Climate adaptation in a minor crop species: is the cocoa breeding network prepared for climate change?

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\textbf{ABSTRACT}

Plant breeding has undoubtedly been successful in increasing the yield of high value commodity crops. In recent decades, efforts have been made to repeat this success in ‘orphan crops’ through a network of regional and national organizations largely composed of public and not-for-profit institutions. Adapting to climate change is a key challenge for these networks. Here we seek to analyze the particular challenges that characterize efforts to develop climate-smart varieties in minor crops, using the example of cocoa. Cocoa is a high-value commodity with a global research network; however, to date it has not received sustained attention from major global research centers. We estimate that globally <100 new cocoa varieties have been released since 2000, and our analysis suggests that this low number is constrained not by a limited availability of germplasm, but by limitations in the infrastructure focused on the final stages of breeding. We conclude that selecting minor crops for a future climate requires a long-term, regional approach that exploits modern technologies, integrates participatory selection, and is managed through a centrally funded network.

\textbf{KEYWORDS}

Climate change; climate adaptation; orphan crops; \textit{Theobroma cacao}; plant breeding

\section*{Introduction}

Agriculture is one of the most vulnerable sectors to global climate change and several studies have already predicted that global agricultural production could suffer progressive yield losses by the end of the 21st century (Challinor et al. 2009; Lobell et al. 2008; Thornton et al. 2011). One means of adapting to these changes is to increase the resilience of crops through plant breeding (Dempewolf et al. 2014; Hellin et al. 2013; Varshney et al. 2011). For major crops the breeding of climate resilient varieties can be viewed as a technical challenge, however, for minor crops there are also challenges at the organizational and policy levels. Here we seek to analyze the particular challenges that
characterize efforts to select varieties for a future climate in minor crop species (sometimes called ‘orphan crops’). We use the example of the cocoa crop and focus on the Caribbean, which has long been a center for cocoa breeding. Although cocoa is not typical of the many minor crop species for which organized breeding is absent, it is an excellent example of an intermediate category of crops that have global reach but have not benefited from the research focus or corporate support that the major crops receive.

Studies suggest the major threat to cocoa production posed by progressive climate change is the high susceptibility of cocoa trees to drought and to the combined effects of hot and dry conditions (Läderach et al. 2013), and there have been a number of calls to produce new cocoa varieties that are more resilient to drought (Carr and Lockwood 2011; Glenn et al. 2013). Cocoa has also received special attention as a possible climate-smart crop, as it has long been grown as part of an agroforestry system that provides additional benefits through enhanced biodiversity and ecosystem services (including carbon sequestration) (Vaast and Somarriba 2014).

Here we assess the degree to which the current cocoa breeding infrastructure is equipped to meet the challenge of adapting to climate change, by making a comparison with more established breeding programs found in major crop species.

**Breeding climate-smart crops: major crops**

Production of major food crops, such as maize and wheat will undoubtedly be adversely affected by global climate change at least in part of their range (Hellin et al. 2013; Lobell et al. 2008; Varshney et al. 2012; Wheeler and Braun 2013). For these major crops large public international breeding programs exist, alongside well-developed private sector programs (Duvick 2005; Braun, Atlin, and Payne 2010; Chapman et al. 2012). Several studies have highlighted the importance of adapting the major crop species to future climate change (Morton 2007; Wang et al. 2011). Indeed, efforts are already underway to develop maize, wheat and rice varieties that are resilient to abiotic stress, as well as to pests and diseases that are associated with climatic changes (Fedoroff et al. 2010; Hellin et al. 2013; Long and Ort 2010; Varshney et al. 2011; Wang et al. 2011).

**Lessons learned from major crops**

The impact of climate change on crop production is predicted to be greatest in the tropics (Hellin et al. 2013; Morton 2007; Rosegrant et al. 2009). Tropical regions face a different set of challenges to temperate ones; with many crops already suffering from frequent heat and drought stress (Hellin et al. 2013; Reynolds, Pask, and Mullan 2012). In this regard, maize provides a particularly
maize is a major crop grown widely in developing regions in the tropics, as well as under highly intensified systems in the developed world. Maize is probably the most intensively researched crop species globally (Duvick 2005), although the recent expansion of rice research may soon change this. Maize is also one of the target crops for the International Wheat and Maize Improvement Center (CIMMYT). CIMMYT is the largest public plant breeding institute in the world. CIMMYT is currently working to develop maize varieties with greater resilience to climate change, utilizing the latest technological advancements, including advanced molecular genetics and the ‘omic’ technologies (Hellin et al. 2013; Reynolds, Pask, and Mullan 2012). This sustained effort has resulted in a steady stream of new varieties and a constant increase in crop yields of maize and other major crops (Anon 2010).

