What the wild things do

The use of crop wild relatives in public international breeding programs and implications for conservation

by

Chelsea Smith

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Masters of Environmental Studies
in
Environment and Resource Studies

Waterloo, Ontario, Canada, 2015

Author's declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

_Chelsea Smith____________
Electronic signature

I understand that my thesis may be made electronically available to the public.

_Chelsea Smith____________
Electronic signature

Abstract

Wild species related to agricultural crops make agricultural systems around the world more resilient. Crop wild relatives (CWR) represent the largest pool of genetic diversity from which to draw when new variation for desired traits is required in domesticated varieties. They contribute towards the development of new crop varieties, particularly those adapted to predicted climate change scenarios. Although CWR are generally inedible, are not used for fuel or fodder, and very few have documented medicinal properties, they support global food production systems from behind the scenes. Placing an economic value on their contributions has had the effect of pulling CWR onto centre stage, and wild species are in fact beginning to garner international attention. The question is whether or not estimating their value in terms of the development of new varieties adequately represents their total value, and in particular the adaptive capacity they provide to agroecosystems. What are the implications of exclusively measuring their direct use value? This thesis explores the space where agrobiodiversity, climate change, advanced crop breeding and economics meet in order to address this question.

Two distinct but related research questions are discussed in sequence. The first asks: to what extent are CWR being used today within crop improvement programs under the auspices Consultative Group on International Agricultural Research (CGIAR)? The main findings are that CWR are being used to a greater extent today than ever before, and that a positive trend is likely to continue in light of both technological advancements and intensifying environmental pressures. Research findings are relevant to the conservation community advocating for increased investment and will help inform policy decisions involving trade-offs and priority setting among conservation objectives.

The second question arises in light on the first: what are the implications of increased use of CWR in breeding? Implications include increased conservation investment and an emerging conservation paradigm that is focused exclusively on facilitating future use of selected species closely related to socio-economically important crops rather than the breadth of diversity that exists today. This diversity is threatened with extinction by range of environmental and anthropogenic forces. The positive feedback between use and conservation will continue to the extent that required genetic variation is available.

This thesis argues that increased use will likely not incite sufficient levels of conservation. Conservation is a reflection of the way humans value biodiversity. CWR are valued for their instrumental use in crop breeding but less so for the resilience they lend to agroecosystems, and not at all for their intrinsic value. Understanding the dynamic between valuation and conservation is useful for making projections into the future and will help inform course corrections at the relatively early stage of the conservation investment game. Policy recommendations stem from a greater recognition of the resilience value provided by the breadth of CWR diversity, agrobiodiversity more broadly defined, and the importance of conserving it both *in situ* and *ex situ*. The availability of genetic variation for agricultural crops in the long term and by extension any meaningful contributions towards achieving sustained food production, depend upon it.

Acknowledgements

Thank you first and foremost to my supervisor, Professor Jennifer Clapp, for her support and guidance throughout the research process. I cannot believe my luck that I found her as both a personal and academic mentor.

Thank you to my committee member, Professor Susan Lolle, who invested her time and care into teaching me the foundations of genetic biology.

Thank you to the Department of Environment and Resource Studies for its financial support, allowing me to present this research at the Plant Genetic Resources Secure Conference: *Enhanced gene pool utilization: Capturing wild relative and landrace diversity for crop improvement,* in Cambridge, UK, June 16-20, 2014.

Many thanks to all those who graciously contributed their time and expertise throughout the research process, no less those who helped to establish contacts through email correspondence. This study was made possible by the incredible collaborative culture among the CGIAR scientists and the CWR research community at large.

Thank you to my very beloved family of friends in Kitchener/Waterloo who together created such a wonderful space to live and work during this very special chapter of my life. This thesis was made possible by Potluck.

Thank you Dan, for the energy you've given me from near and afar and for spending so many hours engaged with the topic of crop wild relatives. Mindful listening accomplished.

And last but certainly not least, thank you to my family in Winnipeg -Mom, Dad, Ryan and Annie- for being there at every single moment of the journey.

For Mom, for having read everything I have ever written and for her (unconditional) love of the wild things.

Acronyms

CBD - Convention on Biological Diversity
CGIAR - Consultative Group on International Agricultural Research
CI - Conservation International
CMS - cytoplasmic male sterility
CWR - crop wild relatives
FAO - Food and Agriculture Organization of the United Nations
FIGS - focused identification of germplasm strategy
GCDT - Global Crop Diversity Trust
GMO - genetically modified organism
ITPGRFA - International Treaty on Plant Genetic Resources for Food and Agriculture
IUCN - International Union for Conservation of Nature
MCA - multi-criteria analysis
PACS - payment for agrobiodiversity conservation services
PES - payment for ecosystem services
PGR - plant genetic resources
PGRFA - plant genetic resources for food and agriculture
REDD - Reducing emissions from deforestation and forest degradation
TEEB - The Economics of Ecosystems and Biodiversity
TEV - total economic value
WAVES - Wealth Accounting and the Valuation of Ecosystem Services
WTP - willingness to pay
UNEP - United Nations Environment Programme
UNESCO - United Nations Educational, Scientific and Cultural Organization
WWF - World Wildlife Fund

List of Figures

List of Tables

Chapter I - Introduction

Wild species related to agricultural crops make agricultural systems around the world more resilient. Crop wild relatives (CWR) represent the largest pool of genetic diversity from which to draw when new variation for desired traits is required in domesticated varieties. They contribute towards the development of new crop varieties, particularly those adapted to predicted climate change scenarios. Although CWR are generally inedible, are not used for fuel or fodder, and very few have documented medicinal properties, they support global food production systems from behind the scenes. Placing an economic value on their contributions has had the effect of pulling CWR onto centre stage, and wild species are in fact beginning to garner international attention. The question is whether or not estimating their value in terms of the development of new varieties adequately represents their total value, and in particular the adaptive capacity they provide to agroecosystems. What are the implications of exclusively measuring their direct use value? This thesis explores the space where agrobiodiversity, climate change, advanced crop breeding and economics meet in order to address this question.

1.1 Contrasting perspectives on agrobiodiversity and global food security

There is no one singular strategy for pursuing global food security - where all people, at all times, have physical and economic access to safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (World Food Summit 1996). The question of how best to achieve food security has been hotly debated within international fora since the mid-1970s (Clay 2002), and is increasingly linked to debates surrounding the impacts of climate change on agricultural systems (Field et al 2014).

Food security has four pillars: access, availability, quality and stability (www.cirad.fr). This strategies for achieving food security discussed in this thesis are focused on the second pillar, availability, or sustained productive capacity. It is acknowledged here at the outset that the strength of the remaining three pillars are essential for the realization of global food security. The production pillar, no mater how strong, cannot alone support the structure that is our global food system.

Narrowing-in on production, food *insecurity* is framed as a mismatch between the demand and supply of food. As the world human population increases and diets shift towards consumption of animal products, oils and other more resource intensive foods more pressure is placed on agricultural systems to increase production (Kastner et al 2012). From a scientific perspective the focus is on increasing food supply through developing crop varieties with higher yields to keep pace with intensifying environmental pressures (Lobell et al 2008; Vincent et al 2013; Dempewolf et al 2014), and by practicing ‘sustainable intensification’ (Garnett et al 2013; FAO 2014).

From an agroecological standpoint, a lack of productive capacity results from a lack of adaptive capacity within agricultural systems to withstand external shocks and fluctuations in markets and environmental conditions. Complex systems dynamics govern agroecological systems, just as is the case with other socio-ecological systems (Tittonell 2014). Agrobiodiversity and diverse livelihood strategies allow smallholder farmers to adapt to these changes and maintain an equilibrium state and maintain food production (ibid). From this standpoint the availability pillar of food security is best pursued by enhancing agrobiodiversity and the resilience of small-scale farming systems (de Schutter 2010). Industrial agriculture, characterized by the production of monocultures, introduction of modern varieties and the displacement of traditional farming systems and the loss of agrobiodiversity, is framed as part of the problem rather than the solution (Altieri et al 2012).

These two seemingly contrasting paradigms share an understanding that human well-being is intimately tied to the health of natural ecosystems and biodiversity. The dual objectives of attaining sustained food production and environmental sustainability are found in policy documents borne from within both paradigms (see FAO 2014 and Altieri et al 2012 for examples). There is a shared understanding that the type of intensification that was promoted during the Green Revolution is no longer appropriate, nor is it feasible (ibid). The ongoing and lively debate between these schools centres on whether to pursue an agenda of sustainable intensification or one based on the principles of agroecology; the former emphasizing the role of science and technology in maintaining production, the latter focusing on the social, political, economic and ecological dimensions of complex food systems.

Agrobiodiversity sits at the crux of this debate - integral to achieving the dual objectives from both perspectives. It represents the genetic variation required to improve crop varieties and develop new cultivars adapted to conditions under predicted climate change scenarios, at the same time representing the adaptive capacity required to maintain the resilience of complex agroecosystems. The result of this rather unique ideological convergence is an immense degree of international attention being placed on agrobiodiversity, and growing recognition of the imperative of its conservation.

These paradigms manifest differently in practice, however. Policies related to the sustainable use and conservation of agrobiodiversity continue fall along ideological lines with regards to roles of the public and private sectors in research and development, and scientific verses traditional modes of innovation and adaptation. Agroecologists recognize the value of the full breadth of diversity that exists within agroecosystems, including both wild and domesticated species and the diversity of traditional farming systems themselves, while crop scientists and breeders narrow-in on a relatively small subset of diversity highlighted for its more immediate potential for the development of new crop varieties. This thesis explores the ongoing pursuit of sustained food production capacity through the use and conservation of CWR and reflects upon how these contrasting paradigms and playing-out on the ground.

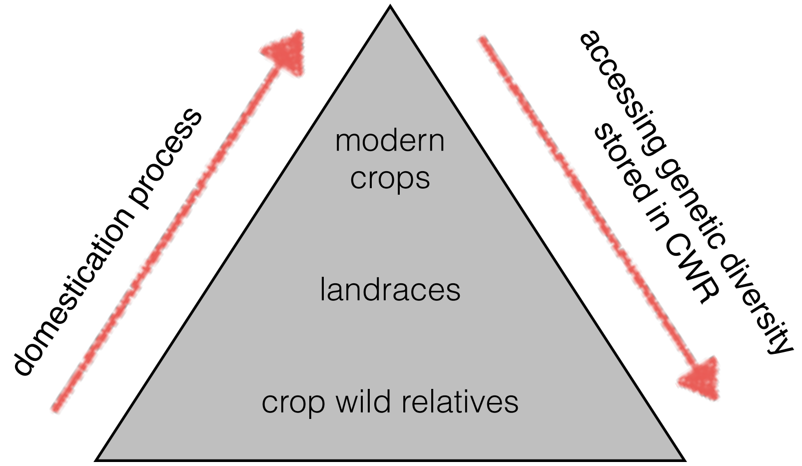
1.2 The role of CWR in achieving global food security

A major constraint to the sustainability of agriculture in an era of climate change is an insufficiency of genetic variation within crop gene pools for traits of interest (Dempewolf et al 2014). Tanksley and McCouch (1997) describe the ‘domestication bottleneck’ process whereby recurrent selection eliminates genetic variation in crop gene pools and leaves modern crops with less diversity to draw from than their ancestors had. More variation is required to overcome extreme conditions and help crops adapt to the shifting spatial boundaries within which they can survive.

The genetic bottleneck process is accelerated by the demand for high crop productivity and crop uniformity in the marketplace and is further perpetuated by the increasing homogeneity of the global food system (Khoury 2014). Over the last 50 years world diets have become increasingly dependent on fewer staple food crops. Rice, wheat, maize and potatoes now account for 60% of human caloric intake, and only about 30 crops make up 95% of total food and energy consumption worldwide (ibid). The narrowing of the genetic bases of staple crops combined with the increasing uniformity of diets means that less overall genetic variation is available to overcome extreme stresses and fluctuations in the production system. This paints a precarious picture of today's global food system.

Breeders can reverse the domestication bottleneck process by reintroducing genetic diversity from related species which have not undergone the same selection pressures. A much wider spectrum of genetic diversity can still be found in farmers' varieties, or landraces, and heirloom varieties cultivated by farmers around the world. An even wider spectrum can be found in more distantly related wild and weedy species. Unlike landrace or heirloom varieties, CWR are not generally used or consumed directly by human populations and have thus not gone through the domestication bottleneck process. Figure 1 depicts how domestication narrows the genetic base of modern crop varieties and how CWR are accessed in order to introduce novel diversity back into crop gene pools.

Figure 1 - Agrobiodiversity pyramid



CWR host beneficial traits such as biotic stress resistances, abiotic stress tolerances and a variety of other unique qualities for which often no other sources remain. Dating back to the beginning of the 1900s crop breeders began to recover some of the genetic diversity lost during the domestication process through crossing cultivated varieties with wild species, introducing novel genetic variation into narrowed crop gene pools (Prescott-Allen and Prescott-Allen 1986). The use of CWR in crop improvement programs gained prominence for a wide range of crops in the 1970s and 1980s (Hoyt 1988), and are now recognised as a significant resource which still largely remains untapped. While the primary strategy for crop improvement today remains recurrent selection among elite modern varieties, scientists and breeders are increasingly looking to wild species as sources of novel material to widen the genetic bases of crops (Hajjar and Hodgkin 2007). Under predicted climate change scenarios wild species will play an increasingly important role in crop breeding, while at the same time CWR populations are threatened with extinction due to both environmental and human influences.

CWR have recently become a popular topic within international fora including the Conference of the Parties to the Convention on Biological Diversity (CBD) and the Food and Agriculture Organization of the United Nations (FAO). They are garnering attention for the vast genetic reservoir they represent, as well as for being an avenue for introducing novel traits into crop gene pools without the use of transgenic technologies associated with high regulatory costs and widespread consumer concern. From a position of being underutilized, undervalued and under threat (Ford-Lloyd et al 2011), CWR are becoming an important component of strategies for achieving food security. Efforts to conserve wild species have naturally ensued.

1.3 Research contributions

This research maps out how CWR are being used within public international breeding programs to overcome a host of biotic and abiotic stresses threatening crop production systems today. The last major review of the use of CWR in crop improvement programs was published in 2007 (Hajjar and Hodgkin 2007). This field is advancing quickly with the advent of new tools and methods for identifying and transferring genes of interest from wild to cultivated species, along with an ever-growing imperative to access genetic variation from more distantly related gene pools. While various research programs and breeding efforts around the world recognize wild species as sources of beneficial traits there is little coordinated effort to communicate advancements, limitations and opportunities for accessing wild genetic diversity across crop communities. This is a significant gap in the literature.

Two distinct but related research questions are presented and discussed in sequence. The first asks: to what extent are CWR being used today within crop improvement programs under the auspices Consultative Group on International Agricultural Research (CGIAR)? The objective is to identify trends in the use of wild species and to make projections about how they will be used in the coming years in light of technological advancements and intensifying environmental pressures. In particular, this research will illuminate their role in adapting agricultural to climate change. This research provides policy makers with an up-to-date account of CWR use. As the majority of ongoing work with CWR is underreported in the literature and undercounted in valuation efforts, policy decisions involving trade-offs and priority setting have been poorly informed.

The second research arises in light on the first: what are the implications of increased use of CWR in breeding? The objective here is to identify the main actors responding to signals from the breeding community regarding the use of wild species in crop improvement, and to explore the potential implications of their responses. The implications of increasing conservation investment from the international community have yet to be explored in the context of CWR.

This thesis argues that increased use will likely not incite sufficient levels of conservation. Conservation is a reflection of the way humans value biodiversity. CWR are valued for their instrumental use in crop breeding but less so for the resilience they lend to agroecosystems, and not at all for their intrinsic value. Understanding the dynamic between valuation and conservation is useful for making projections into the future and will help inform course corrections at the relatively early stage of the conservation investment game. Policy recommendations stem from a greater recognition of the resilience value provided by the breadth of CWR diversity, agrobiodiversity more broadly defined, and the importance of conserving it both *in situ* and *ex situ*. The availability of genetic variation for agricultural crops in the long term and by extension any meaningful contributions towards achieving food security, depend upon it.

A more landscape based approach to conservation protects the breadth of existing diversity within natural habitats. Given the unpredictability of climate change and how difficult it is to anticipate which traits will be required in the future, protection of the full spectrum of CWR diversity, along with its capacity to evolve along with its natural environment, is of the utmost importance. While gene banks provide an invaluable safeguarding function they are not alone sufficient for protecting the adaptive capacity of agroecosystems.

Moreover, the full breadth of agrobiodiversity including landrace varieties is important for maintaining adaptive capacity. A more narrow focus on CWR is characteristic of a production-focused strategy for achieving food security. Using wild species to develop new crop varieties which are then disseminated to farmers around the world, replacing landrace varieties, fits squarely within a paradigm that values advanced science over traditional modes of innovation. The value of landrace varieties along with the vast amount of traditional knowledge associated with them and the genetic diversity they represent should not be discounted.

1.4 Thesis outline

Chapter II develops a conceptual framework for this research. Concepts are borrowed predominantly from the field of ecological economics with some smaller contributions from the schools of complex systems theory, conservation biology and political ecology. The total economic value (TEV) valuation approach is presented as a way of conceptualizing the types of values derived from biodiversity conservation. The gap between private and social benefits derived from biodiversity account for a public goods market failure and the under provision of conservation. Valuation as a means of communicating the need to correct this market failure has been mainstreamed in the context of biodiversity, although remains a controversial tool. In this thesis valuation is used both as a conceptual tool for communicating the types of values derived from CWR, as well as an entry point into a critical engagement with how conservation priorities are set according to the economic value of species. The purpose of this thesis is not to adjudicate this debate, but to critically engage with how valuation as it is used today is impacting wild agrobiodiversity conservation. This framework is put to use in Chapter VII.

Chapter III summarizes in two sections the relevant literature on CWR use and conservation, respectively. A key take-away from the first section is that while there is an immense body of literature available on useful traits identified in wild species, it is an imperfect proxy for estimating the current use of CWR in crop breeding. More thorough investigation is required to uncover the extent of ongoing use. It is flagged in this section that studies to date assessing the economic value of CWR have not been based on accurate estimations of current use. The second section emphasizes the insufficiency of existing conservation efforts, particularly in natural areas where wild diversity is concentrated. The imperative for increased conservation is clear. A global agenda of establishing a network of *in situ* conservation areas must be pursued in particular.

Chapter IV outlines the methods used to collect data and arrive at the results. Targeted semi-structured interviews were conducted with gene bank managers, crop breeders, academics and conservationists. Interviews were transcribed and coded using NVivo qualitative data software, and the themes that emerged provide the foundations for analysis.

Chapter V presents the first half of the research results: how CWR are being used in crop breeding today. It first includes a brief description of the crop breeding process, recent advances which have facilitated increased use and prevailing constraints. This first section provides important context for the discussion of results which follows in Chapter VI. The current gene banking system, which underpins crop improvement, is far from the fail-safe reputation that precedes it. This provides evidence for the need to pursue a balanced approach to conservation. The subsequent sections discuss ongoing use by crop and predictions regarding future use. Key findings include 1) a positive trend in the overall use of CWR; 2) their growing role in adapting cultivated crops to conditions under predicted climate change scenarios; and 3) that the majority of ongoing work with CWR has yet to result in quantifiable breeding outputs. This third point highlights that estimates of CWR use, measured by numbers of varieties released with genetic contributions from wild species, underestimate current use. By extension valuation exercises have undercounted current value and poorly inform policy.

Chapter VI discusses the dynamic relationship between CWR use and conservation. Increased use is credited for inciting increased conservation investment from the international donor community, as well as increased attention from the private sector. It remains to be seen how much private stakeholders will actively participate in the use and conservation of CWR, however their recognition of wild species' value marks a level of interest and perhaps intention. The prevailing conservation strategy is focused on perpetuating the positive feedback between use and conservation by maintaining and expanding gene bank collections. This is taking precedence over the conservation of CWR within their natural habitats, which will have negative implications for the breadth of genetic diversity and the resilience of the global food system in the long term.

The analysis that follows in Chapter VII uses the conceptual framework developed in Chapter II to explain why there will continue to be a less than socially-desirable quantity of CWR conservation despite the influx of attention and investment from the international community. Donors are focused on instrumental use associated with CWR and ignore its other important ecosystem functions, while the unique challenges presented by CWR limit the policy options available for inciting their conservation at the community level. The paradox here is that they receive increased international recognition while the majority continue to face threats of extinction within their natural environments.

The roots to this unbalanced conservation approach are in the ideological divide between the diverging strategies for pursuing global food security. They run deep. An unwavering faith in technological advancement for sustaining the global food supply in an era of climate change underpins the strategy of protecting a small subset of diversity to be used in breeding. This may last as long as diversity is available for inputs. An integrated approach to valuing and managing agrobiodiversity, incorporating principles of agroecology, will ensure the sustainability of global food supply in the longterm. Policy recommendations and areas for future research follow from this analysis.

Chapter II - The ecological economics of biodiversity conservation

The chapter introduces some key concepts that will be useful for analyzing the case of CWR conservation in later chapters. These concepts are borrowed largely from ecological economics, with some contributions from the schools of conservation biology, complex systems theory and political ecology. The first section reviews the very foundations of biodiversity conservation, highlighting how different levels of biodiversity are more or less amenable to the two main types of conservation strategies: *in situ* and *ex situ*.

The second section documents how economic valuation has become the primary tool for communicating the benefits derived from biodiversity and for justifying the allocation of resources towards conservation. Although widely practiced, valuation remains controversial for its tendency to discount important social and ecological indicators. The widely-applied total economic value (TEV) approach to valuation is introduced in the third section to communicate the value of biodiversity and explain how a public goods market failure arises when there is a gap between the private and public benefits derived from biodiversity conservation. This market failure leads to an under provision of conservation. These concepts that have evolved around biodiversity apply equally to the case of CWR.

The final section discusses policies for correcting this market failure aimed at incentivizing conservation. The potential for, and potential pitfalls of, a market-based mechanisms to play a role in conservation is explored.

The purpose of this thesis is not to adjudicate debates surrounding the valuation of biodiversity and ecosystem services, or the use of market-based mechanisms for incentivizing conservation. The goal instead is to describe how biodiversity is managed within the dominant conservation paradigm in order to situate the case of CWR within these broader debates.

2.1 Biodiversity conservation 101

The United Nations Convention on Biological Diversity (CBD) defines biodiversity as "the variability among living organisms from all sources, including terrestrial, marine and the ecological complexities of which they are part…" (UNEP 1992, Article 2).

There are two fundamental strategies for biodiversity conservation: *ex situ* and *in situ,* with many iterations and combinations thereof. *Ex situ* refers to the conservation of components of biological diversity outside of their natural habitats (CBD, 1992). This strategy involves the location, sampling, transfer and storage of species away from native habitats, most commonly in gene bank facilities and community seed banks (Maxted et al 1997a). *In situ* refers to the conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings, or in the case of domesticated or cultivated species, in the surroundings where they have developed their distinctive properties (CBD, 1992). This involves the location, designation, management and monitoring of species in the location where target taxa are found (Maxted et al 1997a; Iriondo et al 2008).

In situ conservation is most commonly associated with formalized protected areas, defined by the International Union for Conservation of Nature (IUCN) as ‘clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values’ (Hunter and Heywood 2011). They are most commonly national parks, nature reserves and wilderness areas.

An extensive body of literature exists on the advantages and disadvantages of both strategies. *In situ* conservation allows for interactions between crops, their wild relatives and the local environment, maximizing evolutionary capacity (Heywood and Dulloo 2005). *Ex situ* conservation is imperative to guard against species extinction in extreme conditions of environmental change or in events of catastrophe (Iriondo et al 2008). The value of a combined approach is widely recognized (Maxted et al 1997a; Maxted et al 1997b; Iriondo et al 2008). Article 9 of the CBD stresses that the two strategies are complementary and need to be practiced in tandem to conserve the maximum range of biodiversity. Biodiversity includes four levels, shown in Table 1.

Table 1: Levels of biodiversity

Levels of diversity	**Physical expression**	**Amenable to ex situ conservation**	**Amenable to in situ conservation**
Genetic	Genes, nucleotides, chromosomes, individuals	✓ (small subset)	✓
Species	Kingdom, phyla, families, genera, subspecies, species, populations	✓ (small subset)	✓
Ecosystem	Bioregions, landscapes, habitats	✗	✓
Functional	Keystone process species, ecosystem resilience, ecological services	✗	✓

Adapted from: Nunes et al 2003.

Genetic diversity refers to the degree of variability within species (Nunes et al 2003). Much of the current debate on biodiversity loss is focused on this foundational level: the extinction of genetic diversity, referred to as *genetic erosion*. The widely-referenced ‘Weitzman approach’ to biodiversity conservation refers to the measurement of genetic distances within and between species and setting diversity-maximizing, cost-effective conservation priorities accordingly (see Weitzman 1992; 1993; 1998). The narrow range of genetic diversity which makes up the selected species stored in gene banks is protected *ex situ.* The full breadth of genetic diversity can only be found *in situ,* actively managed in genetic reserves. Genetic reserves are a type of formalized protected area which entail the location, management and monitoring of target diversity within protected areas (Maxted et al 1997a).

Species diversity refers to the variety of species on earth, or within a given region (Nunes et al 2003). Conservation priorities set according to species' status such as *at risk, threatened* or *extinct* describe this level of biodiversity. The IUCN use the iconic 'Red List' approach to guide conservation action and policy decisions (see http://www.iucnredlist.org/). The criteria put forward by IUCN have become the international standard for monitoring species diversity (Hole, Interview). Economically profitable or 'flagship' species often become the beneficiaries of conservation funds, while others are left out (Hein et al. 2013). Species diversity can likewise be protected *ex situ* in gene bank facilities, but only to the degree that collections accurately represent intraspecific diversity, or the diversity within species' populations. Again, only a narrow range is protected.

