR Storm OR Hurricane OR Rain OR Temperature OR Wetness OR Wind OR Radiation OR Amplitude))
		Species	AND	(Maize OR Corn OR Zea mays OR Maiz OR Milho) OR (Bean OR Phaseolus vulgaris OR Frijol OR Feijão) OR (Coffee OR Coffea OR Café OR Cafeeiro)
		Soil	AND	(Soil AND (Erosion OR Fertility OR Nutrient OR Acidification OR Landslide OR Run off OR Lixiviation OR Loss OR Drainage)
II	OR	Climate	AND	((Climat * AND (Variability OR Extreme OR Drought OR Flood OR Storm OR Hurricane OR Rain OR Temperature OR Wetness OR Wind OR Radiation OR Amplitude))
		Species	AND	(Maize OR Corn OR Zea mays OR Maiz OR Milho) OR (Bean OR Phaseolus vulgaris OR Frijol OR Feijão) OR (Coffee OR Coffea OR Café OR Cafeeiro)
		Crop effects	AND	(Crop AND (Physiology OR Pest OR Disease OR Phenology OR Yield OR Productivity OR Harvest OR Subsistence OR Banana OR "Agroforestry system" OR Quezungual OR Breeding OR Loss)
III	OR	Climate	AND	((Climat * AND (Variability OR Extreme OR Drought OR Flood OR Storm OR Hurricane OR Rain OR Temperature OR Wetness OR Wind OR Radiation OR Amplitude))
		Species	AND	(Maize OR Corn OR Zea mays OR Maiz OR Milho) OR (Bean OR Phaseolus vulgaris OR Frijol OR Feijão) OR (Coffee OR Coffea OR Café OR Cafeeiro)*
		Management practices	AND	(Management AND (Diversification OR Shade OR "Live fences" OR "N-fixing" OR Manure OR Mulching OR "Cover crop" OR Ditches OR "Sediment trap" OR "Planting density" OR "Contour planting" OR "Planting date" OR Terrace OR "Weed management" OR Residues OR Pest control OR Practice OR "Farming system" OR Tillage OR Drain))
IV	AND	Countries	-	Mexico OR Guatemala OR Belize OR Honduras OR El Salvador OR Nicaragua OR Costa Rica OR Panama OR Colombia OR Venezuela OR Ecuador OR Guyana OR Suriname OR French Guiana OR Peru OR Bolivia OR Paraguay OR Brazil OR Cuba OR Jamaica OR Haiti OR Dominican Republic OR Puerto Rico OR Guadeloupe OR Trinidad and Tobago

Appendix C. Scientific Documents Reviewed in Depth for This Review

1. Acevedo, A., Vilches, M. 1992. Comportamiento del rendimiento en plantaciones establecidas con diferentes variedades de sombra, frecuencia y ciclos de poda. *Revista Baracoa* 22 (1): 39-46.
2. Acosta-Díaz, E., Acosta-Gallegos, JA., Trejo-López, C., Padilla-Ramírez, JS., Amador-Ramírez, MD. 2009. Adaptation traits in dry bean cultivar grown under drought stress. *Agricultura Técnica en México* 35 (4): 419-428.
3. Acosta-Díaz, E., Hernández-Torres, I., Rodríguez-Guerra, R., Pedroza-Flores, J., Amador-Ramírez, MD., Padilla-Ramírez, JS. 2011. Efecto de la sequía en la producción de biomasa y grano de frijol. *Revista mexicana de ciencias agrícolas* 2 (2): 249-263.
4. Acosta-Gallegos, JA., White, JW. 1995. Phenological plasticity as an adaptation by common bean to rain-fed environments. *Crop Science* 35 (1): 199-204.
5. Aguiar, AdCF. 2001. Efecto de especies usadas como abono verde en el enriquecimiento de la fertilidad del suelo y en el manejo de plagas. M.Sc. Thesis. Turrialba, CR, CATIE. 93 p.
6. Aguilar Martínez, S. 2012. Análisis económico de la producción de café y uso del bosque en la Reserva de la Biosfera El Triunfo, Chiapas. M Sc Thesis. San Cristóbal de las Casas, MX, ECOSUR. 126 p.
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11. Aleman, F. 2001. Common bean response to tillage intensity and weed control strategies. *Agronomy Journal* 93 (3): 556-563.
12. Alvarado, J., Andrade, H., Segura, M. 2013. Almacenamiento de carbono orgánico en suelos en sistemas de producción de café (*Coffea arabica* L.) en el municipio del Líbano, Tolima, Colombia. *Colombia Forestal* 16 (1): 20-31.
13. Ángeles-Gaspar, E., Ortiz-Torres, E., López, PA., López-Romero, G. 2010. Caracterización y rendimiento de poblaciones de maíz nativas de Molcaxac, Puebla. *Revista Fitotecnia Mexicana* 33: 287-296.
14. Arana Meza, VH. 2003. Dinámica del nitrógeno en un sistema de manejo orgánico de café (*Coffea arabica* L.) asociado con poró (*Erythrina poeppigiana* (Walpers) O.F. Cook). M.Sc. Thesis. Turrialba, CR, CATIE. 100 p.
15. Araújo, A. V., Partelli, F. L., Olios, G., & Pezzopane, J. R. M. (2016). Microclimate, development and productivity of robusta coffee shaded by rubber trees and at full sun. *Revista Ciência Agronômica*, 47, 700-709.
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