The work at CIMMYT and elsewhere has shown that resilience to heat and drought varies widely between maize varieties. This pre-breeding information represents a valuable resource for maize breeders. Indeed, there have been clear successes in maize (Bänziger et al. 2006) and candidate markers for heat tolerance have been incorporated into integrated breeding programs (Hellin et al. 2013; Reynolds, Pask, and Mullan 2012). However, although breeding programs focused on abiotic stress have existed for at least three decades (Bänziger et al. 2006), the process of bringing innovations to market is slow. Even for the most amenable annual crops, bringing a new variety to market typically takes 10 years or more (Cairns et al. 2013; Chapman et al. 2012). Breeding for tolerance to abiotic stress is complex compared to breeding aimed at improving resistance to a single pathogen (Varshney et al. 2011). There are both logistical barriers (i.e. the stress factor is not readily reproducible in the field), as well as biological constraints (abiotic stress responses tend to be controlled by multiple genes with a large genotype × environment interaction). Given this, there are many lessons that can be learned for future breeding programs.

**Broadening the genetic base**

Work with major crops has shown that valuable genetic variation exists for resilience to abiotic stress. Identifying this was only possible due to the large collection of accessions available for study (Anon 2010). Broadening the genetic base of minor crops will be key to allowing the selection of varieties for a future climate. This includes broadening the range of varieties available to growers, as well as conserving the genetic diversity contained in wild populations (Dempewolf et al. 2014).

**Accessing the most appropriate technologies**

There is an increasing awareness that breeding for abiotic stress is best achieved by selecting for resilience to multiple stress factors simultaneously
(Tardieu and Tuberosa 2010; Feller 2016; Varshney et al. 2011). Related to this is the need to use more advanced methods (e.g. marker-assisted recurrent selection and genomic selection) for detecting the important genes, rather than relying on simpler approaches (e.g. marker-assisted back-crossing) used to successfully breed for disease resistance (Varshney et al. 2011). Unfortunately, although methods, such as marker-assisted recurrent selection are used routinely in private sector breeding programs for cereals, they are less common in public breeding programs focused on minor crops (Beebe et al. 2013; Tester and Langridge 2010; Varshney et al. 2011). Nonetheless, recently developed genomic selection approaches have greatly enhanced the effectiveness of recurrent selection for multiple/complex traits in crop breeding programs. Most recently, the use of gene editing approaches has become possible. The effectiveness of these approaches, however, depends on knowledge of the basic biology associated with the traits (e.g. molecular markers or candidate genes). This, in turn, depends on effective and efficient methods of assessing the complex traits in order to update prediction models (Heffner, Sorrells, and Jannink 2009; Tester and Langridge 2010). It is difficult to contemplate how this can be achieved without sustained support from public organizations operating on a regional or international scale.

**Gold standard or fool’s gold?**

The gold standard for plant breeding involves prolonged intensive selection utilizing advanced molecular tools, followed by multi-year and multi-site trials (Braun, Atlin, and Payne 2010). It is difficult to imagine that this kind of approach will ever be feasible for minor crop species. Yet, it would be detrimental if minor species were to be lost due to competition from major crops that have undergone this best practice breeding. An alternative approach needs to be found that allows minor crops to benefit from best practice technology without the resource commitment that is currently required.

**Public and private sector roles**

It is clear from the above discussion that breeding for climate resilience requires a long-term, coordinated approach. Although publicly funded organizations, such as CIMMYT play a crucial role in directing plant breeding, much of the work in producing commercially available varieties is carried out by private for-profit entities (Chapman et al. 2012; Pingali and Traxler 2002). For minor crops, the private sector typically does not engage in breeding programs, thus there is a resource-gap. Although some public sector programs exist, these are fragmented and do not include holistic development of the seed value chain. Funding mechanisms need to be put in place to fill this
gap. This is particularly true for cocoa, as the burden of producing new varieties is largely placed on the producing countries in the developing world, while the profits tend to be earned in the developed world.

**Breeding climate-smart crops: minor crops**

For crops other than the well-researched major crops (e.g. maize, wheat, rice, and soybean), there is a lack of knowledge regarding the direct effects of climate change on their basic physiology (Tubiello, Soussana, and Howden 2007), and there is a noticeable absence of breeding programs aimed explicitly at producing crops resilient to climate change (Smit and Skinner 2002; Varshney et al. 2011). This is in part due to a lack of organizational structures. Smit and Skinner (2002) analyzed the processes behind the production of new varieties in Canada and outlined the structures required for a large-scale breeding program as: government agencies to encourage breeding research; corporations to develop and market new varieties; and producers to grow these new varieties. For minor crop species the middle step is not fulfilled, at least not directly, by the private sector. The Consortium of International Agricultural Research Centers (CGIAR), an international public body, coordinates the pre-breeding stage for a small number of mandated minor food crops. Common bean in particular has received much attention as a crop in need of breeding for climate resilience (Beebe et al. 2013). However, as a global organization, CGIAR are limited in their ability to implement the introduction of new varieties on a local scale (Bellon and Morris 2002; Morris et al. 2006). For the remaining minor crops, such as cocoa, the middle step is performed by a complex network of bodies sharing responsibility (Anon 2010).