Conserving higher levels of biodiversity, thet is, ecosystem and functional levels, necessitates, and in fact describes, *in situ* conservation. Ecosystem diversity refers to diversity at the community, or supra-species level (Nunes et al 2003). Ecosystem stability is not based on diversity of species *per se*, but on a limited number of species that control ecosystem functioning, or keystone processes. Loss of these *keystone species* reduces ecosystems' capacity to accommodate external shocks and return to a state of equilibrium. Overall ecosystem diversity then, rather than individual species, is what is required for ecosystem stability and resilience (ibid). The establishment of protected areas in the form of national parks, nature reserves and wilderness areas in order to eliminate human impact is the quintessential conservation strategy for protecting ecosystem diversity (Hunter and Heywood 2011).

Functional diversity refers to the variety of ecosystem functions or services such as pollination, nutrient cycling, photosynthesis, assimilation of pollutants and the maintenance of gases in the air (Turner et al 1999). These functions arise out of interactions between ecosystem components (plants, animals, soil, air, water, etc.) and ecosystem processes, i.e. the transfer of energy between biotic and abiotic components. Assessing functional diversity is much harder to do than lower levels of biodiversity, which can each be described taxonomically (Nunes et al 2003). Much remains unknown about interactions between ecosystem components and processes, thus functional diversity is very difficult to manage.

While establishing protected areas can be seen as a precautionary approach to conserving functional diversity, conservationists recognize that this is a not always a practical option. Human populations are ecosystem components and are integral parts of socio-ecological systems. This is particularly the case with agroecosystems. A new era of conservation planning has evolved which recognizes that human well-being is intimately connected to the health of natural environments. Literature documenting integrated conservation and development programs has proliferated (see for examples Blom et al 2010; Swaminathan 2011). This is also referred to as an 'integrated landscape approach' to conservation where multiple land uses among multiple stakeholders are balanced (http://www.cifor.org/).

The examples given above illustrate that conservation strategies are tailored to the level of diversity they seek to protect. *Ex situ* conservation targets a specific subset of genetic and species diversity. Targeting the full breadth of genetic and species diversity, as well as higher levels of diversity, requires a more landscape-based approach to conservation *in situ.* Understanding the relationship between conservation strategies and levels of diversity will be useful when looking at the case of CWR, which are predominantly conserved in gene banks rather than in gene reserves. This point is both highlighted within the literature (Chapter III) and reinforced by research findings (Chapter VI).

2.2 Mainstreaming biodiversity valuation

Valuation has become a mainstream tool for justifying the allocation of scarce resources towards conservation, and a cornerstone of the dominant conservation paradigm. A series of landmark reviews have played a major role in mainstreaming the idea that human well-being is dependent on biodiversity. Efforts to quantify the value of biodiversity in economic terms in order to inform policy decisions have stemmed from this. But while valuation has become prominent strategy for rendering the benefits derived from conservation more visible, it has not been without significant controversy.

Biodiversity issues first came to the forefront of the environmental policy debate with the First Report to the Club of Rome, ‘The Limits to Growth’ (Meadows et al 1972). The report presented a scenario analysis of exponential economic and population growth with finite natural resources, and sparked intense debate between growth optimists and pessimists. Economists began to model economic growth and resource use and to develop theories on how environmental policy could correct for environmental externalities (Nunes et al 2003).

The Bruntland Report (1987), ‘Our Common Future,’ mainstreamed the idea that economic growth could be coupled with environmental protection, and that the two goals are not necessarily mutually exclusive. The popularized concept of *sustainable development* was defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Bruntland Report 1987). The pervasive logic up until this point was that economic growth and environmental protection need to be traded-off. Identifying synergies between them has since been the goal of policy interventions (Ninan 2009). Biodiversity is an essential element of discussions on how to achieve sustainable development, both because it provides a range of benefits to humankind and because human activities contribute to unprecedented rates of biodiversity loss (Nunes et al 2003).

The Millennium Ecosystem Assessment (MEA), entitled, ‘Ecosystems and Human Well-being, institutionalized the idea that conserving biodiversity is not only *compatible* with economic development, but is *essential* for the promotion of human well-being and livelihood development (MEA 2005). Human well-being is based on security, resiliency, social relations, health and freedom of choice and action, in addition to material welfare. The report established an obligation to identify the impacts of biodiversity loss on human well-being (Kinzig et al 2007), thereby broadening the range of motivations for conservation beyond an appreciation for the intrinsic value of biodiversity (Ninan 2009). The intrinsic value of nature alone is insufficient for inciting a minimum level of conservation needed to stem accelerating waves of extinctions that negatively impact human beings (Kinzig et al 2007).

The concept of ecosystem services has also entered into the mainstream policy debate. The existing stock of biodiversity is viewed as natural capital, while the continued flow of ecosystem services is the interest that society receives from this capital (Costanza and Daly, 1992). Constanza et al (1997) define ecosystem services as the aggregate of ecosystem functions (biological or system properties or processes of ecosystems), and ecosystem goods (such a food) and services (such as waste assimilation). Table 2 summarizes the four categories of ecosystem services that contribute to human well-being identified by the MEA (2005). Provisioning services include food, fibre, fuel and genetic resources; regulating services include water purification, pest regulation and pollination; cultural services include spiritual and aesthetic values, recreation and ecotourism; and supporting services are those which facilitate the production of all other services, such as nutrient cycling and soil formation.

Table 2: Ecosystem services provided by biodiversity

Provisioning services	Food, water, timber, fibre
Regulating services	Climate, foods, disease, waste, water quality
Cultural services	Recreation, aesthetic enjoyment, spiritual enjoyment
Supporting services	Soil formation, photosynthesis, nutrient cycling

Source: MEA 2005; Ninan 2009

Biodiversity is central to the stability and continuity of each of these ecosystem services (Ninan 2009). Consequently, much attention has been directed towards stemming biodiversity loss as a means maintaining the provision of ecosystem services. This has meant unravelling the complexities of ecosystem service provision, understanding how human impacts affect service provision, expressing these impacts in monetary values to be included in public decision-making processes, and optimizing investments in biodiversity conservation (Kinzig et al 2006); each of which requires the valuation of biodiversity and the ecosystem services it provides (Kinzig et al 2007).

Constanza et al (1997) first ventured to place an economic value on the world's ecosystem services and natural capital, for the ends of 'capturing' them in commercial markets and giving them adequate weight in policy decisions. While recognizing the "economics of the Earth would grind to a halt without the services of ecological life-support systems, so in a sense their total economic value is infinite," they emphasize the utility of estimating the marginal value of ecosystem services, or the rate of change of value compared with changes in ecosystem services from their current levels (pp.253). A detailed account of how valuation efforts proliferated after that of Constanza et al (1997) is beyond the scope of this thesis. The important point here is that valuation is now a predominant feature within environmental policy.

The Economics of Ecosystems and Biodiversity (TEEB) is a global study on the economics of biodiversity loss, launched in 2007 and led by Pavan Sukhdev. It was modelled after the 2006 Stern Report wherein ex-chief economist of the World Bank, Nicholas Stern, concludes that the failure to protect the climate will be economically more costly than taking action. The TEEB reaches the same conclusion. It challenges policy makers to engage with the economic value of biodiversity and ecosystem services, the costs of their loss and develop economic incentives to protect them; and for businesses to internalize the costs of losing ecosystem services. Sukhdev asserts that "the economic invisibility of nature is one of the main reasons why we lose valuable ecosystem services" (http://www.teebweb.org/). The TEEB as an institution has become perhaps the strongest international advocate for economic valuation of biodiversity.

The second phase of the TEEB study was presented in Nagoya, Japan in 2010 to the Conference of the Parties to the CBD (COP-10). A large-scale push was made leading up to the conference for Parties to include biodiversity and ecosystem services into their national accounting frameworks to make biodiversity loss more socially and politically visible (Rodríguez-Labajos and Martínez-Alier 2012). This was successfully internalized and is now enshrined within the Aichi Targets. Target 2 under the strategic goal of addressing the underlying causes of biodiversity loss, reads: *By 2020, at the latest, biodiversity values have been integrated into national and local development and poverty reduction strategies and planning processes and are being incorporated into national accounting, as appropriate, and reporting systems.*

The World Bank Wealth Accounting and the Valuation of Ecosystem Services (WAVES) project is an implementing arm for the TEEB, also launched in Nagoya at COP-10. The goal of the WAVES is to mainstream the natural capital accounting system developed under coordination of the UN Committee of Experts on Environmental-Economic Accounting (UNCEEA) and implement this perspective in developing countries (TEEB 2013). A global partnership and multi-donor trust fund was established in its preparatory phase from January 2011 to June 2012 and, following the 2012 United Nations Conference on Sustainable Development (Rio+20), more than 65 countries have indicated their intention to participate in its implementation (http://www.wavespartnership.org/).

The dominant conservation paradigm is now firmly established, in which biodiversity and ecosystem services are converted into monetary figures to be compared and traded-off. This is reflected not only in countries' national accounting frameworks, but in the context of integrated conservation and development programs (ICDPs). MS Swaminathan, prolific writer and founder of the MS Swaminathan Research Foundation based in India, emphasizes the role that valuation can play in ensuring the sustainability of conservation efforts. When local communities internalize their roles as custodians, conservation is achieved *in perpetuity*. This arises when conservation planning promotes food, health and livelihoods security, and social and gender equity, in addition to ecological outcomes (Swaminathan 2011). In responding to the question, "how can we harness biodiversity for poverty alleviation?” he answers, “obviously, this can be done only if we can convert biodiversity into jobs and income on a sustainable basis” (pp.xiii).

The valuation approach has not proliferated without significant debate. While proponents emphasize its role as a conceptual tool for assisting decision makers allocate resources in a way that ensures the sustainable use of biodiversity (Nunes et al 2003; Pascual et al 2010), critics remind us of the unwanted consequences of reducing nature to a series of tradable monetary units (Keulartz 2013).

Ecologists emphasize the difference between biocentric perspectives of nature, which recognize intrinsic values, and anthropocentric perspectives that focus on its instrumental values (Pascual et al 2010). Nature is conceptualized as a series of assets which facilitate the attainment of human goals, be they marketed commodities, material consumption, aesthetic pleasure or spiritual enlightenment (Barbier et al 2009). Critics argue that adopting strictly utilitarian perspective and making decisions based on cost-benefit rationales may have negative implications in terms of the deconstruction of human-nature relationships (McAuley 2006). The discounting of cultural values and human rights to livelihood are the consequences of this focus on instrumental values (Rodríguez-Labajos and Martínez-Alier 2012). The moral imperative to include intrinsic values in decision making is also largely ignored.

Ecologists assert that a valuation approach should be used to complement rather than substitute for ethical or scientific reasoning relating to biodiversity conservation, based on biocentric perspectives (Turner and Daily 2008). Alternative decision support tools have been developed to integrate different kinds of values. Multi-criteria analysis (MCA) weights different kinds of values in relation to each other and facilitates the ranking of preferences among alternatives without converting values into a single unit (Munda 2004). MCA approaches recognize the *incommensurability* of values which are embedded in contrasting conceptual frameworks (Monfreda 2010: 284). However it is difficult to agree on the relative weights of intrinsic and instrumental values (Pascual et al 2010). Instrumental values tend to be privileged by society (Hillier 1999) and are categorically given more weight in policy decisions in practice (Pascual et al 2010).

Critics also question the reductionist logic of abstracting parts of biodiversity from the complex socio-ecological system in which they are nested (see for example, Keulartz 2013). Holistic conceptions of nature contrast reductionist conceptions. Ecosystem integrity is based on the interconnectedness of ecosystem components, processes, functions and services and cannot be measured by aggregating individual biophysical indicators (ibid). Isolating and putting monetary values of individual ecosystem components poorly informs policy decisions and can result in less than socially-optimal levels of conservation (Ninan 2009).

Trade-offs must occur among the multitude of services produced in an ecosystem because some services are incompatible. Some types of services may dominate management strategies, creating social and ecological problems. Keulartz (2013) describes this as ‘not seeing the forest from the trees.’ The relational aspects of nature and interdependence of functions are ignored when ecosystem elements are viewed as abstract, interchangeable goods. Ecosystem integrity is lost in the process of prioritizing and trading-off between ecosystem services. In this way valuation can be counterproductive by undermining the objectives of conservation (Rodríguez-Labajos and Martínez-Alier 2012).

Conservation is a longterm endeavour, the benefits from which are accrued far into the future. Part of the valuation process is assigning net present values to ecosystem components and services. Discount rates are used to equate future benefits with current costs of conservation in order to inform policy based on cost-benefit analysis. Any positive discount rate at all makes conservation a relatively poor investment today compared with other activities that invite short-term gains for society, thus it very difficult to justify this type of investment. Selecting an appropriate discount rate and reaching consensus on which values should be discounted among relevant stakeholders is no easy feat (Rodríguez-Labajos and Martínez-Alier 2012).

Political ecologists warn us too about social equity concerns arising from valuation (Escobar 1999; Peck and Tickell 2002; Harvey 2003; McAfee 2004; McCarthy and Prudham 2004; Prudham 2007; Sharratt 2010). These writers are ideologically opposed to assigning monetary values to complex socio-ecological systems because of the inescapable power dynamics associated with this process. Valuation leads to the privatization of nature and concentration of ownership among elites. Privatizing ecosystem components in order to equate biological and economic indicators directly facilitates their commodification, and even financialization (Sullivan 2012). Valuing nature not only serves to make natural capital visible within policy discussions, but also to incorporate nature into the capitalist market system. Valuation is then not a benign tool for informing decisions, but an essential step in the ‘rolling out’ of a neoliberal agenda (McCarthy and Prudham 2004) focused on enclosing ‘natural capital’ into the process of capital accumulation.

It will be useful to bear in mind both sides of the valuation debate when studying the case of CWR conservation, where valuation plays a significant role in informing policy but where these critiques have not yet been applied. The dominant conservation paradigm has so far remained unchallenged in the context of CWR.

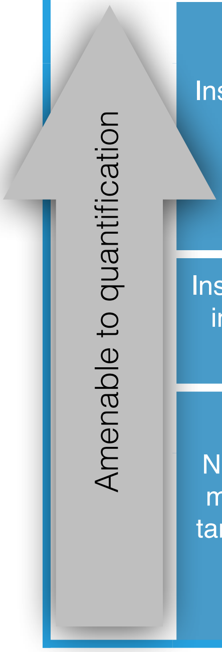
2.3 Ecological economics of biodiversity

There is no singular conceptualization of the value of biodiversity. Some ecological economists separate instrumental from intrinsic values, others categorize values according to direct and indirect benefits received from ecosystem services. There are also many different approaches to valuation including monitoring biodiversity vs. biological resources, genetic vs. species diversity, levels of vs. changes in biodiversity, and local vs. global scales of biodiversity; using biological vs. monetary indicators; and following holistic vs. reductionist approaches (see Nunes et al 2003 for summary of each). The types of indicators, scale and units of measurement selected by the researcher and overall conceptualization of values reflected in a given approach define how biodiversity is conceptualized, and how its value is quantified.

Estimates of values reflect current choices regarding marginal changes in the state of the world (Barbier et al 2009). Changes in variables affect their marginal values, and thus the monetary values assigned to various ecosystem components and services are dynamic (Pascual et al 2010). Valuation is therefore inherently limited by uncertainties relating to changing human preferences and gaps in knowledge about ecosystems dynamics and thresholds. Valuation studies must therefore acknowledge limitations and be guided by 'safe minimum standards' or 'precautionary approach' principles (ibid).

The concept of total economic value (TEV) of biodiversity and ecosystem services is used in this section to communicate the types of benefits derived from conservation. It is the sum of both instrumental and non-instrumental marginal values associated with natural capital and service flows for current and future generations (Pascual et al 2010). Using monetary units to convey TEV to policy makers is the most mainstream approach. Table 3 summarizes types of values which constitute TEV. While disputed, this concept is a useful tool for articulating the benefits derived from conservation efforts.

Table 3: Total economic value of biodiversity



Types of value		Biodiversity benefit
Instrumental, tangible values	Direct use	Resources for human use, consumption, recreation
	Indirect use	Ecosystem processes and functions (nutrient cycling, carbon sequestration, watershed protection, etc.)
	Potential use (option)	Future direct and indirect use
Instrumental, intangible value	Resilience	Adaptive capacity achieved through the maintenance of biodiversity at each level (functional diversity, table 1)
Non-instrumental, intangible values	Bequest	Inheritance for future generations
	Existence	Cultural, spiritual values. Human utility gained from existence without direct benefit
	Intrinsic	The value of biodiversity in its own right, not for the sake of human well-being

Adapted from: Prescott-Allen and Prescott-Allen 1986; Cato 2011

Table 3 is presented in sequence from top to bottom, starting with the values which are most easily quantified and ending with those which are most difficult to quantify. *Direct, indirect* and *potential use* are all instrumental values, or values which can be equated most readily with human utility. Direct and indirect use values can often be equated directly with commercial market prices for good and services (see Pascual et al 2010). Potential use values can be estimated using projections of current use values.

Moving down the list, *resilience value* is more difficult to quantify. Also referred to as 'insurance' value, this refers to an ecosystem's capacity to maintain a sustained flow of benefits. Adaptive capacity ensures the continued provision of both ecosystem services (Table 2) and benefits (Table 3) when external shocks or stresses threaten the integrity of an ecosystem. From a complex systems perspective, it is the value of ensuring that socio-ecological systems do not undergo regime shifts or transformations which have irreversible negative consequences for human wellbeing (Pascual et al 2010). Genetic diversity is critical to maintaining the resilience of an ecosystem, as it houses evolutionary potential (Wunscher and Engel 2012).

Natural resources which do not generate tangible outputs which benefit human society may still have significant resilience value. In this sense resilience is instrumental value, as human well-being is dependent on the adaptive capacity of ecosystems. However the economic value of genetic diversity and the resilience it lends to ecosystems remains difficult to quantify. The resilience value of natural resources increases as the likelihood regime shift increases. A full understanding of systems' adaptive capacity, risks, thresholds and probability of system 'flips' is thus required in order to estimate the resilience value that diversity lends to socio-ecological systems (Pascual et al 2010). Given the immense challenges associated with predicting transformations in complex systems (Walker and Salt 2006), its economic value remains highly intangible.

Bequest and *existence values* denote those that humans derive less tangible benefits from. Neither are instrumental per se, but provide human populations with utility of some kind. Various economic valuation methods associated with stated and revealed preferences have been developed to equate peoples' willingness to pay with these types of values (see Pascual et al 2010 for comprehensive review). *Bequest values* are associated with concerns regarding intergenerational equity. *Existence* and *intrinsic values* are often lumped together, as both are associated with ethical considerations and moral obligations to nature. The essential difference between the two is that the intrinsic value of biodiversity by definition cannot be equated with willingness to pay (WTP). It is defined in the MEA (2005) as the value of something in and for itself irrespective of the utility it provides for someone else. A person may gain utility from knowing that polar bears *exist,* for example, even if they never plan see one. But their WTP for polar bear conservation has nothing to do with the species' intrinsic value.

The sum of the values presented in Table 3 equates to the benefits received by society from biodiversity conservation. However the private benefits accrued by individuals who are custodians of biodiversity are generally limited to instrumental values, and in particular direct use related to consumption or recreation. A traditional food crop may also have significant cultural value, for example, but this would be reflected in the commercial market by individuals' WTP. Non-instrumental values associated with biodiversity, and even to some extent indirect use, potential use and resilience values which are still considered instrumental, provide benefits to society that aren't captured in market prices.

Ecological economists point to the difference between private and social values as the result of a public goods market failure. Biodiversity and ecosystem services are open-access goods available at no private cost, which leads to exploitation beyond socially-optimum levels (Ninan 2009). The flip-side of the same coin is that the private benefit realised from biodiversity conservation is less than public benefit, resulting in less than socially-desirable levels of conservation provided by individuals (Nunes et al 2003). Society on the whole depends upon custodians for responsible stewardship. However individuals and communities make rational decisions based on private costs and benefits and do not take the total economic value of biodiversity into consideration. The result is an under provision of biodiversity conservation, and negative externalities in the form of biodiversity loss and ecosystem destruction. The amount of negative externalities equates to the difference between private and public marginal benefit: the conservation gap.

Continued rates of biodiversity loss provide evidence of a public goods market failure, and a justification for policy interventions to correct for the conservation gap. As Ninan (2009) articulates, “It is clear that one of the key shortcomings of humankind’s existing relationship with its natural or nature-based assets is one of economics. There remains a gulf between the true value of biodiversity and the value perceived by politicians; business and perhaps even the public. There is an urgent need to shift into a higher gear in order to bridge this divide between perception and reality” (pp.xvii). A *higher gear* implies policy actions to correct for this market failure. Measuring the TEV of biodiversity highlights the existing conservation gap and informs policy that seeks to correct in proportion to it. Valuation is then a means of justifying conservation investment (Wale 2011). Tools such as cost-benefit analysis are employed to highlight how the benefits of maintaing biodiversity outweigh the costs of policy interventions (Nunes 2003).

Following suit, economists have described the public goods market failure associated with agrobiodiversity loss (see for examples, Brush 2002; Bertacchini 2008). Agrobiodiversity includes the variability of agro-ecosystem components such as plants, animals and microorganisms relevant for agriculture, as well as wild resources, natural habitats, landscapes and the genetic resources contained therein (Thrupp 2000). Agrobiodiversity loss is associated with higher susceptibility to any kind of stress or shock and has risks and costs to agricultural productivity and food security (ibid).

Smallholder farmers in the developing world are *custodians* of the majority of the world’s agrobiodiversity. Crop diversity has immense public value (Kontoleon et al 2009). However when higher yielding modern varieties are introduced, farmers have financial incentives to abandon traditional varieties and farming systems of which agrobiodiversity conservation is inherent (Heywood et al 2007; Wale 2011). This dynamic is accentuated when government subsidies are put in place that encourage the adoption of modern varieties (see Altieri 2002; Mendelsohn 2003; Mariano et al 2012). Farmers make decisions based on individual preferences and private benefits and underproduce crop diversity because they are not rewarded for their contributions. Society cannot rely on farmers’ choices and market forces alone to produce socially-optimal levels of agrobiodiversity conservation (Wale 2011). Just as is the case with biodiversity more broadly defined, the difference between public and private values associated with crop genetic diversity results in a gap between actual and desired levels of conservation, and a public goods market failure (ibid).

The marginal commercial values of agricultural species are not usually sufficient for industry to invest in conservation efforts (Swanson and Goschl 2000). Smale (2005) reviews the literature documenting the economic benefits of improved crop varieties in commercial agriculture, as well as values assigned to species contributing genetic material to new varieties. Smalle (2005) concludes that "the marginal commercial value expected from an individual plant genetic resource in agricultural use will not be high enough, in general, to fund national innovation or conservation efforts at levels desirable for society" (pp: 22). The fallacy that individual species can incite conservation, or "they myth of enormous value" described by Gollin and Smale (1998: 244-6), is based on anecdotal cases of wild, indigenous plants generating large profits for pharmaceutical companies, and perpetuated by ecological economists emphasizing potential use values of single plant genetic resources. In reality species are highly substitutable and the commercial value of individual contributions to breeding efforts is very low (Smale 2005). Additional policies are needed to incentivize conservation and internalize the costs of diversity loss (Wale 2011).

2.4 Closing the conservation gap

Correcting for this market failure demands a two-fold approach: eliminating policies which encourage the abandonment of traditional farming systems by subsidizing the adoption of modern varieties; and putting policies in place which reward conservation. This section focuses on the latter strategy for closing the conservation gap, while acknowledging that mechanisms in place to reward the adoption of modern varieties present structural barriers to pursuing agrobiodiversity conservation *in situ* (Altieri 2002).

On farm conservation (a subset of *in situ* conservation) represents opportunities to link up conservation with rural development, where economically depressed custodians of agrobiodiversity can receive compensation for conservation. Opportunities for mutually-reinforcing gains to be achieved are available when conservation initiatives support livelihood strategies (Mendez et al 2007). Swaminathan (2011) describes 'Biohappiness Societies' where livelihoods are improved through active conservation. Biovillages, where conservation and enhancement of natural resources is a priority because the productivity and profitability of small-scale farms is dependent upon agrobiodiversity; and biovalleys, where biotechnology and business associated with the production of value-added products with medicinal plants and local foods are likewise contingent upon agrobiodiversity, are two types of societies that automatically internalize the costs of biodiversity conservation (Swaminathan 2011).

Where increasing the private value of agrobiodiversity is not possible additional incentives are required in order to close the conservation funding gap. A series of contingent valuation studies have been conducted to estimate compensation payments that farmers would require in order to conserve specific types of agrobiodiversity (see Wale 2008; Fuwa and Sajise 2009; Krishna et al 2010; 2013). It is noteworthy that agrobiodiversity services are distinguishable from other ecosystem services in that they produce significant private use values in the form of food and fibre (Narloch et al. 2011). Thus supplementary incentives required are likely to be less than is the case of other ecosystem services.

Rewarding conservation through incentives requires funding. A second type of conservation gap arises here: the difference between the funding available and the funding required. For the sake of clarity, this is referred to as the conservation *funding* gap, i.e. the shortage in resources that allow policy makers to correct for the difference between private and public marginal benefits. Hein et al. (2013) highlight the need for substantial increases in conservation funding in developing countries in particular. Low and middle income countries in the tropics, where most of the world's biodiversity is concentrated, have limited resources to fund conservation efforts. Protected area budgets in developing countries represent only 30% of the financial investment necessary for effective conservation, implying a shortfall of 70% that would need to be generated from other sources. Recent statements made by tropical country governments, particularly Ecuador, Guyana and Cameroon, indicating their willingness to preserve biodiversity if financial support can be provided are reviewed (Hein et al. 2013).

The potential for a number of different funding avenues to close the funding gap are discussed in the literature (Bardsley 2003; OECD 2004; Kroeger and Casey 2007; Nijkamp et al 2008; Hein and van der Meer 2012; Alvarado-Quesada et al 2014). Funding sources for conservation include government funding, philanthropic / donor support, biodiversity aid and market-based mechanisms. Donor support includes private foundations, trust funds and conservation NGO funding. Biodiversity multilateral and bilateral aid includes funding for conservation activities, sustainable use of ecosystem services and genetic resources, and the fair and equitable sharing of benefits arising out of the use of genetic resources. However donor funding directed towards protected area management has decreased in the past decade, while the small increase in biodiversity aid has been insufficient to make up the difference (Hein et al. 2013). Funding is also generally concentrated in specific projects of limited time-span rather than steady long-term flow of funds.