**The cocoa breeding network**

Cocoa is a high-value global commodity with a well-developed research network (Monteiro, Lopes, and Clement 2009; Laliberté et al. 2011). Nonetheless, it is a niche commodity grown mainly on small farms and is unlikely to receive sustained attention from major global research centers. Globally, only an estimated 30% of cocoa grown uses officially selected varieties, with the remaining 70% using traditional landraces most of which have undergone some selection in the past (Eskes 2011). It is uncertain whether this approach has the capacity to deal with novel challenges, such as climate change.

Monteiro et al. (2009) described the selection methods used in cocoa breeding programs. Typically, breeders have access to diverse germplasm with considerable variation for the desired traits, this has included on-farm collections (participatory selection). A small subset of this material has been
characterized for the major selection criteria (disease resistance, productivity, and bean quality), and in a few cases genetic markers have been identified. Most breeding programs rely on a single cross, for example combining a recognized variety with a novel accession. The resulting hybrids are allowed to cross naturally, and promising hybrids undergo further phenotypic characterization. Until recently, more advanced recurrent selection methods had only been used in Trinidad, and there has been little effort to record or quantify the genetic gain from breeding material used during the crosses. Promising material is typically evaluated in a single site, or using on-farm trials within a country. Some breeding programs aim to produce a single clone that can be propagated vegetatively, while others distribute hybrid seeds from the desired biparental cross.

The recent growth in global demand for cocoa has resulted in a renewed focus on cocoa production systems. The majority of cocoa is produced in Africa, with notable increases in production in Asia and South America in recent decades (Table 1). The Caribbean has also seen an increase in cocoa production in recent decades, and although representing a relatively small proportion of global production the cocoa produced within the Caribbean accounts for much of the fine-flavor beans (with seven of the eight exclusive fine-flavor producers located in the Caribbean). The majority of cocoa breeding in the Caribbean takes place in Trinidad, which in turn distributes germplasm to other local centers—notably the Dominican Republic. The current structure for cocoa breeding in Trinidad is outlined in Table 2. This relatively complex network is typical of cocoa globally and of breeding in other minor crops (Anon 2010; Medina and Laliberte 2017).

Cocoa was first grown on a plantation scale in the Caribbean by the Spaniards using a type of cocoa called the ‘Criollo’. Following a severe disease outbreak in 1727 that resulted in the deaths of numerous trees, Criollo types were replaced by more resilient ‘Forastero’ types from Venezuela (Bekele, Butler, and Bidaisee 2008; Motilal and Sreenivasan 2013). The natural hybridization between these types resulted in the ‘Trinitario’ types, which combine the fine flavor attributes of Criollo with the resilience of Forastero. Cocoa breeding began in earnest in the 1940s when F. J. Pound of the Imperial College of Tropical Agriculture in Trinidad used the natural Trinitario

| Theobroma cacao production (tonnes) | C. America | Caribbean | S. America | Africa | Asia | World |
|-----------------------------------|------------|-----------|------------|--------|------|-------|
| 1960s                             | 37169      | 46975     | 255892     | 944700 | 9036 | 1317192 |
| 1970s                             | 43587      | 48987     | 365345     | 1006659| 21936| 1518782 |
| 1980s                             | 52102      | 51314     | 523881     | 1145976| 172398| 1982933 |
| 1990s                             | 53544      | 64010     | 466084     | 1775799| 459748| 2859377 |
| 2000s                             | 55908      | 54939     | 372132     | 2559853| 740249| 3835488 |
| 2010-2016                          | 52231      | 85432     | 564592     | 2988763| 740331| 4481925 |
population to select 100 superior mother trees, and distributed genetic material to farmers as varieties (ICS 1–100). A similar selection program in Grenada resulted in the GS varieties. Breeding for resistance to diseases in Trinidad in the 1950s led to the Trinidad Selected Hybrids varieties under the aegis of the Ministry of Agriculture (with support from the Cocoa Research Centre (CRC) at the University of the West Indies). Currently, the Ministry multiplies and sells these varieties directly to growers.

This breeding program is regarded as the oldest recurrent selection program in the world and one that saved the cocoa industry from the most devastating effects of the witches’ broom disease (Bekele 2004; Maharaj et al. 2011). Indeed, much of the pre-breeding for resistance to blackpod and witches’ broom disease was concentrated at the CRC in Trinidad, which houses the international cocoa germplasm collection. The resulting varieties are distributed as genetically identical clones (for grafting). Although clonal breeding is an effective way to achieve genetic gain, this approach limits the genetic diversity within each stand. In the case of cocoa, a mixture of clones is provided to each farmer in order to overcome the problem of self-incompatibility. Nonetheless the genetic diversity within the landscape is limited. Maximizing genetic diversity at the stand and landscape level is a crucial part of protecting crops from unpredictable periods of stress (see following section).