Following the CBD (1992) many conservation biologists began to view economic instruments as a more effective means of stemming biodiversity loss than policies directed towards setting aside protected areas (Rodríguez-Labajos andMartínez-Alier 2012). Market-based mechanisms for biodiversity conservation have been initiated all around the world.

The Ecosystem Marketplace report, '2011 Update, State of the World's Biodiversity Markets: Offset and compensation programs worldwide,' (Madsen et al 2011) plots 45 existing compensatory programs and 27 programs in development. Incentive programs are undertaken by national governments and in some cases with private partners. Goods are units of preserved habitats or groups of species and are represented by credits that can be traded in a market (Alvarado-Quesada et al. 2014). Over 1,100 active mitigation banks make up the existing programs, totalling at least 187,000 hectares of land under conservation management with permanent legal protection. The global annual market size is between USD 2.4 and 4.0 billion, however it is noted that as many as 80% of programs are not transparent enough to accurately estimate their market size (Madison et al 2011).

Pirard and Lapeyre (2014) present a typology in order to highlight the variability of market-based mechanisms in practice. The six types include 1) direct markets, such as those for non-timber forest products or ecotourism; 2) compensatory mechanisms or Cosean-type agreements based on property rights referred to as payment for ecosystems services (PES) schemes; 3) reverse auctions, wherein candidates for service provision (biodiversity conservation) place bids and set the level of desired payment as a response to a call made by public authorities to remunerate landholders; 4) tradable permits, such as in a carbon market system; 5) regulatory price changes, or taxes; and 6) voluntary price signals, wherein goods and services are marketed to consumers for their added conservation value using green marketing and eco-labelling.

Payment for ecosystem services (PES) schemes take many forms but can be defined broadly as a contractual agreement between buyers and sellers of a defined environmental service or the land that produces that service (Hein et al. 2013). The theory behind PES schemes is rooted in Coasean economics (Coase 1960; Engel et al. 2008; Bertacchini 2008). They seek to correct an under-production of environmental services by assigning property rights as a means of internalizing costs and benefits associated with conservation. Hein et al. (2013) highlight how PES schemes may be better suited to long-term funding requirements of biodiversity conservation and tap into additional sources of funding to close the funding gap. Alvarado-Quesada et al (2014) suggest that an international PES scheme has the potential to generate significant funds for biodiversity conservation, while Narloch et al (2011) assert that a system of direct payments may be most effective in providing incentives for conserving global public goods.

Market-based mechanisms are touted as an innovating means of incentivizing conservation; “the new Integrated Conservation and Development Program” (Pirard 2014). However Pirard (2014) suggests that most market-based mechanisms that have been put in practice are not entirely novel, and are not all market-based in the traditional sense where economic efficiency is the single bottom-line. He asserts that PES are in essence subsidy programs, or bilateral agreements, wherein governments pay relatively small groups of people to not develop on certain tracks of land. Payments are tailored to the particular circumstances of the groups involved This is in contrast to a free market characterized by high volumes of transactions guided by price signals (Pirard 2014). Social-equity and livelihood improvement goals can be traded-off with ecological goals in order to affect the overall outcomes of the project (Narloch et al 2011). PES schemes, dependant upon their design and management, have the potential to achieve positive social and ecological impacts.

Most PES schemes to date have been applied to forest conservation for carbon sequestration (Engel et al. 2008; Narloch et al. 2011), most notably the Reduced Emissions from Degradation and Deforestation (REDD) mechanism initiated by the parties to the

United Nations Framework Convention on Climate Change (UNFCCC) in 2007. While outcomes of REDD programs may have positive impacts on biodiversity conservation as a by-product of reducing deforestation, it will likely be insufficient for conserving biodiversity in non-forest ecosystems (Narloch et al 2011).

Narloch et al. (2011) discuss the potential for PES schemes to be applied to agrobiodiversity conservation services as a means for increasing the private benefits accrued by farmers from utilizing traditional landraces in lieu of 'improved' varieties. They suggest that 'payment for agrobiodiversity conservation' (PACS) schemes have the potential to be a low-cost and pro-poor conservation scheme. Narloch et al. (2011) consider the potential PACS schemes to suffer from the so-called 'PES curse,' where a lack of concern over social equity issues related to decision-making, access and benefit sharing may undermine the success of conservation interventions (Narloch et al 2011).

Paralleling the valuation debate, the potential for market-based mechanisms to close the conservation funding gap has been hotly contested in recent years. Economists diverge on the primary goal of compensatory market-based mechanisms. Some economists assert that ecological outcomes are the primary goal, thus social equity and livelihood improvement goals would be necessarily traded-off (Wunder 2007; Engel et al 2008). Others emphasize that the two are mutually-reinforcing and interdependent, and that ignoring the social dimensions to conservation interventions undermines their success and legitimacy (Corbera et al 2007; Pascual et al 2010).

Critics of market-based mechanisms raise ecological concerns regarding their role in biodiversity conservation. Concerns include the potential for 'leakage,' an increase in ecosystem degradation outside of project boundaries or timeframe; the non-permanence of interventions due to social or natural factors; and the unpredictability of complex natural systems, making markets susceptible to disturbances (Keulartz 2013). Biodiversity markets are more complex than carbon markets which manage only one ecosystem service, climate regulation. Bundles of ecosystem services must be the focus of biodiversity markets (Keulartz 2013). Markets also assume that ecosystem components and services can be both substituted with one another and compensated for financially (Rodríguez-Labajos and Martínez-Alier 2012). Ecosystem functions are not well understood and loss of keystone species, for example, may incite system 'flips.' Socio-ecological systems are complex and in-perpetuity credit schemes will not be able to reflect these dynamics by increasing prices as critical thresholds are approached, for example (Hein et al 2013).

Another body of literature raises practical concerns regarding the implementation of incentive or market-based mechanisms for biodiversity conservation. The lack of clear and enforceable property rights among ecosystem service providers is the most commonly cited impediment to a functioning system. On one hand, communities within developing countries currently participating or preparing to participate in compensatory schemes do not have secured land tenure and property rights (Larson et al. 2013; Alvarado-Quesada et al. 2014). On the other hand, communal or open-access resources governed according to alternative conceptions of private property do not readily fit this framework (Castree 2002; Keulartz 2013). For example, the *ejido* system in Mexico is governed under the principle of *usufruct*: the right to enjoyment of communal land (Keularz 2013). Traditional systems of land management such as these, which are equitable and articulate with customary laws, will collapse with the imposition of an incentive scheme based on the individual access, use, transfer and exclusion rights (Lovera 2009).

Where tenure is insecure, powerful elites are able to gain access and rights in the interests of project benefits. Communities with informal rights may be subject to new regulations and restrictions on land use. Where land tenure has been secured, community leaders without access to full information could give rights away unknowingly. In any scenario benefits may not be evenly distributed among those who contribute directly to conservation (Larson et al 2013). While in theory there are opportunities for conservation and development to be mutually-reinforcing, Winkler (2011) asserts that trade-offs between the dual objectives exists in practice in developing countries. Conservation initiatives inevitably restrict or prohibit certain uses of ecosystems and place uneven burdens on local communities (Larson et al 2013). Unemployment and poverty may ensue from the conservation of agricultural land, along with declines in access to land, food, fuel and timber (Keulartz 2013). Local land rights may be usurped ‘in the name of conservation’ depending on how the problem is framed and who is implicated (Beymer-Farris and Bassett 2012).

In addition to physical land tenure rights, intellectual property rights to plant genetic resources are essential for custodians to be recognized and rewarded for their contributions to biodiversity. Farmers’ Rights are enshrined in Article 9 of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) following calls from the COP to the CBD and Agenda 21; as well as in the form of Access and Benefit Sharing (ABS) provisions of the Nagoya Protocol to the CBD and the Multilateral System under the ITPGRFA. However these mechanisms still lack clarity and enforceability (Moeller and Stannard 2013; Halewood et al 2013), threatening the operationalization of Farmers’ Rights and ABS in practice. Without these types of rights the interests of communities may still be marginalized in the context of compensatory mechanisms.

Other preconditions to the functioning of market-based mechanisms are perfect competition with large numbers of buyers and sellers participating, perfect information amongst participants, zero or low transaction costs and free access and exit from the market (Alvarado-Quesada et al 2014). Alvarado-Quesada et al (2014) describe the ‘thinness’ of existing biodiversity markets with small numbers of buyers and sellers, information asymmetries among parties causing moral hazards, and high transaction costs associated with project design, monitoring, reporting and distribution of funds. Institutional challenges relating to enforcement and compliance persist. Landowners may engage in ‘opportunistic behaviour’ and engage in activities prohibited under the contract, especially when changes to regulatory frameworks on behalf of governments or administering bodies are anticipated. Non-compliance measures remain unclear in many of the existing biodiversity markets (Alvarado-Quesada et al 2014). The verification of service delivery is not always in measurable units or easily observable, as is the case with crop genetic diversity. Baseline data is required but not always available (Narloch et al. 2011). Market intermediaries may be in a position to exert power over contracting parties and influence prices (Kosoy and Corbera 2010).

2.5 Chapter summary

There is clearly an appeal to simplifying the problem of biodiversity loss into quantifiable costs to society that can be internalized by incentivizing biodiversity conservation. Valuation is a practical tool for rendering costs and benefits visible to policy makers and facilitating the inevitable decisions that need to be made regarding priorities and trade-offs. The opportunity for mutually-reinforcing gains to be achieved through policy intervention is also attractive. The potential pitfalls in this section arise because of complexities in practice - complexities which not only threaten the success of conservation interventions, but have the potential to negatively impact both human and natural ecosystems.

They key takeaway messages from the preceding four sections are as follows:

I. Conservation strategies are tailored to the level of diversity they seek to protect. The full range of genetic and species diversity, as well as ecosystem and functional diversity, can only be conserved *in situ,* while targeted species and the limited genetic diversity they represent can be captured in *ex situ* gene bank facilities.
II. Valuation has become a mainstream tool for justifying scarce resources being allocated towards biodiversity conservation. Although controversial, this approach is a cornerstone of the dominant conservation paradigm which emphasizes the instrumental use values of biodiversity and ecosystem services.
III. Market failure arises when there is a gap between the private and social values associated with biodiversity. In the case of public goods, private actors do not have incentive to take on conservation and less than socially-optimal levels of conservation are achieved. As we will see in later chapters, this market failure is particularly hard to correct in the case of CWR, from which custodians derive no private benefit.
IV. Market-based mechanisms for biodiversity conservation represent a potentially lucrative way to close the conservation funding gap, particularly in biodiverse rich areas in developing countries, although a host of concerns challenge their practicality.

As will be discussed in later chapters, the conservation of CWR very much falls within the dominant paradigm: valuation is the primary tool used for communicating benefits in monetary terms, and conservation investment is guided by estimates of the instrumental use value of select species. The application of market-based mechanisms for incentivizing CWR *in situ* conservation is currently in its infant stages, while the cast of characters involved in their conservation is still evolving. It is useful to reflect upon the potential implications of this paradigm, using these broader debates as reference points, while interest in CWR is still relatively new and growing. The concepts introduced in this chapter provide the foundations for the argument that socially-optimum levels of conservation may not be reached despite increased use in crop breeding and increasing interest from the international community. Valuation as it is currently practiced may only get us part way there.

Chapter III - Background and context

This chapter reviews published literature on CWR. It is divided into two main sections: 1) the use of CWR - how modern breeding techniques are facilitating the use of CWR today and reviewing efforts to quantify use and to place an economic value on their contributions to modern crop varieties; and 2) the conservation of CWR - their increasingly important role in breeding as climate change threatens agroecosystems, pervasive threats and their historical neglect from conservation schemes, particularly *in situ*. These sections together provide the necessary context in which to situate the findings of this study. This chapter concludes with two succinct lists: the ways in which this thesis reinforces the literature reviewed; and the gaps in the literature that this research seeks to fill.

3.1 The use of CWR

3.1.1 Breeding with wild species

CWR are species closely related to agricultural crops or other species of socio-economic value. They are defined as any wild taxon belonging to the same genus (Maxted et al., 1997b). The concept of CWR is a human construct based on wild species' use as crop progenitors or gene donors for crop improvement, but otherwise are no different than any other wild species found in ecosystems worldwide (Iriondo et al 2008).

CWR have been identified as a critical group of plant genetic resources (PGR) for wealth creation, food security and environmental sustainability in the 21st century by many (Prescott-Allen and Prescott Allen 1983; Hoyt 1988; Maxted et al 1997b; Meilleur and Hodgkin 2004; Heywood and Dulloo 2005; Stolton et al 2006). By facilitating crosses between them and cultivated species breeders can transfer novel genetic material to primary gene pools to achieve pest or disease resistance, yield improvement, stability and quality. As such they are considered important evolutionary genetic reservoirs.

This is not a novel idea. Wild species have been a source of genetic material to develop and improve crops since the beginning of agriculture (Hunter and Heywood 2011). By definition, all domesticated crops came from wild species and crossing between wild and domesticated species is the primary means by which new genetic material is introduced into crop gene pools. The natural and continual introgression of new genes into crops has mostly been unconscious throughout history (Hodgkin and Hajjar 2007), and modern cultivars of most crops contain some genes derived from a wild relative (Hunter and Heywood 2011).

The use of CWR began with the successes introducing pest resistance in grape cultivars around 1900, shortly followed by virus resistance in both potato and sugarcane (Prescott-Allen and Prescott-Allen 1986). All modern sugarcane stalks are derived from the resulting hybrids (Stalker 1980). The first tomato variety was released that contained genes deliberately introduced from a wild relative in 1941, and tomatoes have subsequently become the crop that has made the widest use of genes from the largest number of wild species (Rick and Chetelat 1995). During the 1940s and 1950s the value of wild species to confer useful traits in domesticated crops was more widely recognised and many well-known examples ensued including the late blight resistance in potatoes and stem rust and other diseases in wheat (Prescott-Allen and Prescott-Allen 1986). The use of wild genes in crop improvement programs for a wider range of crops gained prominence by the 1970s and 1980s (Hoyt 1988).

There are, however, limitations to the extent to which the beneficial traits housed by CWR can be accessed. Biological barriers to crossing are the most fundamental impediment. Interspecific compatibility between wild and cultivated species depends on ploidy levels of species, life history traits (when flowering occurs, for example) and the relatedness of species. Harlan and de Wet (1971) use the crop gene pool concept to denote the relatedness of species within crop families. Species that share a primary gene pool are very closely related and can be crossed easily, whereas species found in secondary or tertiary gene pools constraints of cross-incompatibility hybrid sterility are more commonly encountered. CWR are more commonly found in second and tertiary gene pools of cultivated crops. Often crosses between more distantly related species are unsuccessful and result in male sterility and unviable progenies (van de Wiel et al. 2010).

Today, most intraspecific crossing between wild and cultivated species is done using modern breeding techniques to overcome biological barriers (Ford-Lloyd et al 2011). Modern breeding is defined by Brummer et al. (2011) as the science of improving plants to better suit their environments and meet societal needs. This is in contrast to traditional breeding which generally refers to natural selection based on phenotypic traits such as high yield, early development, appearance, nutritional or biochemical properties. Modern plant breeding still involves phenotypic selection, but increasingly employs advanced tools to help identify, select and transfer genes of interest with increasing precision. These include processes for manipulating chromosomes, embryo rescue, marker-assisted selection and the development of introgression lines, inbred lines, core collections and mapping populations (see Ford-Lloyd et al 2011). A significant body of literature documents how these tools are making CWR more *usable* through better understandings of gene-trait relationships and procedures for managing crossing and backcrossing (Dwivedi et al 2008; Upadhyaya et al 2009; Lobell et al 2008; Maxted and Kell, 2009; Hunter and Heywood 2011).

Modern breeding has become synonymous with the use of molecular genetics (the study of single genes in isolation) and increasingly, genomics (the study of relationships between genes and how their expressions are influenced by the environment) (Ford-Lloyd et al 2011). Genomics approaches build upon established breeding techniques and allow for deeper analysis of interactions between genes and with their environment. These include sequencing or whole crop genomes, re-sequencing of related species, map-based trait identification, analysis of quantitative trait loci and gene isolation (see Ford-Lloyd et al 2011). These approaches host an immense potential to unlock the value of wild genetic diversity. Whole genome sequences are available for many crops and the re-sequencing of related gene bank accessions is underway for many crops (Koebner and Ortiz 2013).

It is noteworthy here that while inferring the use of various advanced tools, modern breeding is *not* synonymous with the type of genetic engineering associated with gene-splicing, or the development of genetically modified organisms (GMOs). Gene-splicing is an additional tool that in some cases can be used speed up improvement rates, but is almost exclusively used in the commercial sector (Brummer et al. 2011). Only a few foreign genes can be altered or added into organisms during 'transgenic events,' and is impractical and cost-prohibitive in most breeding programs given the current science available and the cumbersome regulatory approval processes (ibid).

With the advent of genomics breeders can rely on genotypic rather than phenotypic data when selecting individuals to cross - a more efficient way of identifying sources of desired traits among under utilized accessions (Koebner and Ortiz 2013). Phenotypic data refers to observable characteristics that are expressed by a plant. However a significant amount of information about a plant is either not directly observable or is not expressed (recessive traits), and is stored in the plant's genome. Next generation sequencing refers to the high-throughput re-sequencing of large numbers of related genomes, which will allow breeders to screen greater volumes of wild species for desired traits more efficiently than before (Lam et al 2010; Ford-Lloyd et al 2011). Predictive genotyping is described as a 'quantum leap' in this process (Koebner and Ortiz 2013) and will allow breeders to identify sources of desired traits with even more efficiency and accuracy.

Ford-Lloyd et al (2011) assert that biological barriers to crossing wild and cultivated species are being systematically overcome. Koebner and Ortiz (2013) summarize recent developments discussed during the European Association for Research on Plant Breeding, held in June 2013, and agree that the perceived constraints of using CWR in plant breeding programs are outdated. "The history of plant breeding suggests that a level of optimism would not be misplaced" (Koebner and Ortiz 2013: 284).

3.1.2 Efforts to quantify the use of CWR

Despite a lot of optimism expressed throughout the literature, the extent to which CWR are used is a challenge to quantify. An immense body of literature documents the successful transfer of beneficial traits from wild species to domesticated crops over the past four decades. Meta reviews of studies reporting advancements are useful in gaining an overall picture of the state of and trends in breeding (Harlan 1976; Stalker 1980; Prescott-Allen and Prescott-Allen 1986; Hajjar and Hodgkin 2007; Maxted and Kell 2009; Hunter and Heywood 2011). Together they communicate an overall positive trend in use as measured by examples of successes and the volume of studies published. This section underscores that reviews are limited by the extent to which the literature accurately reflects use in practice.

Prescott-Allen and Prescott-Allen (1986) were the first to examine the nature of and trends in the use of wild germplasm in the United States and Canada. Their work continues to be a widely referenced benchmark in the field. The list of crops grown or imported by the US and Canada that had been significantly improved by wild species includes tomato, bread wheat, potato, oat, sunflower, sugar beet, blueberry, alfalfa, sweet clover, cotton, tulip, hops, lettuce, sugarcane, palm oil, strawberry, bell pepper, tobacco and cacao (Prescott-Allen and Prescott-Allen 1986: 277-8). They report that achievements to date were significant, and that there was immense potential for further improvement in terms of both improving yields and quality in domesticated crops and rapid domestication of new crops. However, although the number of important crop species that have benefited from wild genetic resources is “not small,” it is “substantially smaller than might be inferred by the literature” (Prescott-Allen and Prescott-Allen 1986: 276). This is in part due to the terminology used in studies describing resistance, tolerance and immunity without sufficient quantitative evidence.

As of 1986, yield characteristics were the most commonly transferred traits of interest from wild to cultivated species, encompassing pest and disease resistance (most reported), heterosis, high yield potential and precocity. Recorded quality characteristics include colour, chemical content and better aroma or flavour. The extent of environmental adaptability was limited to one species of wild sugarcane and one species of wild cacao lending drought tolerance to their respective domesticates (Prescott-Allen and Prescott-Allen 1986). This reflects that it was not a prioritized breeding output of the time, at least in the context of CWR.

Hajjar and Hodgkin (2007) undertook the first comprehensive review of the use of wild species in breeding since that published by the Prescott-Allens, with the goal of communicating how far breeders had come over the course of 20 years. They reported a steady increase in the release of cultivars containing wild genes, although their list of crops differed substantially, selected according to the mandate crops of the CGIAR. They measured CWR use in terms of the number of varieties released and the number of different traits successfully transferred from wild to those released species, with some references made to varieties under development. Approximately double the number of wild species were used for nine of the crops common to the two reviews, and over 100 beneficial traits had been successfully transferred to released varieties. The crops which had benefited the most from CWR until in the mid-1980s continued to be dominant, namely wheat and tomato (Hajjar and Hodgkin 2007).

Hajjar and Hodgkin (2007) also report that although significant, use was more modest than had been anticipated. Contributions of CWR “remain less than might have been expected given improved procedures for intercrossing species from different gene pools, advances in molecular methods for managing backcrossing programs, increased numbers of wild species accessions in gene banks, and the substantial literature on beneficial traits associated with wild relatives” (Hajjar and Hodgkin 2007:1). Reported constraints include limited interspecific crossability despite the development of techniques for embryo rescue, advanced hybridization and other techniques to overcome interspecific reproductive barriers; hybrid sterility; genetic drag, or the retention of undesirable traits conferred along with beneficial traits associated with poor agronomic performance and the costly and time-consuming nature of breeding out undesirable traits; and the ongoing challenge of understanding pleiotropic effects, when one gene influences multiple traits. These factors have limited the use of CWR.

Hajjar and Hodgkin (2007) grouped beneficial traits into five categories: pest and disease resistance, abiotic stress tolerance, yield increase, improved quality and male sterility or fertility restoration. They found that CGIAR breeders had successfully used wild relatives in 13 out of the 19 crops studied, and traits from each of the categories had been successfully transferred to released varieties. Pest and disease resistance continued to be the most common trait. Very few examples of specifically yield increasing traits were reported, as CWR are generally associated with poor agronomic performance. Cytoplasmic male sterility was reported in pearl millet and sorghum, and some improvements in quality were recorded in cassava, wheat and tomato. Consistent with the results from 20 years prior, the category in which the least benefit had been realised was abiotic stress tolerance, or environmental adaptability (Hajjar and Hodgkin 2007).

Maxted and Kell (2009) provide a comprehensive review of 234 studies published journal papers, reporting the identification of useful traits in 183 CWR for 29 crop species. General findings include that the degree to which CWR are used by breeders varies between crops and are most prevalent in barley, cassava, potato, rice, tomato and wheat. Rice and wheat have benefited the most from wild germplasm, both in terms of the number of successful attempts to transfer useful traits and the number of wild species used. The most widespread use of CWR remains pest / disease resistance (39%), followed by abiotic stress (13%), yield characteristics (10%) cytoplasmic male sterility and fertility restorers (4%) and quality improvers (11%). Although more accounts of abiotic stress tolerance were included in this review than that conduced by Hajjar and Hodgkin (2007), no studies reporting temperature, drought or salt tolerance were published since 2006, with the exception of Chen et al (2008), detailing the use a wild barley specie conferring drought and temperature tolerance which was reported by Hajjar and Hodgkin (2007).

Maxted and Kell (2009) also comment that although quantitative trait loci have been identified in many wild species, their potential to be exploited has yet to be realised in breeding programs. The majority of CWR diversity remains untapped while breeding attempts remain unsystematic and non-comprehensive. The increase in volume of publications citing use of CWR over time is presumed to be the result of technological advancements.

Hunter and Heywood (2011) provide a less comprehensive but even more recent review of published literature. Examples of identified but not yet transferred traits include a specific wild specie of wheat (*Triticum turgidum, subspecies dicoccides*) which has twice the concentrations of zinc, iron and protein as domesticated varieties (Chatzav et al 2010). Schneider et al (2008) document the transfer of genes from a wild species of *Aegilopes* (goatgrass) to a related wheat species resulting in increased resistance to leaf rust, stem rust, powdery mildew and nematodes. Likewise, *Oryza nivara* (wild rice) has been used to breed resistance to brown hopper, a common pest to many domesticated species of rice in Sri Lanka (Central Rice Research and Devleopment Institute of Sri Lanka, adapted by Hunter and Heywood 2011).

These reviews are useful for getting an overall picture of the growing interest in using CWR. However published literature does not necessarily correlate with use of CWR in practice. Studies are difficult to compare with one another and advancements reported cannot easily be aggregated. Terms such as *tolerance, resistance* and *immunity* are used to communicate varying degrees of success and improvements, and are not always quantified. Different modes of resistance have varying effects. Durable verses transient resistance and polygenic verses monogenic resistance indicate varying degrees of effectiveness against variants of pathogens and overall robustness of the resistance (Prescott-Allen and Prescott-Allen 1986).

Moreover, the majority of publications come from a basic research perspective rather than an applied breeding perspective. Research into the basic biology of species, gene-trait relationships and the use of particular wild species as model organisms is published to a greater extent than ongoing work to develop breeding lines with wild germplasm. The identification or even successful transfer of traits does not always result in improved commercial cultivars (Maxted and Kell 2009). This leaves the reviewer with an impression of what *can* be done, rather than what *is* being done.

A case can also be made that ongoing use is underestimated in the literature. Advancements take time to materialize into tangible breeding outputs. CGIAR scientists generally under-publish their ongoing work and prioritize reporting once materials are ready to be released in the form of variety release reports (Khoury; Hearne, Interviews). Contributions from CWR are also difficult to trace as materials get passed between users without associated passport information (Weltzien-Rattunde; Bonierbale, Interviews). It is even more difficult to capture information on ongoing private sector work which is commercially sensitive and not readily available (Maxted and Kell 2009; Eastwood, Interview). Published literature is therefore an imperfect proxy for use and more thorough investigations are required to provide the basis for economic valuations and to inform policy.

3.1.3 Efforts to quantify the economic value of CWR

Economic valuation has been used to justify CWR conservation. Ford-Lloyd et al (2011) emphasize that conservation efforts could be bolstered significantly with a greater recognition of their value in breeding. Valuations have been undertaken by Prescott-Allen and Prescott-Allen (1986), Pimentel (1997), Hein & Gatzeiler (2006), Hunter and Heywood (2011) and PricewaterhouseCoopers LLD (2013), summarized in table 4. This table cannot be used for comparison due to the wide range of parameters and methodologies used.