In addition to formal selection programs, cocoa has benefited from ‘introductions’, and from ‘participatory selection’ where growers participate in the development of new varieties. In the modern era, most introductions of exotic varieties have been from Trinidad to other nations. Some informal selection occurs in the host nations, due to natural crossing and choices made by growers. However, given the low genetic variability of the introduced material, improvements are likely to be negligible. This convention, with national breeding programs relying on a low genetic base is not optimal and may pose a particular limitation in breeding for climate resilience.

| Table 2. Institutional context for cocoa breeding in Trinidad. |
|---------------------------------------------------------------|
| **Public** | Ministry of Food Production, Cocoa Research Section |
| Directly involved in the selection and distribution of improved cultivars within Trinidad. Provides funding for national breeding programmes. |
| **Not-for-profit** | Cocoa Research Centre and University of the West Indies |
| Carries out fundamental and applied research, including long-term plant breeding projects. Relies on funds from national and international bodies, which includes contributions from the private sector (see Table 3). |
| **Public** | Cocoa Development Company of Trinidad and Tobago Limited (CDCTTL) |
| Coordinates actions among stakeholders with the aim of maintaining production and quality standards. |
| **Private** | Various farmers groups involved in participator selection in the field (see Maharaj et al. 2011), supported by the The Cocoa and Coffee Industry Board of Trinidad and Tobago. |

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Concurrent with this are efforts to apply newer biotechnological approaches to cocoa. Mars has an ongoing program carrying out genome sequencing of cocoa collections and recently announced a program working with the University of California-Berkeley to research the use of gene editing methods (CRISPR) as an alternative route to aid in the development of disease resistant cocoa varieties.

Internationally, cocoa breeding programs are facilitated by a network of organizations as set out in Table 3. This institutional arrangement is complex with a great deal of interdependency and potentially conflicting goals. Among their other aims, these organizations seek to facilitate national and regional breeding programs by funding both fundamental and applied research. Historically, there has been little investment in research to improve cocoa production, even in comparison to other tree crops, and most national breeding programs are under-resourced (Laliberté et al. 2011; Medina and Laliberte 2017). For example, the Barbados cocoa quarantine was closed in the mid-2000s due to inadequate resources, which accentuated difficulties in sharing germplasm within the region. There are three international cocoa networks, all of which interact with the Caribbean cocoa industry: the Asian/Pacific Cocoa Breeders’ Group, the African Cocoa Breeders’ Working Group and the America’s Cocoa Breeders’ Working Group. In addition, there are overarching organizations, CacaoNet and INGENIC (Anon 2010; Table 3), which aim to share best practices and determine future policy. Primarily due to the nature of funding, the networks in cocoa are not clearly organized around one single hub, but consist of a diffuse set of organizations. Funding usually comes directly from chocolate manufacturers, through their stakeholder organizations or from national or multinational public funds. In the

| Table 3. International bodies involved in cocoa breeding in the Caribbean. |
|-----------------------------------------------|
| **Global Not-for-profit**                     |
| **CacaoNet**                                  |
| Promotes research into the conservation and use of improved cocoa cultivars by coordinating public and private sector stakeholders. |
| **International Group for Genetic Improvement of Cocoa (INGenic)** |
| Promotes international collaboration on breeding and exchanging improved cocoa cultivars. |
| **The International Cocoa Organisation (ICCO)** |
| Among its other tasks, coordinates private and public funding for breeding programmes. |
| **World Cocoa Foundation**                    |
| Promotes best practices in all aspects of cocoa production, including promoting access to improved cultivars. |
| **Alliance of Cocoa Producing Countries (COPAL)** |
| Primarily focusing on production and marketing issues, but also promotes scientific research (no Caribbean countries are currently members). |
| **The Cocoa Research Association Ltd. (CRA)** |
| Coordinates private funding from UK chocolate manufacturers (Cadbury/Kraft/Mondelez International and Mars). |
Americas, for instance, CATIE in Costa Rica manages the breeding of cocoa on behalf of the Central American countries, while national programs exist in many of the South American cocoa producing countries. Much of the technology that supports these breeding programs are provided by United States Department of Agriculture – Agricultural Research Service or directly by research programs supported by chocolate manufacturers or associated organizations.

The International Cocoa Organization, with funding from the Common Fund for Commodities, has launched several large research projects with a plant-breeding component. Similarly, the World Cocoa Foundation has supported research development and breeding programs. At the national stage, the various projects funded have focused primarily on disease resistance (five projects since 2000) rather than climate resilience (0 projects since 2000). The CRA with Cocoa Research UK Ltd. and their partners have focused on the vital task of supplying tools for breeding. This includes fundamental research into the response of the plants to environmental stressors, which has fed into recent projects dealing with climate resilience at the University of Reading and CRC. The cocoa-specific organizations listed in Tables 2 and 3 work alongside others that fund work in a wide range of crop species. These include Bioversity International, CABI, CGIAR, CIAT, CIRAD, ICRAF, IICA, United Nations Common Fund for Commodities, USDA, and several universities.

Within the Caribbean region, The Dominican Republic, Puerto Rico and Trinidad & Tobago, have active programs where new crosses are being tested. The Caribbean centers exchange material with other active programs, such as those in Brazil, Colombia, Costa Rica, Ecuador, USA, and outside of the Americas. Although this global network remains active, only a small number of new varieties have been registered in recent years. Table 4 shows the stark contrast between maize where >9000 new varieties have been registered since 2000, and cocoa, where only 25 new varieties were officially registered over the same period, with a further 64 publicized but not registered with the International Union for the Protection of New Varieties of Plants (UPOV). The low number of new cocoa varieties undoubtedly underestimates the amount of new planting material made available to growers, as many agencies distribute F1 hybrids rather than named varieties (Eskes 2011). Nonetheless, the low number of named varieties and the absence of information is an indication of the disparity between the two crops and of the lack of a global breeding strategy. Table 5 gives estimates of the number of cocoa accessions held in collections globally (22009), and of the number of unique accessions within these collections (10385). The cocoa accessions held in these national collections were not necessarily developed in that country, in most cases the accessions were develop within the Americas and distributed globally. The total
The number of cocoa accessions held globally is considerably less than that seen for major crops (e.g., 327932 for maize; Anon 2010) as is the number of unique accessions (e.g., 42000 for maize; Hay et al. 2013). However, the number of cocoa accessions seems to be sufficient for effective breeding to take place. Comparing Tables 4 and 5, it is clear that the number of accessions in the germplasm collections is not the factor limiting the release of new varieties. Table 5 also categorizes the accessions into ‘breeding material’ (material selected by professional plant breeders usually by combining known parent plants) and ‘landrace’ (material selected on farms). For cocoa, globally about 15% of the accessions are recorded as

Table 4. Estimated number of Theobroma cacao varieties releases since 2000 and the estimated yields from all planted varieties compared to that of Zea mays (based on FAO 2017). varieties include those listed under Plant Breeders Rights on the UPOV PLUTO database; those included on the Turnbull and Hadley (2011), International Cocoa Germplasm Database (ICGD); USDA, Germplasm Resources Information Network – (GRIN); and other published sources.*

|   | Theobroma cacao |   | Zea mays |   |
|---|----------------|---|----------|---|
|   | New varieties |   | Yield (hg/ha) |   |
| C. America | Caribbean | S. America | Africa | Asia | World | World | World | World |
| 2000 | – | – | – | – | – | 4385 | 349 | 43236 |
| 2001 | 1 | – | – | – | – | 4506 | 460 | 44775 |
| 2002 | – | – | – | – | – | 4702 | 422 | 43884 |
| 2003 | – | – | – | – | 4 | 4816 | 537 | 44610 |
| 2004 | – | – | – | – | – | 4780 | 368 | 49452 |
| 2005 | – | – | – | 5 | 5 | 4639 | 318 | 48196 |
| 2006 | 10 | 4 | – | – | 14 | 5050 | 574 | 47719 |
| 2007 | 6 | – | – | – | 6 | 4509 | 497 | 49980 |
| 2008 | – | – | – | – | – | 4462 | 485 | 50828 |
| 2009 | – | 11 | 4 | – | – | 15 | 4463 | 735 | 51635 |
| 2010 | – | – | – | – | – | 4516 | 662 | 51903 |
| 2011 | – | 11 | – | 5 | 16 | 4517 | 412 | 51751 |
| 2012 | – | – | 10 | – | – | 10 | 4520 | 452 | 48893 |
| 2013 | 1 | – | 1 | – | – | 2 | 4437 | 863 | 54611 |
| 2014 | – | – | 7 | – | – | 7 | 4522 | 886 | 56229 |
| 2015 | – | – | – | – | – | 4436 | 654 | 55379 |
| 2016 | – | – | 3 | – | – | 3 | 4380 | 521 | 56401 |
| 2017 | 5 | – | 1 | – | – | 6 | NA | 333 | NA |
| Total | 13 | 32 | 30 | 0 | 14 | 89 | 77640 | 9528 | 849482 |

* Sources for new cocoa varieties:
2001: 1 Ecuadorian varieties listed on UPOV database
2003: 4 Papua New Guinean HC1 ‘Hybrid Clones’, Efron et al., (2005)
2005: 5 Malaysian MCB clones, Haya et al., (2006)
2006: 10 Rizek clones from the Dominican Republic; 4 Brazilian CEPEC varieties, Stela Dalva et al., (2006)
2007: 6 Costa Rican CATIE-R Cacao Improvement Program selected clones, Phillips-Mora et al., (2013)
2009: 4 Ecuadorian EET 500 series clones; 11 Puerto Rican TARS Series cacao selections, Goenaga et al. (2009)
2011: 11 Trinidadian TSH 1300 series clones, Maharaj et al., (2011); 5 new Indonesian KW clones, www.iccri.net
2012: 2 Ecuadorian varieties listed on UPOV database; 8 Ecuadorian EET ESS clones
2013: 1 Ecuadorian ‘CECAB’ variety; 1 Mexican ‘Carmelo’ variety listed on UPOV database
2014: 4 Ecuadorian EET ESS and 1 ’L-Milagro’ varieties; 2 Colombian ‘Corpoica TCS’ varieties listed on UPOV
2016: 2 Ecuadorian INIAP and 1 ‘PMA12’ varieties listed on UPOV
2017: 3 Mexican CAERI and 2 INIFAP varieties; 1 Peruvian CFCH variety listed on UPOV
breeding material. These numbers are comparable to the numbers for maize, where CIMMYT maintains 12% of its accessions as breeding material and for collections of other major crops (Anon 2010). Taken on face value, this suggests that pre-breeding within the germplasm centers is again not the factor limiting cocoa breeding. Thus, the disparity in the number of cocoa varieties officially released appears to be due to the final stage of breeding where a new variety is optimized, often over multiple years and in multiple locations. This stage is most often undertaken by private sector corporations, and it is this step that is often lacking in cocoa breeding.