Table 4 - Estimates of economic value of CWR

Study	Parameters	Estimated value US$
Prescott-Allens 1986	Annual contributions of CWR to US economy from domestic and imported sources	$350 million
Pimentel 1997	Annual contributions of CWR to US economy	$20 billion
	Annual contributions of CWR to world economy	$115 billion
Hein and Gatzweiler 2006	Net present value of wild coffee genetic resources	$1.458 billion
Hunter and Heywood 2011	Annual contributions of the wild sunflower genepool	$267-384 million
	Annual contributions of a wild tomato species providing a 2.4% increase in solids content	$250 million
PwC 2013	Current value of CWR genetic contributions	$68 billion
	Potential value of CWR genetic contributions	$196 billion

While these studies are useful for raising awareness of the value of CWR, they are limited by the extent to which they capture the breadth of ongoing work with wild species. The value of CWR is commonly estimated by quantifying the economic value of varieties released with genetic contributions from wild species. For example, the valuation conducted by Prescott-Allen and Prescott-Allen (1986) concluded that wild genetic resources contribute US$350 million annually in terms of the economic value of increased yields and quality characteristics, and avoided crop losses achieved by transferring insect and pest resistances from wild to cultivated species. However, as will be discussed in more depth in Chapter V, variety release is only the final stage in a very long process of breeding. Varieties still in the pipeline, as well as a host of basic research efforts with CWR that will never directly result in new varieties, are not counted using this approach.

Valuation exercises are also highly simplified and do not include measures for potential use values or resilience values. PricewaterhouseCoopers LLP (PwC) was commissioned by the Kew Millennium Seed Bank in 2013 to conduct a valuation of the current and potential indicative global production values of CWR for breeding for biotic and abiotic stress tolerance. This valuation exercise is highly simplified. Results from case studies of four sample crops (wheat, rice, potato and cassava) were extrapolated for 29 priority crops. They value current and potential benefits for 29 priority crops at US$42 billion and US$120 billion respectively. If maize, soybean and sugarcane are added to the list, values increase to US$68 billion and US$196 billion. The annual gross production of the 29 priority crops is valued at US$581 billion in 2010, and US$950 billion if the additional three crops are included. The *potential* benefits included in these estimates are assigned based on past economic gains and do not incorporate any risk analysis or consideration of future climate change scenarios (Eastwood, Interview).

Moreover, other types of value beyond their instrumental use are excluded from these estimations. Prescott-Allen and Prescott-Allen (1986) acknowledge that all valuations are incomplete because they undervalue qualitative aspects and intrinsic values. However they advocate for a pragmatic approach. Quantitative assessments render at least *some* values visible to policy makers who underestimate the value of some resources and exclude them from policy debates. “Describing the contribution and estimating its dollar value so that people can judge its significance for themselves does not change the aesthetic and other unquantifiable arguments for conserving wild sunflowers, for example” (Prescott-Allen and Prescott-Allen 1986: 7). It is noteworthy that the tradition of excluding species’ intrinsic values from valuation exercises has continued since.

The absence of any critical engagement with these valuation studies from the conservation biology literature is also noteworthy. The pervasive logic within the CWR conservation community is that there are only utilitarian values associated with them (discussed in Chapter VI), thus critics have not emerged from within this community. It is suggested here that these valuations have not received a wide enough readership outside of this community for the broader debates surrounding biodiversity valuation to be applied to the case of CWR. While it is beyond the scope of this thesis to apply an alternative valuation approach to the case of CWR, it is highlighted here that valuations to date have only incorporated a portion of the social benefits derived from their existence. Potential use, resilience and intrinsic values in particular are absent. This may have negative implications for conservation, as will be discussed in Chapters VI.

3.2 The conservation of CWR diversity

3.2.1 Adapting agriculture to climate change

Climate change is altering environmental conditions at a pace exceeding the natural rate of adaptation of cultivated crops (Maxted and Kell 2009; Hunter and Heywood 2011), and is a significant threat to biodiversity (Iriondo et al 2008; Ureta et al 2012). Phenological cycles of species are being affected (Cleland et al. 2007) with a majority of species trending towards earlier flowering and bud burst (Parmeson and Yohe 2003), shortened lifecycles and reduced seed production and fertility (Wollenweber et al 2003; Iriondo et al 2008). Shifts in altitudinal ranges of species and populations have been recorded (Parolo and Rossi 2007; Lenoir et al 2008), with movements towards poles or upwards in altitude being the most commonly reported trends (Iriondo et al. 2008).

It is widely acknowledged in the literature that greater genetic variation is required to adapt to rapidly changing environmental conditions. CWR are predicted to play an ever growing role in crop breeding as climate change places more acute pressures upon crop production systems (Vincent et al 2013; Dempewolf et al 2014). They are recognized as a valuable repository of ‘climate ready’ traits even more so than landrace varieties (Breithaupt 2008), due to the diversity of habitats in which they grow and the range of conditions to which they are adapted (Maxted and Kell 2009). Most notably, wild species are found in marginal lands around agricultural areas and are not the benefactors of farming inputs such as fertilizers, pesticides and irrigation regimes (Maxted and Kell 2009). CWR are likely the *only* sources for a significant amount of required variation (Jarvis et al 2008; Brummer et al 2011). Feuillet et al (2008) go further, asserting that breeders will be unable to sustain crop yields and quality in light of dynamic abiotic and biotic threats *without* greater use of wild species.

The relatively small number of reported of cases of CWR being used to lend increased environmental adaptability contrasts with these predictions from the conservation biology community. The complexity of traits related to abiotic stress tolerances can account for the gap between expected and achieved contributions from CWR thus far.

Cattivelli et al. (2008) provide an overview of progress made in breeding for drought tolerance. The contribution of genomics has so far been marginal, with only a few examples having been reported. More progress has been made however in terms of a more full understanding of traits which sustain yields under drought conditions. Many different polygenic traits are involved, regulating root depth, timing of phenological cycles, leaf temperature and transpiration efficiency, to name only a few (ibid). Salt tolerance in soils is likewise a highly complex trait due to the number of relevant genes and the large environment by genotype interaction (GxE). Flowers (2004) reviews 68 studies claiming increased salt tolerance with a single gene transfer, and concludes that almost all studies provide insufficient evidence for these claims. Efforts to use wild halophytes (species which grow naturally in saline soils) in breeding programs have had limited success, although quantitative trait loci associated with tolerance have been identified in barley, citrus, rice and tomato and in many wild species (Flowers 2004; Colmer et al. 2006).

Koebner and Ortiz 2013 suggest that sources of desired traits may be identified by screening materials originating from areas with climates similar to predicted climate change scenarios in major production areas. Marker-assisted selection and quantitative trait loci mapping are useful when working with highly complex inherited traits such as drought and salt tolerance and are being used increasingly to speed up the breeding process (Brummer et al. 2011). The extent that these tools have facilitated the transfer of abiotic stress tolerances from wild to cultivated crop gene pools has not been reviewed in recent years. However the pace at which this field is advancing, particularly with the advent of genomics tools for predictive trait mining, provides a strong rationale for investing in CWR conservation.

3.2.2 Conservation in the context of uncertainty

Uncertainty provides a strong rationale for biodiversity conservation. The development of new cultivars, even with the use of modern breeding tools, takes an average of 10-12 years. But this is predicated on the target traits being known and the environment in which the cultivars need to be tested being available (Semenov and Halford 2009). However breeders often do not have access to, or the ability to experimentally mimic, environmental conditions of even the near future to execute field trails (ibid). It is also a guessing game as to which traits may be of significance in 15-25 years. Koebner and Ortiz (2013) discuss the difficulty in identifying desirable traits given the degree of uncertainty associated with climate change.

Brummer et al 2011 predict that in the short term, tolerance to adverse soils conditions including acidic, aluminum-rich and saline soils will likely be increasingly important traits. This is particularly the case for production on marginal lands and where the salt content of irrigated land is increasing (Witcombe et al. 2008). Other desirable traits from wild species are likely to include abiotic stress tolerance to high temperatures, temperature variation and drought (Brummer et al. 2011). Host-pathogen relationships are also influenced by changes in climate and as crops move into new areas of cultivation, thus finding resistances to novel biotic stresses will continue to be a high breeding priority (Brummer et al. 2011). CWR have historically been most able to lend biotic resistances to cultivated varieties.

The effects of climate change on the distributions of CWR are not well known. Species vulnerability to climate change is assessed using distribution models, or climatic models, to estimate how current habitats will decrease or shift under different climate scenarios. Threatened species will have projected narrowed *climatic envelopes*: boundaries drawn around species' habitats based on existing distributions and environmental variables defining their stress tolerance (Iriondo et al. 2008). Reports predict that wild species will generally experience narrowed climatic envelopes and impaired ability to adapt to changing climatic conditions as a result (Schwartz et al 2006; Jarvis et al 2008; Iriondo et al 2008; Lira et al 2009; Uteta et al 2012; Davis et al 2012).

Jarvis et al. (2008) predict the fragmentation of wild peanut, potato and cowpea habitats with 16-22 per cent to become extinct and most species losing over 50 per cent of their range by ~2055. Uteta et al. (2012) model distributions of maize races and wild relatives in Mexico and identify taxa and geographic regions most vulnerable to climate change. Their findings indicate that wild species will experience even more severe declines than maize species. Lira et al. (2009) use a modelling approach to map projected marked contractions of eight wild species of gourd. Their results show few opportunities for species' survival, while many have shown proven resistance to various diseases which may be crucial for domesticated crop improvement (ibid). Cobben et al. (2013) paint an even more dire picture. They warn that such modelling approaches are too optimistic and have overestimated species migration potential by neglecting two important factors: dispersal capacity: species' capacity to reach their new estimated habitat areas, and founder effects: losses in genetic diversity among species while tracking suitable climate conditions. Thus the impacts of climate change on wild species populations may be more severe than predicted.

In addition to climate change, CWR in their natural habitats are subject to an increasing range of threats including habitat loss and degradation due to deforestation, desertification and urbanization, invasive species, abandonment of traditional agricultural systems and weakened traditional knowledge systems (Jarvis et al. 2008). The biodiversity inherent to traditional farming systems is being eroded as modern varieties are introduced and and the dominant industrial agricultural model continues to spread around the world (Wale 2011).

The literature regarding CWR conservation highlights an immense degree of uncertainty. Breeders are operating within a context of compounding unknowns - unknowns relating to the usefulness of species currently stored in gene bank collections, the genetic base of complex traits, what future growing conditions will be like, which traits will be required in the coming decades, and where sources for these traits may be found. Policy makers and conservationists are likewise operating within a context of unknowns - unknowns related to shifting environmental envelopes of both crops and their wild relatives, the impacts of climate change and other environmental and anthropogenic threats on CWR populations, and the relative value of diversity as unknown critical thresholds are approached.

This uncertainty highlights the importance of conserving the breadth of genetic diversity currently available, as well as its ability to continually adapt to changing environmental conditions. This will ensure the availability of inputs into crop improvement programs in the future and facilitate the continued adaptation of crops to new climatic extremes and shifting spacial boundaries (Ortiz et al 2008). However, as is discussed in the following section, CWR have been historically neglected from both *in situ* and *ex situ* conservation efforts despite this urgent need to protect them.

3.2.2 A lack of conservation tradition

The conservation of CWR has been almost entirely focused on their collection and storage in gene bank facilities rather than in protected areas (Ford-Lloyd et al 2011). However to date *ex situ* collections remain predominantly comprised of socio-economically important crops, while the vast majority of crop species remain underrepresented (Maxted and Kell 2009). Wild species are particularly underrepresented, including wild relatives of the world's most important food crops such as *Triticum* and *Aegilops,* proven to be of immense value in wheat breeding (Ford-Lloyd et al 2011). 'Backing up' wild genetic diversity in *ex situ* collections will become increasingly important as environmental change happens at a faster rate than species can migrate, even in assisted migration scenarios (FAO 2010).

In situ conservation of CWR, specifically the establishment of gene reserves, has yet to be systematically applied beyond a very few number of few cases (Ford-Lloyd et al 2011). Protected areas are most commonly designated to protect climax vegetation, whereas CWR are rarely associated with climax communities, usually found in intermediate stages of succession and disturbed, pre-climax communities. They have evolved this way due to human intervention (Maxted et al 1997b; Iriondo et al 2008).

Where the inclusion of CWR in protected areas is incidental their management is often ineffective due to their unique requirements and competing interests with other targeted species (Iriondo et al 2008). CWR often require active conservation or dynamic intervention. Management may entail control of nutrients, erosion control, burning, invasive species, habitat disturbances, grazing and other interventions preventing the site from reaching its natural climax state (Maxted et al 2008; Hunter and Heywood 2011). The removal of such controls is to species' detriment. Outside of protected areas CWR are found in marginal environments such as roadsides and field margins but likewise not actively managed for genetic diversity conservation.

A small subset of protected areas are classified as genetic reserves. A small subset of these are tailored for the conservation of plant genetic resources for food and agriculture (PGRFA) (Hunter and Heywood 2011), of which there are very few to CWR conservation (Irionda et al 2008). The location of reserves is often decided upon based on practical concerns such as the concentration of human populations, suitability of the land for activities such as agriculture, urbanization and logging, or novel ecosystem value and not because they are hotspots of biodiversity (Maxted et al 2007). The conservation of CWR diversity is not deemed to be a priority within the protected area community (Vincent et al 2013).

On farm conservation emphasizes the sustainable management of genetic diversity of locally developed landraces with associated wild species by farmers within traditional agricultural systems. While the primary objective of genetic reserves is the conservation of genetic diversity, that of on-farm conservation is the maintenance of the traditional farming system itself irrespective of genetic diversity (Maxted et al 2006). Iriondo et al (2008) note that although in practice these approaches generally look the same, the difference in focus can have implications for the way the area is managed. For example, the introduction of new high-yielding varieties in an agroecosystem can lead to the displacement of existing genetic diversity while the traditional system in that area is preserved. The genetic reserve approach is more favourable to the conservation of CWR diversity.

Russian botanist N. I. Vavilov is most well known for his identification of centres of origin/centres of domestication for the world's most important food crops (1931). *Vavilov centres of origin* are large geographical areas where domesticated species have survived the longest and where their genetic variation is most highly concentrated. There are very few and small protected ares within Vavilov centres of origin (Maxted and Kell 2009). A study published by the World Wildlife Fund (WWF) in 2004 found that protection in places with the highest levels of crop diversity was less than the global average. Amend et al (2008) note that where the protected areas did overlap with significant areas for agrobiodiversity, little attention was given to the management of landraces and CWR.

Limited *in situ* conservation measures have been undertaken by national governments. Floristic inventories including CWR have been undertaken by some national governments in cooperation with various organizations. Bolivia's Red Book, developed using the IUCN approach to species diversity monitoring, details the country's biodiversity and has become a widely referenced achievement. Some national governments have developed incentive schemes in the form of financial subsidies in an effort to maintain such areas. Such measures can have positive short-term effects, however genetic diversity conservation by definition requires long-term investment. More formal conservation measures are required as such funding mechanisms are difficult to maintain, particularly in developing countries where CWR are largely located and resources are limited (Iriondo et al 2008).

International support has facilitated *in situ* conservation to some extent. The European Union and FAO have provided support to local partners to establish genetic reserves for CWR in the past, as well as international non governmental organizations such as WWF to a lesser extent. It is noteworthy that projects have been short-term and implemented predominantly in isolation of each other (Hunter and Heywood 2011). The timescale of projects is a major constraint of CWR conservation. Generally 30 years or more are required to begin to realize benefits, while funding from international donors is usually limited to 3-5 years without the possibility or renewal. Hunter and Heywood (2011) emphasize that the development of long-term conservation strategies and the securement of sustainable funding sources are more likely if CWR national action plans are already in place.

The largest-scale initiative to date was undertaken by the Global Environment Framework together with the United National Environmental Program (GEF-UNEP) in 2004. CWR projects have been implemented in five partner countries: Armenia, Bolivia, Madagascar, Sri Lanka and Uzbekistan. The project worked with national governments to create legislation consistent with international agreements (CBD and ITPGRFA), develop coherent national strategies to conserve CWR and build capacity to undertake CWR surveys and collect baseline data, develop management plans and put in place monitoring and conservation activities for CWR (Hunter and Heywood 2011).

Other examples include the Potato Park, an indigenous bicultural heritage area in Peru which actively manages for the breadth of agrobiodiversity found within its borders (Argumedo, 2008), and the Tehuacan Cuicatlan UNESCO Biosphere Reserve in Mexico established in 2012 in recognition of it being a centre of origin for a variety of socio-economically important food crops including maize, pepper, amaranth, avocado, pumpkin and beans (UNESCO MAB website).

There are several underlying causes of the lack of investment from the international donor community. One is that agrobiodiversity conservation suffers from a lack of tradition of collaboration. The range of stakeholders affected is extensive because it brings together two sets of actors which normally do not work together: agriculture and biodiversity conservation. “The current disconnect existing among agencies presents considerable challenges for partnership and coordination, as well as for establishing a suitable policy/legal enabling environment for CWR conservation” (Hunter and Heywood 2011: 17).

A second potential cause is donor atrophy. Donors involved in CWR *in situ* conservation such as GEF-UNEP are not in a position to provide long-term support beyond short-term project funding. They need to actively seek out conservation partners with the mandate and capacity to plan and coordinate CWR *in situ* conservation activities, which has proved to be a significant challenge (Hunter and Heywood 2011).

CWR conservation has featured in international policy documents increasingly over the past decade. The European Crop Wild Relative Diversity Assessment and Conservation Forum, launched in 2005, produced the first comprehensive catalogue of CWR and produced baseline data, assessed the threat and conservation status of CWR and developed standardized methodologies for data management, population management and monitoring, and assessment of genetic erosion and genetic pollution (Iriondo et al 2008). The Forum published the *Global Strategy for Crop Wild Relatives Conservation and Use* in 2007 which outlines the creation of a global mechanism/clearing house for CWR conservation and use, national CWR inventories and global priority CWR lists and priority sites.

In 2009, Maxted and Kell published a report on behalf of the FAO Commission on Genetic Resources for Food and Agriculture, entitled *Establishment of a Global Network for the In Situ Conservation of CWR: Status and Needs*. They provide an overview of the priority areas for conservation by both region and priority taxa. The widely cited report outlines steps for national CWR strategy planning, identifies important areas and conservation gaps for CWR and methodologies for selecting priority taxa for conservation. The 2012 report from the FAO Commission on Genetic Resources for Food and Agriculture (CGRFA) Technical Workshop, *Towards the establishment of a global network for in situ conservation and on-farm management of PGRFA*, outlines a set of recommendations and next steps for creating this network.

Other recent international initiatives include the European Union funded European Crop Wild Relative Diversity Assessment and Conservation Forum (www.pgrforum.org), the IUCN's Crop Wild Relative Specialist Group (www.cwrsg.org), and the recently inaugurated CWR global portal (www.cropwildrelatives.org).

In Nagoya, Japan in 2010 (COP 10) the Conference of the Parties to the CBD established the Aichi Biodiversity Targets as a strategic plan to halt the loss of biodiversity by 2020 (http://www.cbd.int/sp/targets/). Target 13 reads, *By 2020, the genetic diversity of cultivated plants and farmed and domesticated animals and of wild relatives, including other socio-economically as well as culturally valuable species, is maintained, and strategies have been developed and implemented for minimizing genetic erosion and safeguarding their genetic diversity.* It remains to be seen whether the Aichi Biodiversity Targets may be achieved, and how a global network may be effectively operationalized in order to work towards this goal. Despite a clear need to safeguard wild species by establishing genetic reserves in Vavilov centres of origin, progress has been very slow and only a very few examples exist today.

3.3 Chapter summary

The literature discussing the use of CWR highlights how modern breeding tools are facilitating the transfer of genetic diversity from secondary and tertiary gene pools to primary crop gene pools with increasing efficiency. Although quantifying use has been a challenge, optimism is pervasive within the scientific community that CWR will play an increasingly important role in crop breeding in the years to come.

The literature regarding CWR conservation highlights an immense degree of uncertainty, which underscores the imperative to conserve the breadth of genetic diversity that exists today along with its capacity to continue to evolve along with changing conditions.

It also highlights the lack of tradition of conservation of crop genetic diversity. The active management of CWR diversity through the establishment of a global network of genetic reserves will ensure the availability of inputs into crop improvement programs in the future while technological advancements continue to facilitate their utilization.

The salient points highlighted in this chapter are as follows:

I. Technological developments are facilitating the increased use of CWR;
II. Efforts to estimate use and quantify economic value have been limited;
III. CWR will become increasingly important as climate change threatens the integrity of agroecosystems;
IV. The full breadth of genetic diversity that exists today along with its capacity to evolve along with changing environmental conditions will be required to secure the global food system in the future; and
V. Progress towards achieving *in situ* conservation has been very slow and examples to date are few in number. A global network of *in situ* conservation areas (Maxted and Kell 2009) has yet to be implemented.

These points are reinforced by the research findings presented in the chapters to follow. The gaps identified throughout this chapter include:

I. An accurate and up-to-date account of the use of CWR in crop improvement programs in light of technological advancements and increasing pressures associated with climate change;
II. An analysis of the extent to which CWR are being used to lend traits associated with environmental adaptation to modern crop varieties;
III. Critiques of valuation efforts which are based exclusively on the economic value of genetic contributions to modern crop varieties; and
IV. Reflections upon the potential implications of conservation policies guided by valuations focused on direct use values associated with CWR.

This thesis seeks to address these gaps in the chapters to follow.

Chapter IV - Methodology

This research is rooted within an ecological paradigm that recognizes the intrinsic values of nature and the essential role that biodiversity plays in maintaining the wellbeing of complex socio-ecological systems. Holistic conceptualizations of nature are held above reductionist approaches to valuing ecosystem components and services. It is important to acknowledge that despite efforts to report objectively, the research paradigm influences how results are interpreted and what gets emphasized or de-emphasized.

This thesis employs a qualitative research methodology. It involves a systematic theoretical investigation into the *why* and *how* of a particular phenomenon, beyond an empirical account of the way things are, through the use of various qualitative research methods.

A mixed method approach is employed comprised of a traditional qualitative research method and grounded theory method. The traditional approach involves using existing theory to develop hypotheses and deduce findings. The conceptual framework (Chapter II) and the literature review (Chapter III) provide a theoretical framework from which to make predictions and analyze data. The grounded theory method is an inductive approach, grounded in the data collected. To a degree the emergent themes from the data informed the selection of an appropriate theoretical framework and most applicable literature. The melding of theory and evidence was an iterative process.

Modes of data collection include content analysis of both existing literature, targeted semi-structured interviews with key informants, and content analysis of additional documents. Literature from a variety of disciplines including crop breeding, conservation biology and ecological economics were reviewed, as well as policy documents and economic valuation studies. Sources of literature were identified through key word searches in the University of Waterloo library online database and recommendations made by key informants.

The first round of interviews was conducted with crop breeders and gene bank managers affiliated with the CGIAR crop improvement centres, with a few supplementary perspectives from university institutions where more appropriate given the context of the crop in question and where significant gaps in data remained. The second round of interviews was conducted with experts in the field of CWR conservation. These included academics and representatives from international organizations engaged in CWR conservation. The selection of key informants was done according to job descriptions and levels of experience, speciality in breeding with CWR or otherwise immense capacity to speak to the topic at hand, irrespective of gender, age, nationality or any other demographic factors. Interviews were conducted between February and April, 2014. Appendix I provides a list of key informants. Questions were open-ended and the interviews followed a conversation-style format. Appendix II provides a general interview template.

A subsequent round of content analysis was done with a series of confidential meeting reports which arose from three years of consultations coordinated by the Global Crop Diversity Trust, in collaboration with Kew Millennium Seed Bank, as part of the ten year *Adapting Agriculture to Climate Change* project (see Dempewolf et al 2014). Consultations brought together a diverse group of scientists and crop breeders on the cutting-edge of their research in taxonomy, genetic resources, applied plant breeding and genomics. Representatives from universities, private breeding companies, national agricultural research centres (NARS) and CGIAR crop improvement programs were brought together to discuss recent advancements in using CWR, bottlenecks in the breeding process and strategies for moving forward.

One forthcoming piece of literature is referenced frequently in the following chapter. Gregory J. Baute (University of British Columbia), Hannes Dempewolf (Global Crop Diversity Trust) and Loren H. Rieseberg (Indiana University) are experts in the field of genomics approaches to breeding. A draft version of their book chapter entitled, 'Using genomic approaches to unlock the potential of CWR for crop adaptation to climate change' provides valuable insight into recent progress and potential of using CWR.

Data analysis was done using a thematic coding approach and NVivo 10 qualitative data analysis software. Interviews were transcribed and uploaded along with the series of consultation meeting reports. Themes were then identified within transcripts and reports and used to connect data with relevant literature. Coding is an interpretive technique that organizes the data is such a way that meaning can be drawn naturally from it. The first step in data analysis was to read through all documents and take note of themes and ideas that resurfaced. The second step was to again read through all documents and assign codes to these themes and ideas. The third step involved arranging the codes into hierarchies, or 'supranodes' and then into a network of concepts. The common strains from each of the stories told by key informants became one story of the use and conservation of CWR.

The selection of crops was done in consideration of those included in previous studies, included in Annex 1 of the International Treaty for Plant Genetic Resources for Food and Agriculture, the mandate crops of the CGIAR, the overall importance of crops in the global food system in terms of staple foods, and the availability of most relevant experts. The crops included in this study are banana, barley, bean, cassava, chickpea, cowpea, finger millet, lentil, maize, oat, pearl millet, potato, rice, sorghum, soybean, sweet potato, tomato, wheat and yam.

Chapter V - What the wild things do

This chapter documents the current use of CWR in public international crop improvement programs. The first section briefly documents the process and current realities and limitations of using CWR accessions stored in gene bank facilities, as well as opportunities which exist for improving the process. This background information provides context for both the research findings to follow in this chapter and discussion and analysis regarding the insufficiency of a dominant conservation paradigm focused on *ex situ* conservation in subsequent chapters.