**Climate smart breeding in cocoa**

The research and breeding network for major crops, such as maize has already begun to adapt to the new challenges due to climate change, however the situation with cocoa is less clear. Although a number of studies have pointed to the need for cocoa varieties that are more resilient to drought (Carr and Lockwood 2011; Läderach et al. 2013; Glenn et al. 2013), to-date no formal programs have been established to select for climate resilience or abiotic tolerance.

As a perennial fruit tree growing in the tropics, cocoa has a particular vulnerability to climate change, and these are discussed in detail elsewhere (Glenn et al. 2013; Läderach et al. 2013; Schroth et al. 2016). In brief, cocoa crops will need to withstand higher mean temperatures with an associated increase in drying from evapotranspiration, higher maximum temperatures that are close to the physiological tolerance of the plants, and more erratic precipitation events in particular instances of prolonged drought. In addition to these direct impacts of climate, disruption of seasonal patterns and life cycles may increase the prevalence of certain pests and diseases or reduce the effectiveness of pollinators (Gregory et al. 2009; Wolkovich et al. 2012).

Figure 1 shows cocoa production in different regions alongside two key climatic indices (annual precipitation and mean temperature of the driest quarter (O’Donnell and Ignizio 2012)). The areas of major cocoa production

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**Table 5. Estimated number of accessions, landraces/farm selections and breeder selected lines of Theobroma cacao.**

| Theobroma cacao accessions in collections | C. America | Caribbean | S. America | Africa | Asia | World |
|-----------------------------------------|-----------|-----------|------------|--------|------|-------|
| Breeding material                       | 200       | 174       | 834        | 315    | 1825 | 3348  |
| Landrace                               | 96        | 275       | 1807       | 543    | 499  | 3220  |
| Other                                  | 932       | 2393      | 6203       | 3430   | 2483 | 15441 |
| Total                                  | 1228      | 2842      | 8844       | 4288   | 4807 | 22009 |

Data from www.cacaonet.org and (Laliberté et al. 2011). Note that accessions may be duplicated across collections; there are an estimated 10385 unique accessions (Turnbull and Hadley, International Cocoa Germplasm Database – ICGD).
follow a fairly narrow climatic range, with western Africa accounting for the
driest areas and Asia holding some of the warmest. **Figure 1** also shows the
changes expected in the two climatic indices based on climate data from
Worldclim (Fick and Hijmans 2017) and climate projections from the IPCC’s

**Figure 1.** Spatial distribution of cocoa production (2012 to 2016; FAO, 2017), current climate
limitations (Worldclim, Fick and Hijmans 2017) and 2050 climate predictions (IPCC 2013). Current
climate limitations based on the Worldclim baseline for 1970-2000 include: annual precipitation
(excluding areas with values < 1250 mm) and mean air temperature of the driest quarter
(excluding areas with values < 20°C). Future climate predictions are based on the Coupled
Model Intercomparison CMIP5 (ensemble of 32 models) using scenario RCP8.5 (+8.5 W/m² in the
year 2100 relative to pre-industrial values) from the IPCC’s Fifth Assessment Report on Climate
Change (IPCC 2013).
Fifth Assessment Report on Climate Change (IPCC 2013). In our analysis, the Worldclim climate baseline represents the climate for 1970–2000, while the future projections use the Coupled Model Inter-comparison (CMIP5, ensemble of 32 models). Annual precipitation is projected to decrease in parts of western Africa and parts of the Americas, having the greatest impact in areas where precipitation is already low (i.e. inland areas of western and middle Africa, and areas of the Americas furthest from the equator). The impact of reduced precipitation is expected to be exacerbated by the projected increase in air temperature throughout the cocoa producing regions (Figure 1).

Loss of cocoa producing land due to dryer conditions in the dry season is a key concern in the major cocoa production regions of western Africa, where severe drought frequently results in tree mortality (Läderach et al. 2013). Within the Caribbean, the direct impact of higher air temperatures is not expected to impact significantly on cocoa production. The major risk factor is expected to be more severe droughts in the dry season (Rhiney et al. 2016 and Eitzinger et al. 2015a; 2015b). Schroth et al. (2016) argue that maximum temperatures may also become deleterious in certain circumstances and higher temperatures have been shown to reduce yield in some plants (Daymond and Hadley 2004; 2008). Given the range of temperatures in which cocoa is currently grown, there is good reason to think that tolerance to heat is achievable (Figure 1; Medina and Laliberté, 2017). Nonetheless, given the interaction between water availability and leaf temperature, it is likely that future cocoa varieties will need to show resilience to combined heat and drought stress (Nankishore and Farrell 2016; Feller 2016; Zandalinas et al. 2018).

Medina and Lieberté (2017) reviewed the current state of knowledge and the capacity of the cocoa breeding network with regard to climate change related heat and drought stress, and in addition to reviewing the literature they implemented a survey of cocoa research institutes globally. They found that research on heat tolerance is limited, but that in recent years there has been an increase in research aimed at selecting varieties that are drought tolerant. They identified >10 institutes with active projects on drought tolerance, with research focusing on water relations, gas exchange and root traits. Since the publication of the cocoa genome (Argout et al. 2011), genomic approaches have also been applied, but application of this approach in cocoa was identified as ‘lagging behind’ in comparison to major crops (Medina and Laliberte 2017).

There is good reason to expect that the cocoa germplasm includes traits that will better equip the crop for drought and heat stress. The range of cocoa in the wild is quite broad and includes considerable bioclimatic variation. A reasonable proportion of this wild variation is represented in global gene-banks (Medina and Laliberté 2017). In addition, although much of the
cultivated cocoa around the globe is the result of breeding that took place in South America and tends to have a low genetic diversity, landraces from outside of cocoa’s center of origin may hold some valuable information with regard to climate adaptation. Landraces that succeed in the dryer parts of West Africa may be one source of drought tolerance traits, while those that perform well in the hotter parts of Asia may be a source of heat tolerance traits (Carr and Lockwood 2011).

The choice of cropping system can also impact on the resilience of cocoa plantations to heat and drought (Moser et al. 2010; Schwendenmann et al. 2010; Vaast and Somarriba 2014). Schwendenmann et al. (2010) used experimental drought implemented in the field with mature shade trees and highlighted the role of the agroforestry system in drought resilience (Schwendenmann et al. 2010). Schroth et al. (2016) argue that the use of shade trees can be viewed as a climate-adaptation measure given the benefits in insulating the cocoa crop from the warming and drying sun. This suggestion is particularly salient given a current trend towards growing cocoa in more open fields often in combination with irrigation. This suggestion is worthy of future study, but it should be noted that interactions between cocoa trees and shade trees are complex, in addition to shade effects, evapotranspiration and root interactions must be considered (Medina and Laliberte 2017; Niether et al. 2017; Schwendenmann et al. 2010; Vaast and Somarriba 2014).

The threat from pests and disease is more complex and is difficult to predict (Glenn et al. 2013), but climate change is thought to have contributed to disease outbreaks in other tree crops (Glenn et al. 2013). More rain in the dry season may be expected to increase the disease load from fungal pathogens within a cocoa stand, but changes on a landscape and ecosystem level may have even larger impacts on individual pests and pathogens (Garrett et al. 2009; Glenn et al. 2013; Gregory et al. 2009). The cocoa breeding network is perhaps better placed to deal with these biotic stresses than with abiotic factors but improvement is still needed.

The recent increase in research focused on abiotic stress is reassuring, however the current efforts appear to be uncoordinated and translating these efforts into new varieties may be hampered by the shortcomings in the cocoa breeding network. What can be done to better align the cocoa breeding network with this challenge?

A policy for minor crops

Worldwide, an estimated 40–50 million people depend upon cocoa for their livelihood (Laliberté et al. 2011) and successful climate adaptation is contingent on the institutional, social, economic and political environments in which key stakeholders operate. In the majority of cases the environments in
which smallholders have to operate have done little to stimulate innovation and diversification of minor crop species. Plant breeding is a vital part of climate adaptation, but it cannot be implemented by individual stakeholders and therefore requires a global and regional policy. We believe the following policy recommendations should be followed to ensure plant breeding is utilized in an equitable and effective way:

**Broadening the genetic base**

‘The future of the world cocoa economy depends on the availability of genetic diversity and the sustainable use of this broad genetic base to breed improved varieties’ (Laliberté et al. 2011)

Genetic diversity provides the building blocks that will be needed to select varieties suited to the future climate. As well as providing individual stress tolerance traits, there is an increasing awareness that incorporating diversity into crop stands increases the resilience to stress (Dempewolf et al. 2014; John-Bejai et al. 2013; Mori, Furukawa, and Sasaki 2013; Tilman, Reich, and Isbell 2012). This genetic diversity includes germplasm held in genebanks, on-farm and in native habitats. Despite the relatively large number of cocoa accessions (Table 5), there are still large areas of wild cocoa that have not been explored (Bekele, Butler, and Bidaisee 2008). Although, recent efforts have improved the prospects for cocoa held in genebanks, on-farm diversity continues to fall and native plants are under increasing pressure from destruction of forest in the Amazon Basin. Laliberté et al. (2011) and Medina and Laliberté (2017) concluded that much of the material held in national collections is ‘under-used or at risk’ and that funding remains ‘insufficient and unstable’. They also point out that although the two international collections have been supported by state and industry funding for many years, this support has not been secured for the long-term. Thankfully, there has been a concerted effort over the last decade to support these genebanks (e.g. CacaoNet). This approach should be replicated in other minor crops as a matter of urgency. In many crops this can be done with support from the Global Crop Diversity Trust and CGIAR.