The second and third sections document the key results from the first research question: to what extent are CWR being used within CGIAR crop improvement programs today? These sections discuss emerging trends and how wild species are being used in particular to adapt cultivated crops to predicted climate change scenarios. The fourth section puts forward predictions regarding future use, using the availability of genomics resources and the genetic variation within crop gene pools as indicators. Assuming that this model has predictive value, it suggests that CWR will be used more in the coming years. This is consistent with predictions from both crop breeding the conservation biology communities. These findings are relevant to the CWR conservation community advocating for increased conservation investment.

A key message echoed throughout this chapter is that the majority of ongoing work with CWR has yet to result in tangible breeding outputs in terms of modern varieties being released. Valuation exercises based on the economic value of the genetic contributions to improved crop varieties thereby underestimate the potential use values of CWR for crop improvement. This is particularly noteworthy given that valuations are based exclusively on instrumental use values of species, which should include potential use value. This point will be elaborated upon in Chapter VII.

5.1 The current realities of the breeding process

The network of CGIAR gene banks around the world hold the genetic diversity used as inputs into crop improvement programs. This system is well-established and is characterized by a very high degree of technical capacity among scientists, relative financial stability provided for by the Global Crop Diversity Trust endowment fund and protocols for managing the viability of accessions stored within them. However there remains a series of limitations to the extent that the overall gene banking system can facilitate use of wild species. This section summarizes the process of and challenges to accessing the benefits housed within wild genetic diversity.

The process of using CWR for crop improvement requires a significant amount of time, resources and expert capacity. Both basic and applied research is involved. Basic research includes *inter alia* gene discovery, or the identification of resistance / tolerance genes in novel species, and the development of advanced genomics approaches and the sequencing and re-sequencing of whole genomes. These scientists tackle unanswered questions regarding species' basic biological traits and taxonomy which need to be addressed in order to make use of CWR. Applied breeders develop new crop varieties and evaluate materials as they move along the continuum (Sackville-Hamilton, Interview).

The term 'pre-breeding' is often used to describe the critical link between gene discovery and variety development. Pre-breeding extends to all activities relating to the identification of desirable traits and associated genes from wild genetic material that cannot be used directly in breeding programs, and the transfer of traits to an intermediate set of materials that breeders can then use in variety development (FAO 2008). 'Pre-breeding' material then refers to varieties in the very beginning stages of development when wild genes are first transferred into cultivated crop backgrounds. Many rounds of evaluation and selection are then required to 'breed-out' undesired traits while retaining the desired contributions from the wild parent. This is process is referred to as backcrossing.

Consistent with the literature, biological barriers to crossing wild and cultivated species remain one of the most significant constraints to use. While progress has been made to overcome crossing barriers they remain a substantial hurdle for the increased use of CWR in crop improvement programs. It is important to note that interspecific crossability between wild and cultivated species varies considerably among crops. Some wild species of sorghum, for example, are considered as primary gene pool material and naturally occurring hybridization between wild and cultivated species is common (Weltzien-Raltunde, Interview). In the case of cowpea on the other hand breeders have been unable to achieve viable crosses between wild and cultivated species (Fatokun, Interview).

Intuitively, wild species retain many of the traits associated with poor agronomic performance that have been systematically selected out of domesticated species. These include *inter alia* low yields, seed shattering and small seed size. *Linkage drag* refers to the transfer of unwanted traits along with wanted traits into cultivated crop gene pools. Blocks of traits are often inherited together (large sections of chromosomes) and it is a challenge for breeders to isolate targeted traits within these blocks and transfer them individually. Efforts to increase genetic recombination rates are focused on breaking up these blocks in order to isolate targeted traits and reduce linkage drag (Jena, Interview). Methods such as transgressive segregation are still under development and are not widely accessible to most breeding communities. Linkage drag remains a significant deterrent to using wild species in crop improvement programs.

The lack of any information for accessions currently held in gene banks is highlighted as another significant constraint. Passport data is missing for significant portions of collections, which includes collection coordinates (latitude and longitude) and information about species' habitats including vegetation and soil types (including soil pH and soil samples), population size, evidence of habitat disturbances, location relative to agricultural fields and associated local knowledge. Basic documentation is also missing. Basic characterization and evaluation data is also missing. This includes species' phenotypic characteristics and how they respond to different stresses under various growing conditions. While gene banks are well placed to undertake gene discovery and collect phenotypic information for accessions such as grain size that can be recorded at one place at one time, the investment required of evaluation is beyond the budget of gene banks (Sackville-Hamilton, Interview). Without sufficient passport, characterization and evaluation data it is a guessing game for breeders to select new material for screening for a particular trait. Breeders have not developed systematic or comprehensive strategies for characterizing CWR (Jansky et al 2013).

Breeders then restrict the use of wild species to those which have natural history records, some curator knowledge about a given accession's characteristics, or have been used in prior breeding programs and for which there is already some phenotypic and genotypic information available (Baute et al, forthcoming). The underutilization of wheat accessions illustrates this point well. The use of CWR in wheat improvement is very well established and much attention has been devoted to the collection and conservation of wild wheat species because of this extensive history. Existing collections now cover much of the diversity of primary, secondary and tertiary wheat gene pools, yet this diversity remains largely unexplored on account of the lack of characterization data available for accessions. Wheat breeders continue to limit their use to material which has been used before. Only about 4-5% of the wild accessions stored in the CIMMYT gene bank are used to develop pre-breeding materials, while it is predicted that sources of resistance to most biotic and abiotic stresses will be found in the existing collection (Braun, Interview).

It is difficult to predict how genes from wild species will be expressed once transferred into cultivated crop backgrounds, even in the event that some characterization information is available. Wild species can carry beneficial allelic variation for traits without expressing them directly, revealing these 'masked' or 'cryptic' traits during the crossing process. Experts in wheat and banana in particular emphasize how cryptic variation can result in significant, and often unexpected, superior performance of crosses between wild and cultivated species (Swennen; Braun, Interviews). The perception of wild species' inferiority based on their agronomic performance at face value deters breeders from exploring them for useful traits.

Experts across the crop communities call for a more systematic evaluation and screening of trait variability within CWR collections. However screening all wild species for hidden traits of interest, whether directly expressed or cryptic, is an impossibility for most crops. While single gene traits such as pest resistances are often expressed directly (i.e. the absence of the pest indicates the plant's resistance), other traits are best screened for once transferred into domesticated backgrounds as pre-breeding materials. This requires significant effort that is beyond the means of most breeding programs, so the vast majority wild diversity remains unexplored.

The usefulness of existing collections is further limited by the challenge of maintaining genetic stocks. In some cases funding constraints limit how often managers can grow out accessions and maintain the viability of collections. Gene flow between accessions during regeneration cycles threaten the integrity of collections (GCDT internal reports). Handling errors are also unavoidable when dealing with large collections (Baute et al, forthcoming) and capacity limitations persist without standardized seed dormancy and germination protocols to follow (GCTD internal reports).

To make matters worse, information is also lost when accessions are moved between gene banks around the globe and are involved in various breeding programs. When samples are sent and received by gene banks it is not clear whether they can be traced to the same origin as existing samples or are morphologically duplicate (GCDT internal reports). Some accessions that have been held for decades may be misidentified without their taxonomy ever being confirmed. Where taxonomy is identified correctly, information recorded for ecological and environmental conditions is not passed along with the germplasm being exchanged (GCDT internal reports). Without accurate documentation both gene bank curators and potential users of materials are left with unanswered questions regarding how much diversity is in each accession, how similar accessions are and where duplication exists, and which cross-section of a collection captures the most diversity (Baute et al, forthcoming).

Having core collections that accurately represent the genetic variability available in wild populations is essential. Core collections are cross-sections of gene bank collections put together by gene bank curators for the purpose of condensing the genetic variation present in the collection to a manageable number of accessions to be screened for traits of interest. Core collections are assembled by dividing accessions into phenotypic, life history, taxonomic or ecogeographic groups and then selecting representatives from each group (Baute et al, forthcoming).There is an increased expectation that gene banks keep more detailed passport data on all new accessions coming in and develop core collections which adequately represent the genetic variation available across primary, secondary and tertiary crop gene pools (Sackville-Hamilton, Interview).

Passport data may facilitate *predictive trait mining:* the selection of wild species for crossing based on the likelihood that they house a particular trait given where they were collected from. The focused identification of germplasm strategy (FIGS) is an approach for assembling core collections that uses collection locality information to predict which accessions are most likely to have specific traits of interest (Mackay and Street 2004; Khazaei et al 2013). When new mutations are favoured by selection, i.e. when a random genetic recombination event results in a desirable trait that is then widely selected for, that allele is brought into higher frequency in a given geographic location. Locations linked to the mutation event will by extension have reduced diversity. Genomic data on the presence, size and number of regions within the genome that have experienced high selection pressure will lend valuable insight into how local adaptation happens and how they can be harnessed in breeding programs. Genomics approaches will help identify sources of candidate genes for traits of interest (Baute et al, forthcoming).

Intuitively, detailed data on collection sites should lend valuable insights into the potential usefulness of species. For example, species which have co-evolved in the same region as a given pathogen likely host sources of resistance. Likewise species from drought-affected areas likely host mechanisms for drought tolerance (Khazaei et al 2013). Experts from the bean community highlight how geographic information systems

(GIS) data will help orientate germplasm evaluation. Different types of drought stress (intermittent, terminal) result in bean species that have developed different phenotypic traits to adapt (GCDT internal reports). Experts from most crop communities acknowledge the value in assessing environmental factors at collection sites for predicting the value of accessions in breeding, however very little is published on this (GCDT internal reports).

Strategies for increasing coordination and information sharing among gene banks, pre-breeding and breeding programs have been initiated. CWR will become exponentially more usable as coordination and information sharing improves. Online databases and portals such as the Plant Genetic Diversity Gateway (http://pgrdiversity.bioversityinternational.org/) and the Diversity Seek initiative (http://www.divseek.org/) are being developed. These resources will increase access to CWR accessions, pre-breeding materials in development, associated characterization and evaluation data and genomics resources among crop scientists along the breeding chain.

Funding constraints underpin the majority of the challenges discussed in this section. Identifying, isolating and transferring traits of interest from wild species into cultivated crop backgrounds, and then evaluating this material, is a time consuming endeavour and requires longterm funding commitments. Funding is identified as a limiting factor to increasing the use of CWR across all crop communities surveyed. Breeding programs with relatively well-secured sources of funding have enabled crop scientists to take advantage of some of advancements made to a greater extent, in particular genomics resources and tools for predictive trait mining. Strategies for increasing use are unique to each community depending on information and resources available. This likewise accounts for much of the disparity in use among crops, documented in the following section.

5.2 A positive trend in the use of CWR

The steady increase in the use of CWR reported by Hajjar and Hodgkin (2007) has continued until today. Pre-breeders and gene bank managers report a range of advancements, including new varieties released and new sources of traits identified. A strong positive trend is described explicitly by experts in barley, chickpea, lentil, rice, soybean, tomato, wheat and yam breeding communities. Experts highlight ongoing explorations, advancements and great potential for all other crops with the exceptions of cowpea and common bean.

Figure 2 presents the state of use across three time intervals: until the mid 1980s, from 1986 to 2007, and from 2007 until the present, plus projected use post 2014. *Extensive use* describes the successful development and release of many new cultivars with genetic contributions from wild species; *considerable use* denotes that few varieties have been released; *moderate use* describes crop communities which have yet to release varieties with wild germplasm but that have made significant gains in terms of identifying sources of new traits, successfully transferring traits to cultivated crop backgrounds and overcoming crossing barriers; and *modest use* denotes that very little exploration into wild gene pools has taken place.

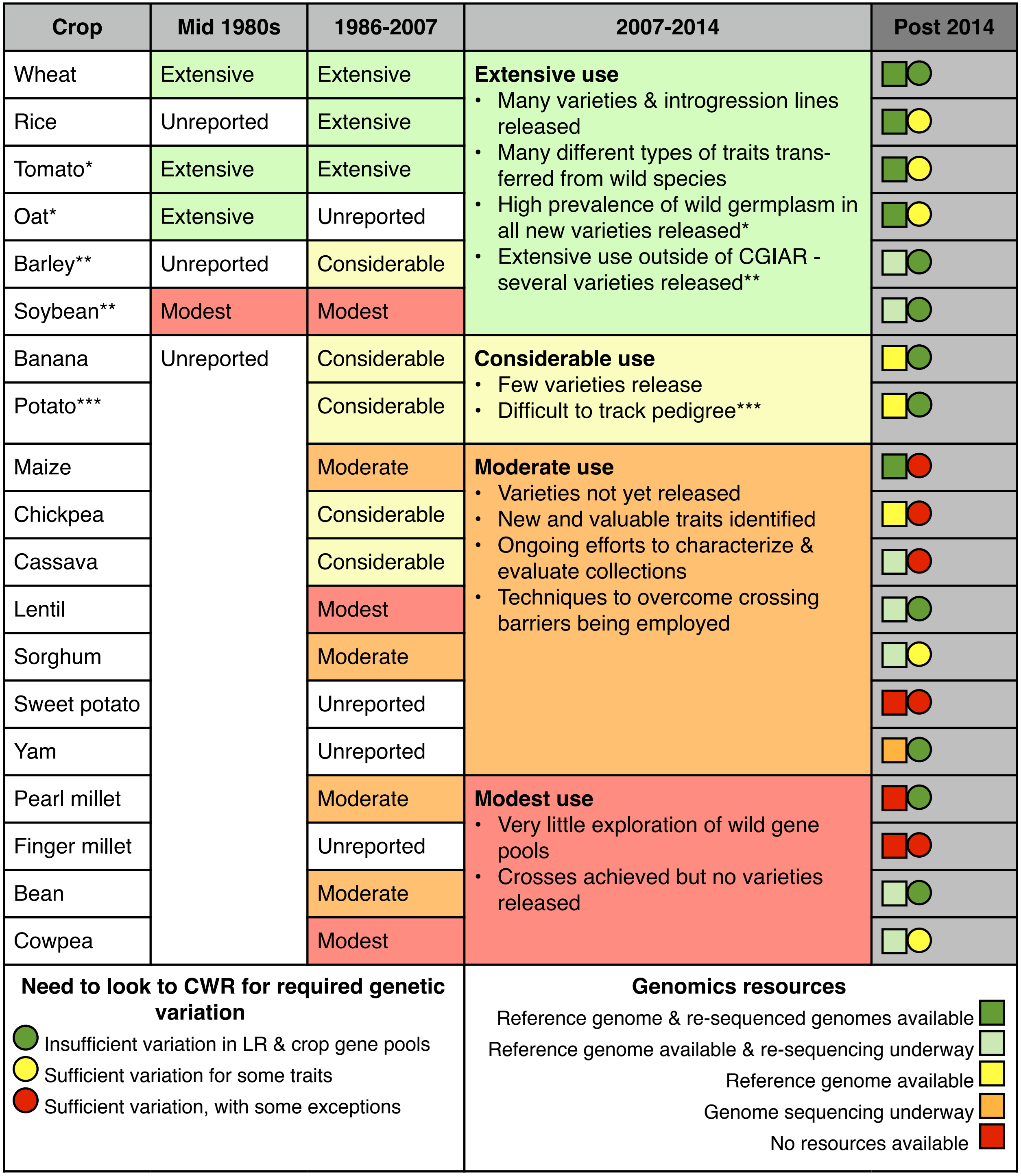
The use of CWR remains highly crop-dependent. Crops with long histories of breeding with CWR continue to benefit the most from wild progenitors, having well established breeding programs with relatively secured sources of funding. Rice, tomato and wheat in particular have well-established pre-breeding programs that focus specifically on CWR and more advanced tools at the disposal of pre-breeders for identifying traits of interest and making crosses. Looking at rice for one example, new breeding lines have been developed and a number of wild species' genomes have been re-sequenced to understand the function of genes and how genes control for various types of resistances and tolerances to different stress conditions since 2007 (Jena, Interview).

At the other end of the spectrum cowpea, cassava, lentil, sorghum, sweet potato, yam, pearl and finger millets are in the earlier states of using CWR. These are commonly referred to as 'orphaned' or 'neglected' status crops which have yet to benefit from large-scale investment in pre-breeding programs. Substantial progress has been made within the majority of these crops since last reported, including the identification of new sources of resistances/tolerances and collection of characterization and evaluation information through screening of wild germplasm for traits of interest.

Advanced tools and methods for facilitating interspecific crosses are now being employed outside of the crop communities which have traditionally benefited the most from CWR. For example, while lentil breeders at ICARDA have historically made very limited use of wild germplasm, genes for many traits have been successfully transferred into cultivated crop backgrounds facilitated through embryo rescue (Agrawal, Interview). This work suggests that CWR will make significant contributions in the coming years. In fact, optimism is pervasive across the crop communities surveyed that advancements will, and in many cases already have, facilitate increased use of CWR.

Contrary to expert opinions that there is an overall positive trend in use, Figure 2 depicts a mixed story with some advancement and some regression. Two more crops have benefited from *extensive use* (barley and soybean); two fewer have benefited from *considerable use* (chickpea and cassava); and there is a net loss of one crop benefiting from at least *moderate use*. Just as reviewers before had found, progress measured in terms of tangible breeding outputs paints a more modest picture of the current use of wild species than is described by pre-breeders, gene bank managers and conservationists.

Figure 2 - CWR use by crop



Crop	Mid 1980s	1986-2007	2007-2014	Post 2014
Wheat	Extensive	Extensive	**Extensive use** - Many varieties & introgression lines released - Many different types of traits transferred from wild species - High prevalence of wild germplasm in all new varieties released* - Extensive use outside of CGIAR - several varieties released**	🟩🟢
Rice	Unreported	Extensive		🟩🟡
Tomato*	Extensive	Extensive		🟩🟡
Oat*	Extensive	Unreported		🟩🟡
Barley**	Unreported	Considerable		◻🟢
Soybean**	Modest	Modest		◻🟢
Banana	Unreported	Considerable	**Considerable use** - Few varieties release - Difficult to track pedigree***	🟨🟢
Potato***		Considerable		🟨🟢
Maize		Moderate	**Moderate use** - Varieties not yet released - New and valuable traits identified - Ongoing efforts to characterize & evaluate collections - Techniques to overcome crossing barriers being employed	🟩🔴
Chickpea		Considerable		🟨🔴
Cassava		Considerable		◻🔴
Lentil		Modest		◻🟢
Sorghum		Moderate		◻🟡
Sweet potato		Unreported		🟥🔴
Yam		Unreported		🟧🟢
Pearl millet		Moderate	**Modest use** - Very little exploration of wild gene pools - Crosses achieved but no varieties released	🟥🟢
Finger millet		Unreported		🟥🔴
Bean		Moderate		◻🟢
Cowpea		Modest		◻🟡

Need to look to CWR for required genetic variation

🟢 Insufficient variation in LR & crop gene pools

🟡 Sufficient variation for some traits

🔴 Sufficient variation, with some exceptions

Genomics resources

Reference genome & re-sequenced genomes available 🟩

Reference genome available & re-sequencing underway ◻

Reference genome available 🟨

Genome sequencing underway 🟧

No resources available 🟥

The cases of chickpea and cassava seem to represent regressions in use since 2007. But significant work has been initiated since 2008 to develop varieties from wild chickpea accessions selected for cold and drought tolerance and Fusarium wilt, Asocyta blight and other biotic resistances (Hamwieh; Amri, Interviews). In the case of cassava, passed reports of CWR being used to lend pest and disease resistances have been called into question. At the same time new sources for traits have been identified since 2007, including a number of quality traits (post-harvest deterioration, high protein content and amylose-free starch), many different pest and disease resistances, and drought tolerance by deepening root systems (Hershey, Interview).

On the other hand, advances in soybean since 2007 are overstated by Figure 2. While there has been no use of wild species within the IITA soybean program (Agrama, Interview), the US has long since made extensive use of CWR for improving soybean (Jackson, Interview). Most, if not all, of disease resistance in the last 30 to 50 years have been achieved through accessing CWR collections, and as a byproduct yields have been protected. While Jackson suggests that there has in fact been an increased interest in using CWR within the past five years, the history of use precedes that of the last decade (Jackson, Interview).

5.3 The role of CWR in adapting agriculture to climate change

Hajjar and Hodgkin (2007) grouped beneficial traits into five categories: pest and disease resistance, abiotic stress tolerance, yield increase, improved quality and male sterility or fertility restoration. Figure 3 uses these categories to illustrate the types of traits transferred from wild species to released crop varieties across the same three time intervals, in addition to ongoing work depicted in the last column, *Post 2014.*

Today, biotic resistances continue to be the most common type of trait borrowed from CWR (column 2007-2014, Fig 3). This makes sense given that resistances to pests and diseases are generally easier to identify and transfer as they tend to be less complex than abiotic stress tolerances and are expressed directly in the wild species themselves, facilitating screening. The presence of resistance genes from CWR is prevalent across all new tomato introversion lines distributed to national partners and new oat varieties released since 2007 (Hanson; Diederichsen, Interviews). Progress been made to identify new sources of resistance and create more durable resistances. For example in the case of wheat, the Saintsbury Laboratory in the UK is currently working on stacking multiple genes for rust resistance into a 'cassette,' making the resistance more difficult to circumvent (Steffenson, Interview).

Yield improvements have been achieved in potato, rice and wheat, although tracing contributions of CWR in potato varieties released is a recurrent challenge (Bonierbale, Interview). Wheat is the only crop to have had varieties released with enhanced quality traits. Two varieties of bread wheat have been released since 2007 with enhanced micronutrient content - iron and zinc - derived from wild species, as part of the Harvest Plus biofortification initiative (Braun, Interview).

Figure 3 - Types of traits borrowed from CWR in varieties released

	Mid 1980s	1986-2007	2007-2014	Post 2014
Banana	unreported	🟩	🟩	🟩🟦
barley		🟦	🟦	🟩🟦🟧⬛
bean		🟩🟦⬛		
cassava		🟩🟧		🟩🟦🟧
chickpea		🟦		🟩🟦
cowpea				🟩
finger millet		unreported		🟩
lentil				🟩🟦🟧
maize				🟩
oat	🟩	unreported	🟩	🟩🟧
pearl millet	unreported	🟩⬜		🟩⬜
potato	🟩	🟩	🟩⬛	🟩🟦🟧⬛
rice	🟩	🟩🟦⬜⬛	🟩⬛	🟩🟦🟧⬛
sorghum	unreported			🟩
soybean			🟩	🟩🟦
sweet potato	unreported	unreported		🟩🟦
tomato	🟩🟧	🟩🟦🟧	🟩	🟩🟦🟧
wheat	🟩⬛	🟩🟧⬛	🟩🟦🟧⬛	🟩🟦🟧⬛⬜
yam	unreported	unreported		🟩🟦🟧

🟩**Biotic** 🟦**Abiotic** 🟧**Quality** ⬜**CMS** ⬛**Yield**

Experts report a greater emphasis on developing crops adapted to climate change scenarios. Extensive efforts are ongoing to identify and transfer resistances to abiotic stresses such as drought, heat and soil salinity within barley, cassava, chickpea, lentil, potato, rice, soybean, sweet potato, tomato, wheat and yam pre-breeding programs. Progress has been achieved in understanding the genetic base of polygenic traits and mechanisms which control complex environmental stress tolerances. This is consistent with the literature from the conservation community: CWR not only have the *potential* to contribute to food security in the context of climate change, but it is *imperative* that they play a feature role in adaptation and mitigation efforts (see for examples, Heywood et al. 2007; Ford-Lloyd et al 2011; McCouch 2013; Dempewolf et al 2014). According to Breithaupt (2008), CWR are better placed than even landrace varieties to lend ‘climate ready’ traits to domesticated crops, being adapted to more marginal environments themselves.

However looking only at progress achieved between 2007 and 2014 this trend does not stand out. Only barley and wheat varieties have been released with improved abiotic stress tolerances since 2007. The genetic base of complex traits associated with abiotic stress tolerances are not yet well understood (as was discussed in Chapter III). Breeders have historically been able to make use of wild species for single-gene traits, most commonly pest and disease resistances, where a particular trait of interest is regulated by a single gene. More complex traits, such as drought or saline soil tolerance, are regulated by multiple genes which together create mechanisms for tolerance. These mechanisms must first be understood before species can be screened for individual traits of interest. Mechanisms for stress tolerance may in some cases include undesirable traits, negatively affect crop performance and negating gains from increased tolerance (Bonierbale, Interview).

Column *Post 2014* in Figure 3 depicts the extensive ongoing work to transfer abiotic stress tolerances from CWR and pre-breeding materials at various stages of development. Each square represents an interesting story told by pre-breeders not yet captured by those reporting on the use and potential use values of CWR. CWR of banana, barley, cassava, chickpea, lentil, potato, rice, soybean, sweet potato, tomato wheat and yam are being explored as sources of improved tolerances. Using rice again as an example, genes associated with saline soil tolerance has been successfully transferred from a wild halophyte species to cultivated rice. Varieties will be developed and released in the coming years (Jena, Interview).

It is also striking that biotic traits are being borrowed to the benefit of every crop surveyed, with the sole exception of bean. Biotic and abiotic stresses are intimately linked. Crops face changing and intensifying pressures from insects and pathogens as environmental conditions change (Maxted, Interview), thus biotic resistances will continue to be a top priority for breeding programs under climate change.

5.4 Predicting future use

There are many factors which together determine the extent of CWR use. These include, among others, the availability of funding, characterization and evaluation data, and human capacity; the persistence of crossing barriers; and the availability of sufficient genetic variation within crop gene pools. Two indicators are used to predict future outputs based on these factors: genomes resources currently available and the relative size of cultivated crops' gene pools. The genomics resources available today is a proxy for investment and technological advance facilitating use of CWR. The genetic base of crops represents the *need,* as identified by experts, to look outside of landrace and cultivated gene pools for traits required to adapt to changing environmental conditions. It is predicted that today's technological advancement coupled with more extreme environmental pressures will incite greater use of CWR in the coming years.

The rapidly developing field of genomics promises to help researchers identify useful regions of re-sequenced wild genomes with much more precision, reduce linkage drag and the time required of transferring genes into cultivated crop backgrounds (Baute et al, forthcoming). The availability of genomic resources are summarized in column *Post 2014,* Fig 2. Whole genome sequences have been released for all crops except sweet potato, yam, finger and pearl millets. Efforts to re-sequence CWR for the remainder of crops have been at least initiated, with the exceptions of potato, banana and chickpea. Green squares denote the most advanced crop communities with extensive genomic resources and red squares denote crops which have not yet benefited from genomics.

As with previous advancements, it will take time for these resources to yield tangible breeding outputs for most crops. While this technology hosts immense potential for the future, it does not account for the extent of increased use of CWR over the past decade. Genomic resources on their own are insufficient for predicting the breeding value of species, and utility is predicated on the availability of extensive phenotypic data for gene bank collections. High throughput genotyping approaches, namely genotyping-by-sequencing, will then be used to link re-sequenced genomes with phenotypes of interest to breeders (Baute et al, forthcoming). The insufficiency of characterization and evaluation data for CWR accessions has prompted experts from some crop communities to question the immediate benefit of genomic resources (GCDT internal reports).

Strategies for mapping allelic variation using genomic data will facilitate predictive trait mining of core collections based on where accessions are collected from (Mackay and Street 2004; Khazaei et al 2013). Current progress being made in predictive trait mining will likely result in increased breeding outputs in the future, although numbers of varieties released do not yet reflect this work. Increased coordination and information sharing among gene banks, pre-breeding and breeding programs will also increase the impact of genomic resources available.

The second indicator for predicting future use is the need to search for greater genetic variation in more distant gene pools. As a reminder from the introduction of this thesis, the domestication bottleneck process describes how species lose genetic diversity through recurrent selection (Tanksley and McCouch 1997). The result for many crops has been a narrowing of the genetic base, necessitating exploration into the wild.

The red circles in column *Post 2014* of Figure 2 identify crops with wide enough genetic bases. Sufficient variation for most traits has been found in crop gene pools for maize, chickpea, cassava, sweet potato and finger millet without going to distantly related species, where crossing barriers and linkage drag are concerns. Yellow circles identify crops with sufficient variation for some traits of interest. Green circles identify crops with more narrow genetic bases, where breeders have been increasingly incited to look to wild species as sources for novel traits and more extreme tolerances. There is an imperative for breeders to access wild gene pools in order to reverse domestication bottlenecks in wheat, barley, soybean, banana, potato, lentil, yam, pearl millet and common bean.

It is important to note that the value of CWR for crops that have retained wide genetic bases is still widely recognised. Primarily, exploring wild gene pools contributes to a better understanding of the history of cultivated crops - valuable for understanding the co-development of hosts and pathogens and finding sources of resistances. Secondly, the potential use value of genetic diversity is immense given the difficulty in predicting future climate chance scenarios and which traits will be needed. Furthermore, the greater adaptive capacity of wild species will likely be required as climate pressures become more extreme. Referencing cassava as an example, many cultivated varieties currently exist in dry climates and breeders have not yet been compelled to seek out sources of more extreme drought tolerance from the wild. However greater variability for drought tolerance will likely be found within wild gene pools and breeders may need to explore this diversity in the coming years (Hersey, Interview). Experts across crop communities emphasize the potential use value of CWR regardless of the genetic base of cultivated crops.

If these two indicators have predictive value, there will continue to be extensive use of CWR in wheat improvement programs and modest use in finger millet. These two examples fit with expert opinions on trends (Braun; Ojulong, Interviews). In the case of maize, the availability of genomics resources will not necessarily incite greater use of CWR, as sufficient genetic variability for most traits has been found within the crop's wide genetic base. This fits with the story told by maize experts (Hearne; Banziger, Interviews). The value of these indicators is perhaps best exemplified by the cases of lentil, sorghum and yam. Wild species of these three crops have tremendous potential for contributing to varieties in the future and a significant amount of work is being done to make use of wild species that is not otherwise reflected in quantitative progress made since 2007.

On the other hand, very little advancement is predicted in sweet potato, while Craig Yencho, applied sweet potato breeder at NSCU, emphasizes their potential. Wild species represent a "potentially very fertile territory that, as we are beginning to develop new tools and methodologies, we need to look to as a source of new traits and a source of understanding of cultivated germplasm" (Yencho, Interview). In the case of bean, the high potential highlighted in Figure 1 is not currently reflected in crop improvement efforts (Raatz, Interview).

5.5 Chapter summary

This chapter has provided evidence of an increase in use of CWR since last reported by Hajjar and Hodgkin in 2007, as well as a growing emphasis on accessing wild genetic diversity for traits related to environmental adaptation and climate change mitigation. It is predicted that the use of CWR in breeding with continue to increase as a lack of genetic diversity within primary crop gene pools pushes pre-breeders to explore more distant gene pools for sources of novel genetic material, while genomics tools and resources facilitate their work with increasing efficiency.

The key take-away from this chapter is that although some increase in use has been observed since 2007 in terms of new varieties released, the majority of ongoing work and potential / future use is not reflected in these numbers. Estimations of the current use report here are imperfect while predictions of future use, based on only two indicators, may have limited predictive value, especially in the context of multiple uncertainties. Given the constraints to accessing the benefits of CWR stored in gene banks, the unknown impacts of climate change and the difficulty translating advancements in genomics into practical breeding applications, it remains unclear *exactly* how rapidly the use of CWR will advance in the coming decade. What is clear, however, is that optimism is pervasive across the crop communities surveyed that use has, and will continue to, increase.

The findings presented in this chapter are relevant to the conservation biology community, which emphasizes the role of CWR in adapting agriculture to climate change in the literature in absence of an up-to-date, comprehensive review of recent advancements and ongoing work within crop improvement programs of the CGIAR.

The *implications* of these research findings is the theme of the following chapter. It presents findings from interviews with the CWR conservation community and looks critically at the type of conservation investment that has been sparked by increased use.

Chapter VI - Implications for conservation

This chapter presents findings relevant to the second research question: what are the implications of increasing use of CWR? It discusses emerging trends in CWR conservation, both in terms of the actors involved and what their responses look like. A dominant conservation paradigm has emerged and how it is manifesting in practice will have implications in terms of the future productive capacity for the global food system.

6.1 Trends in CWR conservation

6.1.1 Increased interest from the international donor community

The profile of CWR has been raised in recent years. The many recent policy documents identified in the literature review which articulate the importance of CWR conservation are evidence of this. This is in direct acknowledgement of the value of CWR, which will have positive outcomes for conservation. Communicating the value of CWR provides incentive for a variety of stakeholders to undertake conservation measures (Dulloo, Interview). “It’s all fitting together, as one might expect” (Maxted, Interview).

CWR have a rather unique appeal to the international donor community. They have been described as the ‘nexus’ between food security, climate change adaptation and biodiversity conservation issues (Khoury, Interview). They represent an opportunity for donors to allocate resources in a way which contributes to each of these ends at once. Interestingly, the unique appeal has allowed CWR to garner more support in recent years vis-a-vis landrace varieties which are categorically easier to use in breeding programs (Maxted, Interview). This last point deserves reflection and is discussed in Chapter VII (section 7.2).

The Government of Norway’s US$ 50 million *Adapting Agriculture to Climate Change* project, specifically geared towards increasing the use of CWR through *ex situ* conservation, represents their climate change adaptation and global development contributions for the next several of years (Khoury, Interview). The Global Crop Diversity Trust (the Trust), in collaboration with the Kew Millennium Seed Bank (Kew), is the administering arm for the Norwegian Government’s investment.

Major players in CWR conservation include those which have traditionally been oriented towards agrobiodiversity conservation, but that have now made their involvement in CWR far more explicit. The Trust is the endowment fund for the CGIAR gene banks with the mandate of securing all plant genetic resources for food and agriculture stored within, in perpetuity. While the endowment fund has always funded some CWR conservation, wild accessions have traditionally been underrepresented in gene bank collections. The *Adapting Agriculture to Climate Change* project, representing the largest investment in CWR conservation to date, will allow for their representation to be increased substantially (Dempewolf, Interview).

Kew has a 20 year history of helping international partners collect endangered and threatened plants. Now they are putting an explicit focus on CWR for the first time and facilitating their collection in 20 countries. As Kew project leader Ruth Eastwood articulates, “we’re trying to raise awareness of CWR among [international partners] so that where possible, they might develop a longterm programs specifically targeting wild species” (Eastwood, Interview). A new training course has been developed for strengthening national capacities to collect, store and do genetic sampling of CWR accessions. Kew is also prioritizing the processing of CWR for gene bank storage to ensure that prebreeders have access to this material within the timescale of the project (Eastwood, Interview).

Bioversity International likewise has a long history with agrobiodiversity conservation. They are now working to develop an incentive mechanism for CWR conservation with member states of the South African Development Community (SADC), funded by the EU-ACP Programme (African, Caribbean and Pacific Group of States). The project was initiated in January, 2014 with representatives from national governments, conservation authorities and agriculture departments and forestry departments in South Africa, Zambia the the Indian Islands. The goal is to develop a strategic action plan for the *in situ* conservation of CWR, involving an incentive mechanism to engage local communities (Dulloo, Interview).

Other organizations which have not traditionally been interested in agrobiodiversity are beginning to support CWR conservation. Conservation International (CI) is a new implementing agency for GEF-UNEP project funding, the funding source credited for facilitating the establishment of some of the few existing CWR gene reserves in the world (Chapter III). CI is borrowing the IUCN Red List assessment approach to map distributions of CWR in Peru. The IUCN criteria, which has become the international standard for biodiversity assessment (Hole, Interview), has not been applied to CWR up until this point. They have also identified the potential for CWR included as natural capital in countries’ national accounting frameworks through the World Bank’s Wealth Accounting and the Valuation of Ecosystem Services (WAVES) partnership (Hole, Interview). This marks the first discussion of having CWR be included as part of countries’ national wealth, building from the conceptual work done by the TEEB in relation to incorporating biodiversity in broader terms into both countries’ and companies’ accounting frameworks (Chapter II).

An acknowledgement of the value of CWR has been made this year by the Governing Body to the ITPGRFA for the first time. Three CWR-specific projects have been invited to develop full project proposals following the Third Call for Proposals in May, 2014. Project funding is supplied from the International Benefit-Sharing Fund: the fund which collects contributions from private companies when they make proprietary claims to new commercialized varieties developed using plant genetic resources from the Multilateral System (MLS). The International Benefit-Sharing Fund to date has only received voluntary payments from national governments and is not yet functioning as it was designed to. However it is projected that this funding mechanism has significant potential to collect contributions from the private sector in the future (Moeller and Stannard 2013). The mechanism is currently being revised by the 'Working Group to Enhance the Functioning of the Multilateral System,' headed by Michael Halewood of Bioversity International. It is foreseeable that CWR conservation may be a future priority funding category. Table 5 displays the first three projects to be acknowledged as appropriate benefactors of the International Benefit-Sharing Fund.

Table 5: CWR-specific projects: Potential benefactors of the International Benefit-Sharing Fund

Applicant organization(s)	**Target countries**	**Project title**
National Agricultural Research Organisation (Uganda)	Uganda, Burundi, Tanzania, Rwanda	Genomic and phenotypic exploration of cultivated and wild rice germplasm for resistance to biotic and a biotic factors in East Africa
NCARE (Jordan)	Jordan, Tunisia, Turkey	Conservation and Sustainable Utilization of Food and Feed Legumes Seeds for Adaptation to Climate Change in NENA Region.
University of Harran University of Dicle University of Saskatchwan Agriculture and Agri-Food Canada	Turkey	Assessing and utilizing resistance to Orobanche in wild lentil species and intespecific hybrids to stabilize lentil production in Turkey

Source: ftp://ftp.fao.org/ag/agp/planttreaty/funding/call2014/cfp_3_2014_pp_shortlisted_1.pdf

It is important to qualify that this signal from the international community has yet to materialize into increased funding for pre-breeding programs across the board (Bonierbale, Interview). Funding to date represents a relatively small amount of resources when spread across all crops and all CGIAR centres (de Haan, Interview). Especially given that the majority of work with CWR has yet to result in tangible breeding outputs (Chapter V), the international community still underestimates the extent to which CWR are currently being used. More excitement is likely to ensue as more varieties are released, and given time, more conservation investment will materialize.

6.1.2 Increased interest from the private sector

Breeding with CWR has traditionally been done exclusively within the public sector, and depending on both the crop and private company in question, the private breeding sector on the whole still steers clear of CWR (Dempewolf, Interview). Private breeders work with their own fine-tuned breeding material in the interests of maintaining the progeny of elite cultivars, and then access public pre-breeding materials when they need to expand their diversity set (Dempewolf; Eastwood, Interviews). Public breeding programs that used to do variety development have even been pushed towards pre-breeding as governments anticipate variety development being done by the private sector in the future. This dynamic will be perpetuated in the context of increasing public-private partnerships in agriculture (Dempewolf, Interview).

On the other hand there is some evidence to suggest that private companies are becoming engaged in using CWR directly. The shift in the last decade from public to private sector crop breeding is evidence of the diminishing role of the public sector and perhaps the growing impetus that the private sector take on (traditionally public) pre-breeding efforts (Dulloo, Interview). Private sector participants at a major stakeholder meeting for the EU-funded project, *PGR Secure,* in Wageningen in 2013, and the first meeting of a European partnership geared towards increasing the use of *ex situ* collections in Rome in 2014, expressed their interest in using CWR. “What they were saying was music to my ears. They are running out of options” (Dulloo, Interview). There is likely to be a lot more use of CWR in breeding companies’ pipelines than is reflected in the literature because private sector research tends to be more commercially sensitive and is reported on to a lesser degree than public sector work (Eastwood, Dulloo, Interviews; Maxted and Kell 2009).

It is difficult to ascertain the extent of private interest in using CWR. But what is clear is that companies are beginning to acknowledge their value (N. Maxted, Interview), and acknowledge that they depend on CWR indirectly (Dempewolf; Eastwood; Dulloo, Interviews). In the case of soybean in the US, for example, private companies have invested in public sector pre-breeding and university research with wild species as a longterm strategy (Jackson, Interview). Significant funding contributions have yet to be made although some negotiations have been initiated (Maxted, Interview). How much of a role the private sector will play in CWR conservation remains to be seen. This does however represent a potentially lucrative source of future conservation funding.

6.1.3 Gene banking for the future: The dominant conservation strategy

A closer look at the conservation investment so far reveals a bias towards supporting *ex situ* conservation. This is consistent with past investment reported in the literature (Chapter III; see Hunter and Heywood 2011 for comprehensive review). While the importance of an integrated approach to conservation, or integrated gene management (Swaminathan 2011), is widely recognised in the literature, *in situ* conservation has yet to be practiced beyond relatively few isolated examples of gene reserves being established over the past decade (Chapter III). This study lacks the empirical evidence required to assert that less international donor funding is being channelled towards *in situ* conservation. It instead suggests that initiatives are disparate and have had relatively modest outputs compared with efforts to increase the representation of CWR in gene bank collections.

In the FAO report,*Towards the Establishment of a Global Network for in situ CWR Conservation,* Maxted and Kell (2009) outline the steps required to coordinate the mapping and prioritization of CWR populations *in situ*, for the ends of establishing gene reserves. The EU-funded *Plant Genetic Resource Secure* (PGR Secure) took up the torch facilitating the development of national CWR conservation strategies, coordinated by Bioversity International. National level partners undertook baseline surveys / inventories of genetic resources present within borders and gap analyses for existing gene bank collections, and set priorities for future collection based on results. These are the first steps towards the establishment of the proposed global network. However this work has been slow to get off the ground and tangible results may be years away. During the the project's culminating event, the PGR Secure Forum, national partners presented results from baseline surveys conducted throughout Europe. However a much greater focus was placed on enhancing the use of CWR through pre-breeding, improved gene bank management and bioinformatics.

Bioversity International is an exception to this trend. Bioversity's project to develop an incentive mechanism for CWR conservation is being modelled after their payment for agrobiodiversity conservation services (PACS) schemes piloted in Peru, Equator and Bolivia (see Narloch et al 2011). Adam Drucker, senior economist at Bioversity International, believes that a payment scheme is amenable to CWR. Reward payments may be made to communities for active monitoring of CWR populations or compensatory payments for refraining from developing new tracks of land for agriculture purposes or otherwise. Drucker suggests that school programs be involved in monitoring, reminiscent of Swaminathan's recommendations to spread 'bioliteracy' among communities. There may be little opportunity cost associated with marginal lands surrounding fields. In these cases increasing monitoring capacity may be sufficient for ensuring species' conservation. The incentive mechanism has yet to be developed (Drucker, Interview).

There remains a lack of mechanisms in place to coordinate and support *in situ* conservation in areas where species are most concentrated, i.e in CWR hotspots or Vavilov centres of origin, and most threatened, as identified by Maxted and Kell (2009). The dominant strategy has instead been to conserve species in gene banks in order to facilitate breeders' access - a strategy rooted in optimism that technological advancements will continue to facilitate the increased use of CWR.

Collecting CWR populations that are unrepresented in existing gene bank collections is the most commonly proposed conservation strategy among breeders and gene bank managers interviewed. This is unsurprising given their vantage point from within the network of crop improvement programs. To be sure there are exceptions to this. For example, wild yam accessions at IITA have been kept *in situ* in a 400 hectare forest for more than ten years. Breeders recognize the value in integrated conservation particularly for the interspecific hybrids that are created under natural conditions (Lopez-Montes, Interview). Others explicitly emphasize the value in establishing 'gene reserves' for CWR *in situ* (for example, Jena, Interview). However for the most part, protecting species outside of their natural habitats is the favoured solution. The Adapting Agriculture to Climate Change project is focused on increasing the *usability* of wild germplasm by collecting wild species not yet represented in gene bank collections and increasing the capacity of breeders to make use of them using advanced techniques.

Underlying this focus on collection and preservation outside of habitats is a sense of urgency associated with rapid genetic erosion. Brian Steffenson, barley and wheat breeder at the University of Minnesota, highlights how species of wild goatgrass with resistances to a variety of strains of rust affecting wheat are only found in a particular plane in Israel that is being developed due to urban expansion (Steffenson, Interview). Other experts from the wheat community reference their own experiences on collection missions, noting the decline of populations in the field cause by environmental degradation, human population expansion and urbanization (Internal report, GCDT 2013). Experts in sorghum, barley, cassava, millets and potato also reference continued threats of genetic erosion despite increased attention from the international community (Hassan; Steffenson; Hershey; Deshpande; de Haan, Interviews). Collection for *ex situ* storage is the only option for many species in the context of climate change, urban development and absence of protected areas.

The imperative to preserve *ex situ* is also propelled by concerns regarding future access in politically sensitive areas. Interviewees cite increasingly restrictive access to germplasm as a threat to their conservation and justification for collecting while they still can (Hanson; Jackson; de Haan; Steffenson; Diederichsen, Interviews). There are uncertainties regarding how the Nagoya Protocol will be implemented by national governments once it becomes ratified, particularly in Peru and Bolivia (Hole, Interview). Questions are also raised regarding collection in areas of civil unrest such as Syria and Israel where genetic diversity is concentrated for a number of crops (Steffenson, Interview). In the case of soybean, CWR are concentrated in China where access is completely restricted. Extensive ongoing breeding efforts with wild soybean in the US exclusively use germplasm collected before 1950 (Jackson, Interview). Likewise, the Canadian national gene bank hosts the largest collection of oat CWR in the world, while collection from its centre of origin in Iraq and Iran is not currently possible (Diederichsen, Interview). Public sector breeders in other crop communities prioritize collection in anticipation of this type of enclosure.

6.2 Implications of the dominant conservation strategy

The outcome of a focus on *ex situ* conservation is the protection of a very narrow subset of diversity, without the capacity to adapt to changing environmental conditions. This has implications in terms of the resilience of the global food system.

6.2.1 A small sub-set of diversity is conserved

In the absence of infinite conservation funding, species which are most likely to be of value for crop improvement are prioritized (Maxted, Interview). The most common criteria for prioritizing CWR are: (a) relative socio-economical importance of the related crop, (b) potential use for crop improvement (i.e., ease of crossability with the related crop or previously reported known use or potential use in crop improvement programs), and (c) threatened status (taken directly from Vincent et al 2013). Criteria (b) can be understood as a combination of (i) relatedness of species to socio-economic crop (estimated using the crop gene pool concept developed by Harlan and de Wet in 1971), and (ii) history of prior use in crop improvement programs. These criteria may be used in combination or independently to prioritize species' conservation (Maxted and Kell 2009; Magos Brehm et al 2010; Kell et al 2012).

The Harlan and de Wet global inventory of important CWR taxa (database is available at http://www.cwrdiversity.org/checklist/) criteria (a) and (b) are "deemed to be the most important, as they are directly related to the *raison d'etre* for defining CWR (i.e., their use for crop improvement)" (Vincent et al 2013: 267). CWR are to be scored for these criteria by collecting publications on CWR use and experiments relating to crossability (Maxted et al 2006; Vincent et al 2013).

The limitations of these criteria are evident. First, available literature is an imperfect proxy for use (Chapter III). Second, very few species have made tangible contributions to new varieties developed in crop improvement programs relative to the breadth of diversity that has yet to be explored (Chapter V). Third, biological barriers to crossing with species from more distant gene pools are being overcome systematically (Chapter III; see Ford-Lloyd et al 2011 for comprehensive review). The majority of species would thereby not meet these criteria while their potential use values may be enormous. Although a practical approach to conservation planning, this narrowing-in on specific species based on past success must be viewed as an incomplete strategy for CWR conservation.

The identification of 'useful species' is predicated on the availability of data for species, including passport, characterization and evaluation data, complete understandings of intra-specific diversity within populations and the basic biology of the useful species (i.e. ploidy levels, flowering times, crossability) and species' threatened status in relation to critical thresholds. Section 5.1.1 (Chapter V) highlights how missing passport, characterization and evaluation data for species limits the usefulness of gene bank collections. Unresolved taxonomic issues relating to ploidy levels and crossability further hinder breeders' capacities to make use of collections (GCDT unpublished reports). Incomplete understandings of intra-specific diversity within species populations limits the extent to which this diversity can be protected. Current collections of banana CWR are under-representative of the diversity within wild banana populations not only lack resources but are missing information. Even the leading experts in wild banana populations lack understandings of diversity that exists in the wild (Swennen, Interview). This story is echoed by experts from potato and sweet potato communities (Yencho; de Haan, Interviews). Without sound understandings of the breadth of diversity that exists, it is impossible to make assertions regarding the diversity which is most threatened, or approaching critical thresholds. Missing data within each of these categories underscores that *in situ* is the most appropriate fail-safe strategy for the conservation of species with yet unidentified potential use value.

Some entire crop families are excluded from prioritization all-together. The Trust works exclusively with the crops and crop families listed in Annex 1 of the ITPGRFA (FAO 2001), as per requirements set by the Norwegian government. Most notably soybean, maize and the wild relatives of cassava are explicitly excluded from this list. This list is a serious impediment to the conservation and use of cassava CWR in particular (Hershey, Interview). Hershey suggests that most funding agencies look to the Trust for guidelines on setting priorities, thus almost no work has been done to collect the 100 known species of wild cassava that under threat. While select species are protected within the prevailing conservation paradigm, the breadth of genetic diversity is susceptible to a similar fate as wild cassava.

6.2.2 A less resilient global food system

The fundamental logic behind *ex situ* conservation is that it facilitates use. “Funding gene banks gives [CWR] a chance to be used. In the wild and protected areas the theory is that they will continue to evolve and then we can collect and use them, but that is another step. It’s banking for the future a little bit more” (Khoury, Interview). Khoury questions whether *in situ* conservation areas will be of use in another 50 years in the context of climate change. Relatively little work has been dedicated towards predicting the impacts of climate change species and mapping their future migration according to changing climatic envelopes (see section 3.2.2, Chapter III). Banking for the future, i.e. *in situ* conservation, is thereby described as a risky investment. However, following the logic of both the Stern Report and the TEEB (Chapter II), as well as literature from the conservation biology community (Chapter III), inaction is arguably much riskier.

Table 7 revisits the levels of biodiversity discussed in Chapter II. Gene banks can protect a small sub-set of species and genetic diversity, but not its full breadth nor the important functions of ecosystem and functional diversity. Evolutionary potential, complex interactions between ecosystem components, and ecosystem resilience cannot be captured. Genetic diversity conservation is best achieved by establishing gene reserves in Vavilov centres of origin, in the case of CWR. This strategy will help maintain the adaptive capacity of the global food system.

Table 7 - Levels of biodiversity (revisited)

Levels of diversity	**Physical expression**	**Amenable to ex situ conservation**	**Amenable to in situ conservation**
Genetic	Genes, nucleotides, chromosomes, individuals	✓ (small subset)	✓
Species	Kingdom, phyla, families, genera, subspecies, species, populations	✓ (small subset)	✓
Ecosystem	Bioregions, landscapes, habitats	✗	✓
Functional	Keystone process species, ecosystem resilience, ecological services	✗	✓

Source: Turner et al 1999; Nunes et al 2003.

Extracting specific species from their habitats for preservation must be valued for what it is: a contingency plan. The limitations of *ex situ* conservation and the need for more balanced conservation approaches is acknowledged by the same experts who inform CWR prioritization, recognizing the practical need to inform policy regarding trade-offs. While *ex situ* conservation has undeniable value as a back-up for existing genetic diversity, it is in no way a replacement for *in situ* conservation. The danger highlighted here is that the collection of samples to be stored in gene banks may take precedence over the establishment of gene reserves. Conservation funding that is dedicated to building up *ex situ* collections checks off the ‘CWR conservation’ box, satisfying donor’s desire to contribute to the goals embodied in the CWR ’nexus.’ But it is important that this investment does not take the place of *in situ* conservation efforts.

6.3 Chapter summary

This chapter has discussed the implications of the findings presented in Chapter V. The widespread optimism shared among crop scientists, pre-breeders and conservationists that wild species will continue to become more and more useful in the coming years has inspired investment. The Government of Norway, the Global Crop Diversity Trust, Kew Millennium Seed Bank, Conservation International, Bioversity International and the ITPGRFA (through the Benefit-Sharing Fund of the MLS) are the largest players today. Interviews highlight that private sector actors may become influential players tomorrow.