In the short term, one mechanism for increasing the genetic diversity of cocoa stands is the use of ‘seed gardens’, as have been used in Africa (Opoku et al. 2007) and Brazil (Monteiro et al. 2009). In a seed garden a selection of compatible out-crossing accessions are grown together to allow cross-pollination, the resulting seeds can be used to produce planting material. Seed gardens maintain some control over the consistency of the planting material, but allow for increased genetic diversity as the cross-pollination enhances the diversity of the progeny that are distributed to the growers (this approach also increases the probability of heterosis among the progeny).
**Public and private sector programs**

“While there is more plant research being conducted today than at any time in history, the increased effort has not been evenly distributed geographically, or across crops. Commercially oriented producers in temperate zone countries continue to gain substantially from the increase in private sector research... tropical producers with some marketed surplus in tropical countries are likely to lose due to low incentives for private sector research investments in their environments” (Pingali and Traxler 2002).

Chocolate is largely produced and consumed outside of the tropics and less than 10% of the sale price goes to the grower (Gilbert 2008). Given the current structure of the cocoa value chain, the cost of plant breeding cannot be borne by the growers or their host countries alone. Currently, the funding of plant breeding relies on the goodwill of multinational companies, which at any time may choose to abandon one crop in favor of another (or in favor of some other more profitable venture). Multinational seed companies are unlikely to invest in breeding programs for niche crops, used by small, resource-poor growers. This is especially true for tree crops like cocoa, where generation times are long and intellectual property is difficult to protect as the crop is reproduced clonally (Glenn et al. 2013; Morris, Edmeades, and Pehu 2006). For tropical commodity crops, such as cocoa there is also a justice issue, as the companies trading, selling, and profiting from cocoa are largely based outside of the tropics. Benefit-sharing mechanisms must be put in place to improve public–private partnerships (Lybbert and Sumner 2012; Pingali and Traxler 2002; Roa et al. 2016), and to align the funding of breeding to the profits accrued from the trading and sale of the cocoa commodity. In the long-term the breeding process must be recognized as a public good (Morris, Edmeades, and Pehu 2006).

**Participatory selection**

‘Increased efficiency and sustainability in cocoa breeding is best obtained through direct involvement of cocoa farmers in selection and validation of new varieties and through increased international and regional collaboration...’ (Eskes 2011).

In minor crops, traditional landraces often form a significant component of the genetic diversity. This offers a route for participatory selection as has been implemented for several minor crops worldwide (Almekinders and Elings 2001; Almekinders, Thiele, and Danial 2007; Bellon and Morris 2002; Temple et al. 2011). In cocoa, for example, preliminary evaluations of on-farm populations have uncovered a wide range of genetic traits (Eskes
If participatory selection can be combined with standardization of data collection and coordination of data analysis, this approach could offer a dynamic approach to plant selection, facilitating incremental improvements in the germplasm as different material becomes favored in different locations. This offers an alternative to the gold-standard of multi-year, multi-site fields trials, while still allowing for validation across diverse environments. Participatory selection implemented on a regional scale, could ensure that information and resources are used to the benefit of all growers.

**International collaboration and breeding networks**

“Most of the countries involved in the improvement and production of cacao are highly dependent on genes and varieties characterized and conserved in other countries and regions. Effective management of cacao genetic resources can therefore only be carried out through international collaboration” (Laliberté et al. 2011).

There is a complex array of organizations involved in cocoa research. The CacaoNet project is a welcome initiative aiming to bring these organizations together in a sustainable way. Efforts to stimulate regional collaboration in cocoa breeding have also begun (Efron et al. 2005; Eskes 2011). In other minor crops, ‘breeding networks’ have emerged to bring greater efficiency in breeding by dispersing the cost of conducting trials to end-user countries, while centralizing the costs of science and technology development (and also allowing breeders to assess the response of varieties to a range of environments). These networks typically have a hub, often a CGIAR center, which offers a variety of services, including developing the scientific and technological basis for breeding, providing services, conducting training, and establishing the overall breeding approach (Bellon and Morris 2002; Dempewolf et al. 2014; Spielman, Hartwich, and Grebmer 2010). In common bean, this approach has been successful in providing the knowledge of which traits and which germplasm is likely to be of value in selecting for climate resilience (Beebe et al. 2013), thus local breeding programs can combine these traits with other traits that are important locally. Similar models are needed in other minor crops if they are to overcome the challenges of climate change.

**Conclusions**

In this paper, we have discussed the particular challenges that characterize efforts to develop minor crop varieties suited to future climatic conditions, using the example of the cocoa crop. In the past, breeding initiatives have been led by a network of regional not-for-profit organizations, whose
activities have centered on the collection and selection of germplasm in genebanks and on-farm. Adapting to climate change is a key challenge for this network, not just in terms of scale, but also because selecting crops for a future climate requires a long-term approach that will be difficult to implement through an ad hoc and under-resourced network.

We conclude that selecting minor crops for a future climate requires a coordinated, long-term, approach that is knowledge-led and exploits both modern technologies and participatory approaches. However, to maintain such a network in the long-term, funding from the public and private sector will need to be formalized at a regional level.

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