The investment that has been inspired so far has been focused on increasing the representation of CWR of socio-economically important crops in gene bank facilities. This strategy will facilitate their use in the relative short-term. A small subset of wild species selected based on their predicted economic value for crop improvement will be accessible to breeders. In the meantime most wild species, and in fact some whole crop families, are neglected completely. This narrow conceptualization of the economic value of CWR will have negative implications for the adaptive capacity of agroecosystems in the future.

If you do not change your direction, you will end up where you are headed
-Chinese proverb

Chapter VII - Analysis & Recommendations

As was discussed in the previous chapter, increased use of CWR has incited increased conservation of plant genetic resources. But has this influx brought us up to a socially-optimum level of conservation?

Given that the CBD Aichi Biodiversity Targets (http://www.cbd.int/sp/targets/) have not yet been met and that CWR continue to face threats of genetic erosion around the world, it seems that the answer is at best, *not yet*. Donors still underestimate the extent of ongoing work with CWR, and interest takes time to percolate down into concrete funding for either pre-breeding or conservation programs.

The question is then best reframed, has investment to date moved us *towards* a socially-optimum level of conservation?

This chapter suggests that the answer to this question is also no. The conceptual framework developed in Chapter II to argue that the current conservation paradigm will continue to result in the under provision of conservation, unless course corrections are made. The first section discusses how the total economic value (TEV) of CWR is not reflected in valuations and policy decisions regarding conservation priorities and trade-offs. The increased conservation investment has been sparked by growing recognition of the direct use values of wild species in crop breeding but ignores the other types of values associated with them. These include potential use, indirect use, resilience and intrinsic values.

The second section highlights that *in situ* conservation of CWR is difficult in practice. The unique qualities of CWR limit the policy options available to correct for this public goods market failure. These include the complete lack of private benefits derived by custodians from their conservation, complexities and challenges associated with the management of CWR within socio-ecological system, and the long-term time commitment required before direct benefits can be realized. Opportunities for integrated conservation and development programs, or landscape-based approaches to conservation, are limited. As a result, donors interested in the ‘nexus’ of food security, climate change adaptation and environmental sustainability and are drawn towards supporting *ex situ* conservation efforts in lieu of contributing towards the establishment of CWR gene reserves.

The third section uncovers the root of the problem: CWR are valued disproportionately for their instrumental use in crop improvement programs in the relative short-term rather than for their contributions to the sustainability of agroecosystems in the very long-term. The dominant conservation paradigm is rooted in production-centric values and a faith in technological advancement for achieving food security. Species that are identified as having more immediate direct use value are valourized while all other diversity, including the full breadth of wild genetic diversity, landrace varieties, and crops of ‘neglected’ or ‘orphaned’ status are left exposed to continued genetic erosion in the face of environmental and anthropogenic impacts.

Recommendations stem from a greater recognition of the other types of values associated with CWR, as well as the value of agrobiodiversity more broadly defined. An agroecological approach to conservation needs to be pursued in light of research findings. Opportunities for course correction are identified in the final section.

7.1 Underestimated total economic value of CWR

CWR are valued explicitly for their direct and potential use values (Maxted, Interview). Conservation has been sparked by increased recognition of these values, as CWR have become more *usable* (through advancements and breeding) and *needed* (for the greater genetic variability they represent). Increased funding to date reflects the more immediate instrumental use offered by wild genetic diversity and ignores its other functions. Potential use, resilience and intrinsic values in particular are discounted within the prevailing conservation paradigm.

Potential use values are underestimated in economic valuations. Ruth Eastwood, the Crop Wild Relative Project coordinator at Kew, discusses the CWR valuation study conducted by Pricewaterhouse Coopers LLP (2013) which was commissioned for Kew. The valuation underestimates the true value of CWR because it doesn’t incorporate climate change. “It projects current values into the future, but does not recognize that threats are going to get bigger, and the CWR contribution is going to be more important that is now” (Eastwood, Interview). Eastwood chalks this underestimation up to a lack of published data. Moreover, the wealth of ongoing work with CWR that has yet to result in tangible breeding outputs also represents a kind of potential use value that is underestimated in current valuations (Chapter V).

In terms of indirect use value, it is unclear what ecosystem services and functions CWR provide within their respective habitats. Nigel Maxted proposes that although wild species do not tend to be dominant in any particular environment, any one that *happens* to provide keystone functions within their ecosystems are the responsibility of protected area mangers to protect. “We are trying to conserve species specifically for use, we are not conserving them because they are wild species. That does not stop anyone else from conserving them for their ecosystem value” (Maxted, Interview). However, as has been noted previously, most CWR are not found within such undisturbed, climax ecosystems, but instead most commonly around farmers’ fields where they are vulnerable to human impacts (Chapter III). This point is absent from conversations surrounding CWR conservation, and is absent from the criteria for prioritizing species’ conservation.

The resilience value that CWR diversity represents is arguably its most important function and most significant contribution to the sustainability of the global food system. It has gone unrecognized in valuation efforts. And while the international community acknowledges the role of wild species in adapting agriculture to climate change, conservation efforts do not reflect the imperative that they themselves continue to evolve along with changing environmental conditions within their natural habitats. The criteria used for prioritizing species' conservation reflect the single goal of increasing direct use. While prioritization is a practical approach in the absence of infinite funds, its impact is to select a very narrow sub-set of existing diversity (Chapter VI). This strategy does not reflect the resilience value of CWR and will be insufficient for conserving the immense adaptive capacity that it hosts.

There is minimal mention of non-instrumental use values in the literature. A lack of existence value is intuitive. They are not used directly by humans and thus do not share in the values attributed to cultivars with particular cultural or spiritual traditions. This contrasts with landraces varieties which often have significant cultural and spiritual values associated with them. The exception of unique wild species with medicinal properties stands. In the absence of instrumental or existence values there is nothing to wish to *bequest* to future generations, as there would be in the case of landrace varieties of cultural significance.

Discussion of wild species' intrinsic values is almost completely absent from the literature and did not come up at all during interviews and content analysis. Intrinsic values by definition cannot be given a monetary value representing human utility or willingness to pay. As economic valuation is the primary means by which the importance of CWR conservation is communicated, the intrinsic value of this diversity gets immediately lost in translation. Conservation planning based on such economic cost-benefit analysis does not take species' inherent value into consideration.

Ecologists assert that a valuation approach should be used to complement rather than substitute for ethical or scientific reasoning relating to biodiversity conservation, based on biocentric perspectives (Turner and Daily 2008). A existing TEV approach to valuation could be improved in the context of CWR if potential use and resilience values are incorporated to a greater extent. It is important that risk analyses and precautionary approaches be applied in recognition of the unpredictably of agroecosystem dynamics and unknowns regarding critical thresholds. However in order to incorporate species' intrinsic values into the framework alternative decision support tools are required, such as multi-criteria analysis (MCA). MCA has been developed to integrate different conceptualizations of the value of biodiversity (Munda 2004; Pascual et al 2010; see section 2.2). While it is beyond the scope of this thesis to develop an alternative valuation framework, it acknowledged here that this work needs to be done in order to render the total value of CWR visible to policy makers.

The increase in private sector involvement is impossible to ignore in the context of CWR conservation. The implications of their involvement have yet to unfold. It is hypothesized here that funding will reflect instrumental use values to an even greater extent than is the case with existing national government and international donor support. Intuitively, private breeding companies will support conservation for the genetic diversity of crops of high economic value with which they work (i.e. wheat, rice and maize). Within this diversity selected species with known or predicted tolerances and resistances based on geographic indicators will be targeted. It is foreseeable that conservation priorities would be even more heavily weighted towards direct use value than is currently the case, while the lion's share of CWR diversity will remain under threat. If this is an accurate prediction, conservation will not increase to any meaningful extent outside of specific cases of treasured species. Further research and more time are required to see how this dynamic will play out.

7.2 Closing the CWR conservation gap

Correcting for the public goods market failure associated with CWR conservation, or closing the conservation gap, is particularly challenging given the unique characteristics of CWR. These include the lack of private benefits accrued by custodians from their conservation, challenges associated with their management within complex socio-ecological systems, and the long-term time commitment required in order for benefits to be realized.

There are no direct or potential use private values associated with CWR. Individuals and communities living among CWR generally do not use them directly. There of course may be exceptions to this rule in the case of species traditionally valued for their medicinal properties, for example. This is contrast to landrace varieties which are considered quasi-public goods, providing private benefits to farming communities (Wale 2011).

Both private and social benefit is derived from the resilience value provided by CWR. Everyone benefits from a global food system characterized by staple crops with wide genetic bases allowing them to adapt to stresses and fluctuations in the production system. Custodians stand to benefit indirectly from outputs from public research centres in the form of new varieties with genetic contributions from wild species. However such benefit is too distanced conceptually to incite individual action, given the long time frame required of breeding and the inaccessibility of modern breeding techniques. New varieties classified as global public goods may never directly benefit those who live where the contributing wild species were originally collected.

The conservation gap, or the difference between the private and public values attributed to biodiversity, results in a public goods market failure (Chapter II). Table 6 summarizes the lack of private benefits associated with CWR (column 4). The CWR conservation gap (difference between columns 3 and 4) is larger than that of landrace varieties (difference between columns 1 and 2). This means that additional resources are required in order to incite custodians to undertake conservation measures, and by extension, for a socially-optimum level of conservation to be reached as represented by the Aichi Biodiversity Targets of the CBD (http://www.cbd.int/sp/targets/).

Table 6: Social and private benefit derived from landraces and CWR

Types of value		(1) Social value Landraces	(2) Private value Landraces	(3) Social value CWR	(4) Private value CWR
Instrumental, tangible values	Direct use	✓	✓	✓	✗
	Indirect use	✓	✓	?	?
	Potential use	✓	✓	✓	✗
Instrumental, less tangible value	Resilience	✓	✓	✓	✓ (far removed)
Non-instrumental, intangible values	Bequest	✓	✓	✗	✗
	Existence	✓	✓	✗	✗
	Intrinsic	✓	✓	✓	✓

CWR are found predominantly outside of protected areas such as national parks and wildlife reserves (Chapter III), where conservation is a lot more complex due to human involvement. They also have specific management requirements (see Hunter and Heywood 2011 for comprehensive review). The continued flow of social benefits from CWR depends upon responsible stewardship on behalf of individuals and communities living in Vavilov centres of origin. Given the lack of private benefit derived from them, conservation requires that custodians have incentives to undertake monitoring and protection efforts, in addition to the capacity to actively manage CWR populations (Drucker, Interview).

Policy options available for incentivizing conservation by linking it to livelihood improvement opportunities are limited because of the lack private ownership and benefit associated with them. Opportunities for mutually-reinforcing gains to be achieved through integrated conservation and development projects are very limited in the case of CWR. The ‘Biohappiness Societies’ described by Swaminathan (2011) are based on raising the private values associated with agrobiodiversity conservation. ‘Biovillages’ cannot be operationalized in the context of CWR because farming communities’ production is not based on this type of natural resource. ‘Biovalleys’ likewise cannot be in the absence of opportunities to add value to under-valued species through green consumerism or labelling initiatives, for example. The strategy is predicated on the buying and selling of goods and services.

While flagship or iconic species have the potential to attract ecotourism (Hein et al 2013), CWR also have no associated recreational value that could bring benefit to communities. Agro-ecotourism projects which host immense agrobiodiversity and display principals of agroecology to visitors represent a commercial opportunity not available to wild species, which do not play a direct role in small-scale agriculture.

Where increasing the private value of agrobiodiversity is not possible additional incentives are required in order to close the conservation funding gap. Contingent valuation studies have been conducted for landrace varieties. Supplementary incentives required for CWR are likely to be more considering that landraces supply some private benefits. Bioversity International's initiative to increase private benefits of CWR conservation by providing compensation to farmers will provide a future case study. The funding mechanism has yet to be developed. This project is also dwarfed by efforts to further increase the usability of CWR in crop improvement programs.

From a social-equity perspective the success of incentive mechanisms for biodiversity conservation is predicated on communities having secured land rights and effective and inclusive decision-making processes. Questions regarding who is included and who is excluded, who benefits and who does not will need to be tackled. From an ecological standpoint effective monitoring must be in place to ensure desired conservation outcomes are being achieved, and conservation is a long-term endeavour. The possibility of 'crowding out' those who would otherwise have undertaken conservation in absence of reward is a possibility (Drucker Interview). This seems less likely to be the case with CWR than with landrace varieties however, as custodians do not usually have incentives to undertake any degree of CWR conservation.

There is also the challenge of establishing a funding mechanism *in perpetuity*. In the context of carbon markets there are companies which are willing to pay to offset their carbon emissions, but identifying who the equivalent downstream users are of agrobiodiversity is more of a challenge (Drucker, Interview). The longterm funding requirements of *in situ* conservation can account for some of the lethargy on behalf of the international donor community. Donors such as the Global Environmental Facility that were involved in the establishment of CWR gene reserves a decade ago (Chapter III) are not in a position to provide long-term support beyond short-term project funding. They need to actively seek out conservation partners with the mandate and capacity to plan and coordinate CWR *in situ* conservation activities, which has proved to be a significant challenge (Hunter and Heywood 2011).

Lastly, the long-term commitment required of conservation makes investment guided by cost-benefit analysis difficult to justify. This challenge is acknowledged in the literature on CWR conservation, and in agrobiodiversity conservation more generally (Iriondo 2008; Maxted and Kell 2009; Hunter and Heywood 2011). The discount rate of future benefits needs to be very small, approaching zero, in order for long-term programs to be initiated. Given the trend in international donor funding towards supporting short-term projects and pressure for project administrators to practice results-based management (Stem et al 2005), long-term funding is not easy to secure. For each of the reasons discussed in this section, donor interest has been concentrated in supporting *ex situ* conservation efforts in lieu of contributing towards the establishment of CWR gene reserves.

7.3 Contrasting approaches to achieving global food security

Reflecting upon the two contrasting paradigms introduced in Chapter I sheds some light on the root of the problem as it is framed within this thesis: the under provision of CWR conservation *in situ*. Both scientific and agroecological paradigms are concerned with the sustainability of the global food system in the context of climate change. While agrobiodiversity is the linchpin of both strategies, the fundamental difference between them lies in the type of conservation pursued.

The scientific paradigm has a more narrow focus on achieving food security through the development and dissemination of modern varieties. This has clearly had a strong influence on the dominant conservation strategy. Put differently, the dominant conservation strategy is a *manifestation* of the productionist paradigm in practice. Extracting species from their natural habitats and storing them in gene banks for the ends of developing new varieties fits well within this ideological camp. Tangible, immediate and direct benefits are pursued before less tangible, long-term and abstract benefits to be *potentially* accrued in the future. The result is a conservation system designed to support the development of modern varieties that are adapted to predicted climate change scenarios.

The agroecological paradigm approaches food security from a complex systems perspective, recognizing the complex interactions among social, ecological, political and economic dimensions of the global food system. A more landscape-based approach, or *in situ* conservation, falls in line with this paradigm. Agroecologists have biocentric perspectives of nature (Pasual et al 2010), recognizing species' intrinsic values as well as their role in securing the adaptive capacity of agroecosystems. This is opposed to anthropocentric perspectives which focus on instrumental values (ibid) and conceptualize nature as a series of assets for achieving human goals (Barbier et al 2009). The establishment of dynamic gene reserves wherein custodians actively manage and monitor CWR populations, as well as landrace varieties and traditional farming systems themselves, would be the manifestation of this paradigm in practice.

Policies that encourage the conservation of agrobiodiversity more broadly defined and support small-scale farming systems, as opposed to industrial farming systems characterized by the large-scale production of monocultures, are part of an agroecological approach to pursuing global food security.

The full breadth of agrobiodiversity, including CWR, is valued by agroecologists. But periodically throughout this research an interesting question resurfaced: why are CWR getting so much more international attention than landrace varieties?

Figure 4 - Agrobiodiversity pyramid (revisited)

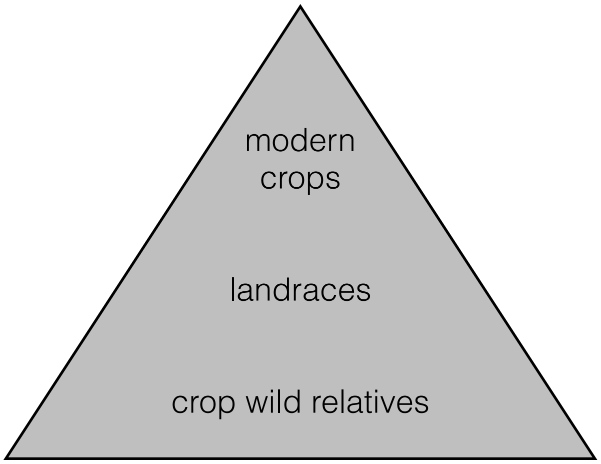


Figure 4 again pictures the agrobiodiversity pyramid. The genetic bases of landraces are on the whole wider than those of modern varieties but narrower that what is found in the wild. While there may be more diversity found in the wild, there is still an enormous amount of diversity within landrace gene pools (Maxted, Interview). It may be more logical to focus on landraces rather than CWR for combating food security. Landraces are categorically easier to breed with as they are closer in relation to modern crop varieties and have fewer biological barriers to crossing. From thousands of years of experience custodians have vast amount of characterization and evaluation data for varieties (Drucker, Interview), which has been a significant constraint to the use of CWR. Using CWR necessitates the use of advanced technologies and long-term funding - characteristics that only a very few large-scale crop improvement programs share - while the benefits of landraces are accessible to people around the world.

With the exception of a few species it can be a disadvantage for farmers to use CWR whereas landraces are used directly (Maxted, Interview). By extension the cost of conserving landraces would be less than CWR. Landraces have private use values which give custodians incentive to internalize the costs of their conservation. While studies have highlighted that compensation payments may be required to negate the opportunity cost of *not* switching to high-yielding varieties, these payments would intuitively be lesser than those required to adequately incentivize CWR *in situ* conservation.

In light of this perspective, the donor trend in funding CWR projects over landrace conservation seems counter-intuitive. Although landrace varieties have been collected since the 1910s and 1920s when Vavilov first put forward the concept that crop diversity is concentrated within centres of origin, collections have not been systematic. There is not a single country with an inventory of landrace varieties, while there has been an international push to do CWR inventories using an IUCN Red Listing approach (Maxted; Hole, Interviews). Landrace diversity refers to intra-specific diversity where taxonomies are not defined. Nigel Maxted draws a parallel to the hypothetical challenge of setting out to conserve bears without a list of types of bears wished to be conserved (ibid). In comparison CWR are appealing for being amenable to taxonomical categorization.

Conserving landrace diversity does not fit within the dominant conservation strategy. Moreover, landrace diversity is not valourized to the same extent as wild genetic diversity for crop improvement. Breeding modern varieties using CWR is a strategy rooted in optimism that technological advancement will continue to facilitate crop improvement, keeping pace with climate change. The conservation of landrace diversity has gotten by-passed within this paradigm that valourizes the development of modern varieties using advanced science. In contrast, landrace varieties and traditional modes of innovation are devalourized. They are viewed as things to be replaced as modern agricultural systems undergo process of 'sustainable intensification' (Garnett et al 2013).

Upon reflection it becomes clear that landrace varieties should be valued for their contributions to food security - for both their use in breeding and the material and cultural benefits they provide directly to farmers and communities - to at least the same extent as CWR. Conservation efforts should encompass the full breadth of agrobiodiversity, guided by policies informed by principles of agroecology and alternative valuation tools for integrating different perspectives of the value of agrobiodiversity.

7.4 Opportunities for course correction

Interest in CWR is still relatively new and the cast of characters involved in their use and conservation is still growing. There are not enough data points here to identify trends in conservation beyond that more players are becoming interested in CWR, nor is there sufficient evidence to say that more money is going towards *ex situ* rather than *in situ* conservation, however disparate efforts appear. This research has shown that the role of CWR in crop improvement will continue to increase in the coming years as climate change and scientific advancements encourage breeders to look outside of primary crop gene pools. The imperative to protect CWR is ever increasing regardless of the paradigm one prescribes to.

The most important take-away from this chapter is that what conservation will look like will depend a great deal on how species are valued. Given the high stakes of maintaining the adaptive capacity of agricultural crops, this deserves a great deal of reflection.

It is useful to look at trajectory of conservation investment at this very early stage so that course corrections can be made where required. The proverb introducing this is chapter relevant here. Conservation planning in the coming years will likely be informed by economic valuations, given the strength and momentum of the discourse echoed in policy documents such as the TEEB. "The only way that governments and businesses are really going to start caring about the national global commons is if someone does put a dollar value on it, for all the limitations that dollar values have" (Hole, Interview). This view is shared among all the CWR conservationists interviewed. If valuation efforts moving forward take into account the total economic value of CWR, and the establishment of a global network of *in situ* conservation areas is justified based on this economic analysis, then socially-optimum levels of conservation *may* be achieved, or at least worked towards. However as long as valuation efforts focus on the instrumental values of CWR then only a select sub-set of prioritized diversity will be conserved in gene banks. The result will be a loss of adaptive capacity for agricultural crops along with the erosion of the breadth CWR genetic diversity.

The conclusion drawn from this analysis is that the establishment of a global network of *in situ* conservation areas, as originally advocated for by Maxted and Kell (2009), is essential for achieving global food security.

Donor organizations are well placed to fund capacity building for monitoring CWR populations and to spread *bioliteracy* (Swaminathan 2011) among individuals and communities living in areas where CWR are concentrated. But this funding is invariably short-term. For longer term conservation an endowment fund comparable to that of the Trust's which funds the CGIAR gene banks would need to be established. This fund could either be managed by an independent body or as an extension of an existing conservation body.

There exists a great deal of potential to have private breeding companies contribute to such an endowment. Their involvement in CWR conservation would thereby have positive implications beyond the conservation of relatively few treasured species. The potential for more funds to emerge out of the Multilateral System under the ITPGRFA in the future is highlighted by Moeller and Stannard (2013). This may also be an appropriate avenue to explore for the creation of an endowment fund. Valuation studies which take into account the wealth of ongoing work with CWR and communicate their total economic value will be useful for justifying the scale of conservation investment required.

Areas for gene reserves may be selected according to the priority areas identified as CWR 'hotspots' by Maxted and Kell (2009), the areas of of biocultural significance highlighted by the Globally Important Agricultural Heritage Systems Programme under the FAO (Howard et al 2008), in areas where threats are most acute due to anthropomorphic impacts and climate change, and where partnerships with local community organizations or institutions can be established. Incentive mechanisms will likely play a key role in conservation *in situ* in order to internalize opportunity costs associated with conservation among custodians, and so that conservation and livelihood improvement goals can be worked towards simultaneously. It is of the utmost importance that communities in centres of diversity are recognized for their role as custodians with rights affirmed in accordance with the provisions laid out in the CBD and the Nagoya Protocol.

This proposal can be boiled down into a suite of six recommendations; the first four of which are focused on CWR conservation, the latter two on agrobiodiversity conservation more broadly defined, guided by principles of agroecology:

I. Increased conservation funding dedicated towards raising *bioliteracy* and capacity to monitor and manage CWR populations among communities.
II. Establishment of an endowment fund for *in situ* conservation, *in perpetuity*.

III. Selection of gene reserves based on CWR ‘hotspot’ areas, other ares of biocultural significance, areas where threats are most pervasive and where partnerships with local organizations can be made.
IV. Development of incentive mechanisms in collaboration with local partners which are contextually appropriate and mindful of social equity and ecological outcomes.
V. Development of alternative valuation tools which integrate different perspectives on the value of agrobiodiversity, incorporate risk analyses and undertake precautionary approaches.
VI. Pursuit of a broader policy portfolio, based on principles of agroecology, which encourages the conservation of agrobiodiversity and support small-scale farming systems.

It is beyond the scope of this thesis to explore the potential for an *in situ* endowment fund in any greater depth, or even attempt to identify the types of policy alternatives which may support small-scale farming systems and the agrobiodiversity conservation which is inherent to them (Wale 2011). It is instead only emphasized yet again how important it is that a balanced conservation strategy be pursued, and the imperative to move towards the realization of a global network for *in situ* conservation of CWR.

Many areas of further research have been identified in this thesis. Those most relevant to the realization of *in situ* conservation include:

I. Refine the sites identified as CWR ‘hotspots’ within Vavilov centres of diversity as identified by Maxted and Kell (2009) (Maxted, Interview).
II. Conduct further studies on the predicted impacts of climate change of CWR populations in order to inform the selection of gene reserves in light of species’ changing climatic envelopes.
III. Determine how incentive mechanisms may best be employed among communities with customary laws pertaining to collective ownership over plant genetic resources.
IV. Monitor how the evolving landscape of actors involved in CWR conservation and use affects investment, particularly with respect to private sector involvement and the role of public-private partnerships.
V. Conduct valuation studies that more accurately reflect potential use, resilience and intrinsic values of CWR in order to effectively communicate the importance of establishing gene reserves with policy makers.

Chapter VIII - Conclusions

CWR represent an immense wealth of genetic material for improving modern crop varieties. Sustaining the production of the world's most socio-economically important staple crops requires having this pool to draw from. This is will continue to be the case as the genetic bases of crops become increasingly narrow on account of the continuing process of domestication and genetic refinement, and as climate change pushes crop breeders to find more extreme resistances and tolerances from more distantly related species.

This research has shown that CWR are being used more today than ever before across the nineteen crops surveyed. A qualitative analysis of the current use of CWR reveals a positive trend in overall use, as well as a greater emphasis on their role in developing modern crop varieties adapted to predicted climate change scenarios. These trends will likely continue if not intensify in light of new tools and methods emerging from the burgeoning field of genomics and more extreme environmental pressures threatening the viability of crop production systems. All evidence suggests that crop scientists and pre-breeders will be exploring wild gene pools for traits of interest increasingly in the coming decades.

An unforeseen and important finding of this study is that the vast majority of ongoing work *upstream* with wild species has yet to be realised *downstream* in the form of new varieties. By extension, efforts to quantify use of CWR based on cultivars released underestimate their current role in agricultural research and development. The It takes time for pre-breeders to evaluate wild accessions for traits of interest and develop lines useful to breeders. Ongoing research into the biology of wild species, the genetic base of complex traits associated with adapting agriculture to climate change, and relationships between genes, traits and the environment that will facilitate future use of CWR is less visible to policy makers. Valuation efforts undertaken to date underestimate potential use values of CWR by focusing exclusively on the economic contributions of certain key species. As these benefits are realized more and more, interest in CWR conservation is likely to keep pace.

This study has also highlighted the benefits that CWR provide to society which are not currently reflected in CWR conservation planning and investment. Only direct use, and to a lesser extent potential use values have been 'counted' in valuation exercises to date. Resilience and intrinsic values are ignored. The TEV valuation approach to conceptualizing the value of CWR is useful for identifying the range of benefits provided by CWR and conceptualizing why a socially-optimum level of conservation may not been reached by focused exclusively on direct use for breeding. However economic valuation approaches to conservation have their pitfalls - they risk reducing nature to the sum of quantifiable, exchangeable parts without regards to social, ecological or ethical dimensions. Alternative decision support tools need to be applied to the case of CWR where multiple perspectives are integrated and risk analyses and critical thresholds are taken into account. A precautionary approach to conservation and policies which recognize the importance of agrobiodiversity and actively support small-scale farming systems will stem from the use of such a tool.

Until today, however, policies relating to the conservation of CWR and agrobiodiversity more broadly have been informed by valuation exercises and a collection of studies prioritizing species based on a set of criteria focused almost exclusively on direct use value. The influx in CWR conservation investment that has begun to materialize is disproportionately geared towards increasing the representation of wild species in gene bank collections that have high predicted economic value, as measured by their use in crop improvement, and develop tools and capacities to use them. This forms the dominant conservation paradigm: the protection of a small sub-set of economically important species where scientists and pre-breeders have access it, and honing of a very sophisticated variety development chain.

The dominant conservation paradigm can be understood as an extension, or manifestation, of the scientific paradigm for achieving sustained food productive capacity worldwide. An unwavering faith is put upon the scientific development of new varieties that are adapted to changing environmental conditions and less resource intensive than the modern varieties of past generations. A degree of confidence may not altogether be misplaced, as advancements in genomics approaches to breeding, for example, are in fact facilitating the use of CWR.

But while this investment sparks a positive feedback between conservation and increased use, this will be limited by the extend to which diversity is available. The paradox alluded to by experts within each of the crop communities surveyed is that genetic erosion and habitat destruction due to a variety of environmental and anthropogenic forces is continuing alongside of well-intentioned conservation investment. Given uncertainties relating to which traits will be required, where sources of resistances / tolerances will come from and how technological advancements may facilitate use, conserving the breadth of diversity within its natural environments is the most fail-safe strategy for securing the productive capacity of crops.

An analysis of the implications of this dominant strategy unearths the dangers of putting all of our proverbial eggs in one basket. The development of modern varieties contributes to the displacement of the rich genetic diversity found within agroecosystems, as well as traditional farming systems themselves. Diverse farming systems go hand-in-hand with agrobiodiversity conservation. The maintenance of the existing stock of genetic diversity, its continued flow, and traditional farming systems themselves is essential to the resilience of the global food system. Perspectives from agroecology will be useful in designing and implementing more landscape-based conservation and development strategies. Conservation measures that have ecological and social-equity considerations at their heart have the potential to achieve both conservation and livelihood improvement goals. It is recognized, however, that the challenges associated with managing CWR populations *in situ* and inciting responsible stewardship among custodians in centres of origin are immense. Much more policy discussion and debate, further research and resources are required to close the conservation gap.

Perhaps there is some room for convergence between the two paradigms. An integrated approach may take advantage of scientific advancements in crop improvement while recognizing the immense value of landrace diversity, small-scale farming systems and *in situ* agrobiodiversity conservation. Understanding gene-trait relationships and being able to accurately predict which species may be of particular value within particular environmental conditions under predicted climate change scenarios may be of immense value to small-scale farmers. At the same time, landrace varieties and associated traditional knowledge may be of greater value for formal crop breeding crop than is currently recognized.

The key message echoed throughout this thesis is that, while beneficial, preserving species for the ends of developing new crop varieties must not eclipse a broader appreciation for species' roles within complex agroecosystems. CWR conservation has now entered into mainstream policy discussions. At this critical point, it is important for the international community to engage in a broader conversation regarding the value of agrobiodiversity and its role in securing the global food supply. Reflecting upon the dynamic relationship between valuation and conservation is helpful for understanding why agrobiodiversity loss continues despite increased international attention. Those informing policy and those from within the international donor community need to step back and reflect upon how future adaptive capacity of agroecosystems is being traded off for variety development today. In an era where there is so much urgency to foster adaptive capacity within socio-ecological systems the imperative to mindfully manage agrobiodiversity is clear.

References

Altieri, M. A. (2002). Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agriculture, ecosystems & environment*, 93(1), 1-24.

Altieri, M.A., Nicholls, C., Funes, F. (2012). *The scaling up of agroecology: spreading the hope for food sovereignty and resiliency*. SOCLA's Rio+ 20 position paper.

Alvarado-Quesada, I., Hein, L., Weikard, H.P. (2013). Market-based mechanisms for biodiversity conservation: a review of existing schemes and an outline for a global mechanism. *Biodiversity and Conservation*, 1–21.

Amend, T., Brown, J., Kothari, A., Phillips, A., Stolton, S. (eds) (2008). Protected Landscapes and Agrobiodiversity Values. Vol 1 in the series Protected Landscapes and Seascapes, International Union for Conservation of Nature (IUCN) and Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Kasparek Verlag, Heidelberg, Germany: 139.

Argumedo, A. (2008). The Potato Park, Peru: Conserving agrobiodiversity in an Andean indigenous biocultural heritage area. Protected Landscapes and Agrobiodiversity Values. Volume 1 in the series, Protected Landscapes and Seascapes, IUCN & GTZ, 45.

Barbier, E.B., Baumgartner, S., Chopra K., Costello C., Duraiappah A. (2009). "The valuation of ecosystem services." In Naeem S., Bunker D., Hector A., Loreau M., Perrings C. (eds) Biodiversity, Ecosystem Functioning, and Human Wellbeing: An Ecological and Economic Perspective. Oxford: Oxford University Press: 248–262.

Bardsley P. (2003). *Missing environmental markets and the design of "Market based instruments."* In 6th Annual AARES National Symposium: Market Based Tools for Environmental Management, Canberra.

Baute, G.J., Dempewolf, H., Rieseberg, L.H. (forthcoming). 'Using genomic approaches to unlock the potential of CWR for crop adaptation to climate change.'

Bertacchini, E. E. (2008). Coase, Pigou and the potato: Whither farmers' rights? *Ecological Economics*, 68(1-2): 183–193.

Beymer-Farris, B. A., & Bassett, T. J. (2012). The REDD menace: Resurgent protectionism in Tanzania's mangrove forests. *Global Environmental Change*, 22(2): 332-341.

Blom, B., Sunderland, T., Murdiyarso, D. (2010). Getting REDD to work locally: lessons learned from integrated conservation and development projects. *Environmental Science & Policy,* 13(2): 164–172.

Breithaupt H. (2008). Up to the challenge? Rising prices for food and oil could herald a renaissance of plant science. EMBO Reports, 9: 832–834.

Brummer, E.C., Barber, W.T., Collier, S.M., Cox, T.S., Johnson, R., Murray, S.C., … Thro, A.M. (2011). Plant breeding for harmony between agriculture and the environment. *Frontiers in Ecology and the Environment*, 9(10): 561–568.

Bruntland Commission (World Commission on Environment and Development) (1987). *Our Common Future*. Oxford: Oxford University Press.

Brush, S.B. (2002). The lighthouse and the potato: internalizing the value of crop genetic diversity. Political Economy Research Institute Working Paper, 37.

Castree, N. (2003). "Commodifying what nature?." *Progress in human geography*, 27(3): 273-297.

Cattivelli, L., Rizza, F., Badeck, F.-W., Mazzucotelli, E., Mastrangelo, A. M., Francia, E., Stanca, a. M. (2008). Drought tolerance improvement in crop plants: An integrated view from breeding to genomics. *Field Crops Research*, 105(1-2): 1–14.

Chatzav, M,; Peeg, Z.; Ozturk, L., Yazici, A.; Fahima, T.; Cakmak, I.; Saranga, Y. (2010). "Genetic diversity for grain nutrients in wild emmer wheat: potential for wheat improvement." *Annals of Botany Preview*, published 3 March 2010.

Clay, E. (2002). Food Security: Concepts and Measurement, Paper for FAO Expert Consultation on Trade and Food Security: Conceptualising the Linkages Rome, 11-12 July 2002. Published as Chapter 2 of Trade Reforms and Food Security: conceptualising the linkages. FAO, Rome.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., & Schwartz, M.D. (2007). Shifting plant phenology in response to global change. *Trends in ecology & evolution*, 22(7): 357-365.

Coase, R. (1960). The problem of social cost. *Journal of Law and Economics,* 3: 1–44.

Cobben, M.M.P., van Treuren, R., & van Hintum, T. J. L. (2013). Climate change and crop wild relatives: can species track their suitable environment, and what do they lose in the process? *Plant Genetic Resources,* 11(03): 234–237.

Colmer T.D., Flowers T.J., Munns R. (2006). Use of wild relatives to improve salt tolerance in wheat. *Journal of Experimental Botany*, 57: 1059–1078.

Cooper, J.C., Lipper, L.M. and Zilberman, D. (2005) 'Synthesis chapter: managing plant genetic diversity and agricultural biotechnology for development,' in Cooper, J.C., Lipper, L.M. and Zilberman, D. (eds) *Agricultural Biodiversity and Biotechnology in Economic Development*, Springer, New York: 3-13.

Corbera, E., Brown, K., Adger, W.N. (2007). The equity and legitimacy of markets for ecosystem services. *Development and change*, 38(4): 587-613.

Costanza, R., d'Arge, R., Groot, R.D., Farber, S., Grasso, M., Hannon, B., ... Belt, M.V.D. (1997). The value of the world's ecosystem services and natural capital. *Nature*, 387: 253-260.

Costanza, R. and Daly, H.E. (1992). Natural capital and sustainable development. *Conservation Biology*, 6: 37-46.

Daly, H.E., Townsend, K.N. (1993). *Valuing Earth: Economic, Ecology and Ethics*. MIT Press, Cambridge, MA, USA and London, UK.

Davis, A.P., Gole, T.W., Baena, S., Moat, J. (2012). The impact of climate change on indigenous Arabica coffee (Coffea arabica): predicting future trends and identifying priorities. PloS one, 7(11): e47981.

de Schutter, O. (2010). Report submitted by the Special Rapporteur on the right to food. UN General Assembly. Human Rights Council Sixteenth Session, Agenda item 3 A/HRC/16/49.

Dempewolf, H., Eastwood, R. J., Guarino, L., Khoury, C. K., Müller, J. V., & Toll, J. (2014). Adapting Agriculture to Climate Change: A Global Initiative to Collect, Conserve, and Use Crop Wild Relatives. *Agroecology and Sustainable Food Systems*, 38(4): 369–377.

Dwivedi S.L., Upadhyaya, H.D., Thomas Stalker, H., Blair, M.W., Bertioli, D.J., Nielen, S. and Ortiz, R., (2008). Enhancing Crop Gene Pools with Beneficial Traits Using Wild Relatives. *Plant Breeding Reviews*, 30: 180–230.

Engel, S., Pagiola, S., Wunder, S. (2008). Designing payments for environmental services in theory and practice: an overview of the issue. *Ecological Economics,* 65(4): 663–674.

Feuillet, C., Langridge, P., Waugh, R. (2008). Cereal breeding takes a walk on the wild side. *Trends in Genetics*, 24(1): 24-32.

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., ... Genova, R.C. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

FAO (2001). International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA). Food and Agriculture Organization of the United Nations, Rome.

FAO (2008). *Climate Change and Biodiversity for Food and Agriculture.* Food and Agriculture Organization of the United Nations, Rome.

FAO (2010). *Second report on the state of the world's plant genetic resources for food and agriculture*. Food and Agriculture Organization of the United Nations, Rome.

FAO (2014). *The State of Food and Agriculture*. Food and Agriculture Organization of the United Nations. Available at http://www.fao.org/publications/sofa/2014/en/

Flowers, T.J. (2004). Improving crop salt tolerance. *Journal of experimental botany,* 55(396), 307–19.

Ford-Lloyd, B.V., Schmidt, M., Armstrong, S.J., Barazani, O., Engels, J., Hadas, R., … Maxted, N. (2011). Crop Wild Relatives—Undervalued, Underutilized and under Threat? *BioScience*, 61(7): 559–565.

Fuwa, N., Sajise, A.J.U., (2009). *Exploring environmental services incentive policies for the Philippines rice sector: the case of intra-species agrobiodiversity conservation.* In: Lipper, L., Sakuyama, T., Stringer, R., Zilberman, D. (Eds.), Payment for Environmental Services in Agricultural Landscapes: Economic Policies and Poverty Reduction in Developing Countries. Food and Agriculture Organization of the UN, Rome: 221–238.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J. (2013). Sustainable Intensification in Agriculture: Premises and Policies. *Agriculture,* 341(6141): 33-34.

Gollin, D., Evenson, R.E. (1998) *An application of hedonic pricing methods to value rice genetic resources in India*. In: Evenson, R. E. Gollin, D. and Santaniello, V. (eds.) Agricultural values of plant genetic resources. CAB International., Wallingford, U.K., pp. 139-150

Halewood, M. (2013). Implementing 'Mutually Supportive' Access and Benefit Sharing Mechanisms Under the Plant Treaty, Convention on Biological Diversity, and Nagoya Protocol. *Law, Environment and Development Journal* 9(2). Available at http://www.lead-journal.org/content/13068.pdf

Hajjar, R., Hodgkin, T. (2007). The use of wild relatives in crop improvement: a survey of developments over the last 20 years. *Euphytica*, 156 (1-2): 1–13.

Harlan, J.R. (1976). Genetic resources in wild relatives of crops. *Crop Science,* 16: 329-333.

Harlan, J. R & de Wet, J.M.J. (1971). Agricultural origins: centers and noncenters. *Science,* 174: 468-474.

Harvey, D. (2003). The New Imperialism. Oxford: Oxford University Press.

Hein, L., Gatzweiler, F. (2006) The economic value of coffee (Coffea arabica) genetic resources. *Ecological Economics*, 60: 176–185.

Heywood,V.H., Dulloo, M.E. (2005). *In Situ Conservation of Wild Plant Species – A Critical Global Review of Good Practices.* IPGRI Technical Bulletin, no 11, FAO and IPGRI, International Plant Genetic Resources Institute (IPGRI), Rome.

Heywood, V., Casas, A., Ford-Lloyd, B., Kell, S., & Maxted, N. (2007). Conservation and sustainable use of crop wild relatives. *Agriculture, ecosystems & environment*, 121(3): 245-255.

Hein L., van der Meer, P.J. (2012). “REDD+ in the context of ecosystem management(4/6 Climate systems)”. *Current Opinion in Environmental Sustainability*, 4(6): 604–611.

Hein, L., Miller, D. C., de Groot, R. (2013). Payments for ecosystem services and the financing of global biodiversity conservation. *Current Opinion in Environmental Sustainability*, 5(1), 87–93.

Hillier, J. (1999). What values? Whose values? *Ethics, Place and Environment*, 2(2): 179-199.

Holling, C.S. (1987). ‘Simplifying the Complex, the Paradigms of Ecological Function and Structure.’ *European Journal of Operational Research*, 30: 139-46.

Howard, P., Puri, R., Smith, L., Altierri, M. (2008). *A Scientific Conceptual Framework and Strategic Principles for the Globally Important Agricultural Heritage Systems Programme from a Social-ecological Systems Perspective*. Food and Agriculture Organization of the United Nations, Rome.

Hoyt, E. (1988). Conserving the Wild Relatives of Crops. IBPGR, IUCN, WWF, Rome/Gland, Switzerland.

Hunter, D., Heywood, V. (2011) *Protected Areas and CWR Conservation. Planning for CWR Conservation and Partnership Building*. In: Hunter, D., Heywood, V. (eds.) Crop Wild Relatives: A manual for in situ conservation. Earthscan.

Iriondo, J.M., Maxted, N., Dulloo, M.E. (eds) (2008). Conserving Plant Diversity in Protected Areas, CABI International, Wallingford, UK.

Jansky, S.H., Dempewolf, H., Camadro, E.L., Simon, R., Zimnoch-Guzowska, E., Bisognin, D., Bonierbale, M. (2013). A Case for Crop Wild Relative Preservation and Use in Potato. *Crop Science*, 53(3): 746.

Jarvis, A., Lane, A., Hijmans, R. (2008). The effect of climate change on crop wild relatives. *Agriculture, Ecosystems and Environment,* 126: 13-23.

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S. (2012). Global changes in diets and the consequences for land requirements for food. *Proceedings of the National Academy of Sciences*, 109(18): 6868-6872.

Kell, S.P., Maxted, N., Bilz, M. (2012). European crop wild relative threat assessment: knowledge gained and lessons learnt. In: Maxted, N., Dulloo, M.E., Ford-Lloyd, B.V., Frese, L.L., Iriondo, J.M. and Pinheiro de Carvalho, M.A.A. (eds.), Agrobiodiversity Conservation: Securing the Diversity of Crop Wild Relatives and Landraces. CAB International, Wallingford: 218–242.

Keulartz, J. (2013). Conservation through Commodification? Ethics, Policy & Environment. Taylor & Francis. doi:10.1080/21550085.2013.843379

Khazaei, H., Street, K., Bari, A., Mackay, M., & Stoddard, F. L. (2013). The FIGS (focused identification of germplasm strategy) approach identifies traits related to drought adaptation in Vicia faba genetic resources. PloS One, 8(5).

Khoury, C. (2014). “Increasing homogeneity in global food supplies and the implications for food security.” Proc Natl Acad Sci 111: 4001-4006.

Kinzig, A., Perrings, C., Scholes, B. (2007). ‘Ecosystem services and the economics of biodiversity conservation,’ available at http://www.public.asu.edu/~cperring/Kinzig%20Perrings%20Scholes%20(2007).pdf

Kinzig, A.P., Ryan, P., Etienne, M., Allyson, H., Elmqvist, T., Walker, B.H. (2006). Resilience and regime shifts: assessing cascading effects. *Ecology and Society*. 11(1): 20.

Koebner, R., & Ortiz, R. (2013). Fishing in the gene pool – how useful was the catch? *Plant Genetic Resources*, 11(3): 283–287.

Kontoleon, A., Pascual, U.; and Smale, M. (2009). *‘Agro-biodiversity for economic development: what do we know?’* in A. Kontoleon; U. Pascual; M. Smale (eds.), Agro-biodiversity Conservation and Economic Development, Routledge, London and New York: 1-24.

Kosoy, N., & Corbera, E. (2010). Payments for ecosystem services as commodity fetishism. *Ecological economics*, 69(6): 1228-1236.

Krishna, V.V., Pascual, U., Zilberman, D., 2010. Assessing the potential of labelling schemes for in-situ landrace conservation: an example from India. *Environment and Development Economics,* 15: 127–151.

Krishna, V.V., Drucker, A.G., Pascual, U., Raghu, P.T., E.D. Israel Oliver King (2013). Estimating Compensation Payments for On-farm Conservation of Agricultural Biodiversity in Developing Countries. *Ecological Economics*, 87: 110–123.

Kroeger, T., Casey, F. (2007). An assessment of market-based approaches to providing ecosystem services on agricultural lands. *Ecological Economics*, 64(2): 321–332.

Lam, H. M., Xu, X., Liu, X., Chen, W., Yang, G., Wong, F. L., ... & Zhang, G. (2010). Re-sequencing of 31 wild and cultivated soybean genomes identifies patterns of genetic diversity and selection. *Nature genetics*, 42(12): 1053-1059.

Larson, A. M., Brockhaus, M., Sunderlin, W. D., Duchelle, A., Babon, A., Dokken, T., … Huynh, T.-B. (2013). Land tenure and REDD+: The good, the bad and the ugly. *Global Environmental Change*, 23(3): 678–689.

Lenoir, J., Gégout, J.C., Marquet, P. A., De Ruffray, P., & Brisse, H. (2008). A significant upward shift in plant species optimum elevation during the 20th century. *Science*, 320(5884): 1768-1771.

Lipper, L., Sakuyama, T., Stringer, R., Zilberman, D. (2009). *Payment for Environmental Services in Agricultural Landscapes: Economic Policies and Poverty Reduction in Developing Countries*. Food and Agriculture Organization of the UN, Rome, Italy.

Lira, R., Tellez, O., Davila, P. (2009). The effects of climate change on geographic distribution of Mexican wild relatives of domesticated cucurbitaccae. *Genetic Resources and Crop Evolution*, 56: 691-703.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science,* 319: 607–610.

Lovera, S. (2009). REDD realities. Contours of Climate Justice: Ideas for Shaping New Climate and Energy Policy. *Critical Currents*, 6.

Mackay, M.C., Street, K. (2004). Focused identification of germplasm strategy–FIGS. In Proc 54th Australian Cereal Chem. Conf. and the 11th Wheat Breeders' Assembly, Canberra, ACT, Australia: 21-24.

Madsen, B., Carroll, N., Moore Brands, K. (2010). State of biodiversitymarkets report: offset and compensation programs worldwide. Available at http://www.ecosystemmarket place.com/documents/acrobat/sbdmr.pdf 2010.

Magos Brehm, J., Maxted, N., Martins-Loução, M.A., Ford-Lloyd, B.V. (2010). New approaches for establishing conservation priorities for socio-economically important plant species. *Biodiversity and Conservation*, 19: 2715–2740.

Mariano, M.J., Villano, R., Fleming, E. (2012). Factors influencing farmers' adoption of modern rice technologies and good management practices in the Philippines. *Agricultural Systems*, 110: 41-53.

Maxted, N.; Ford-Lloyd, B.V.; Hawkes, J.G. (1997a). Complementary conservation strategies. In Plant Genetic Conservation: The In Situ Approach. Chapman and Hall, London.

Maxted, N.; Ford-Lloyd, B.V.; Hawkes, J.G. (eds) (1997b). Plant Genetic Conservation: The In Situ Approach. Chapman and Hall, London.

Maxted, N., Ford-Lloyd, B.V., Jury, S.L., Kell, S.P., Scholten, M.A. (2006). Towards a definition of a crop wild relative. *Biodiversity and Conservation*, 15: 2673–2685.

Maxted, N., Kell, S. P., Ford-Lloyd, B. V., Iriondo, J. M., Dulloo, M. E., & Turok, J. (2008). *Crop wild relative conservation and use: establishing the context.* In: Proceedings of the First International Conference on Crop Wild Relative Conservation and Use, CABI Publishing, Rome: 3-30.

Maxted, N.; S.P. Kell (2009). *Establishment of a Global Network for the In Situ Conservation of Crop Wild Relatives: Status and Needs*. FAO Commission on Genetic Resources for Food and Agriculture, Rome, Italy.

McAfee, K. (1999). Selling nature to save it? Biodiversity and the rise of green developmentalism. *Environment and Planning,* 17: 133–154.

McAuley, D. (2006). Selling out on nature. *Nature*, 443: 27-28.

McCarthy J. (2004). Privatizing conditions for production: Trade agreements as neoliberal environmental governance. *Geoforum*, 35: 275–283.

McCouch, S. (2013). “Agriculture: Feeding the future.” *Nature,* 499(7456): 23-24.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W. (1972). The Limits to Growth. The Report for the Club of Rome’s Project on the Predicament of Mankind. Universe Books, New York.

Mendelsohn, R. (2003). The challenge of conserving indigenous domesticated animals. *Ecological Economics*, 45(3): 501-510.

Méndez, V.E., Gliessman,S.R. and Gilbert, G.S. (2007). Tree biodiversity in farmer cooperatives of a shade coffee landscape in western El Salvador. *Agriculture, Ecosystems & Environment*, 119: 145-159.

Meilleur, B.A., Hodgkin, T. (2004). In situ conservation of crop wild relatives: status and trends. *Biodiversity and Conservation*, 13: 663-684.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being*. Island Press, Washington, DC.

Moeller, N.I., Stannard, C. (2013). *Identifying Benefit Flows: Studies on the Potential Monetary and Non-Monetary Benefits Arising from the International Treaty on*

Plant Genetic Resources for Food and Agriculture. Food and Agriculture Organization of the United Nations, Rome.

Monfreda, C. (2010). Setting the stage for new global knowledge: Science, Economics, and Indigenous knowledge in 'The Economics of Ecosystems and Biodiversity' at the Fourth World Conservation Congress. *Conservation and Society*, 8: 276–285.

Munda, G. (2004). Social multi-criteria evaluation: Methodological foundations and operational consequences. *European journal of operational research*, 158(3): 662-677.

Narloch, U., Drucker, A. G., Pascual, U. (2011). Payments for agrobiodiversity conservation services for sustained on-farm utilization of plant and animal genetic resources. *Ecological Economics*, 70(11): 1837–1845.

Nijkamp P., Vindigni G., Nunes, P.A.L.D. (2008). Economic valuation of biodiversity: a comparative study (Special Section: Biodiversity and Policy). *Ecological Economics,* 67(2): 217–231.

Ninan, K. N. (Ed.). (2009). Conserving and valuing ecosystem services and biodiversity: economic, institutional and social challenges. Routledge, New York.

Nunes, P.A.L.D., Nijkamp, P. (2003). Introduction to the special issue on biodiversity policy. *Ecological Economics*, 67: 159-161.

OECD (2004). Handbook of Market Creation for Biodiversity: issues in Implementation. OECD Publishing, Paris. doi:10.1787/9789264018624-en

Ortiz R, Sayre KD, Govaerts B, et al. (2008). Climate change: can wheat beat the heat? *Agr Ecosyst Environ*, 126: 46–58.

Parmesan, C., Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421: 37-42.

Parolo, G., Rossi, G. (2007). Upward migration of vascular plants following a climate warming trend in the Alps. *Basic and Applied Ecology,* doi:10.1016/j.baae.2007.01.005

Pascual, U., Muradian, R., Rodríguez, L.C., Duraiappah, A., (2010). Exploring the links between equity and efficiency in Payments for Environmental Services: a conceptual approach. *Ecological Economics*, 69(6): 1237–1244.

Peck, J., Tickell, A. (2002). Neoliberalizing Space. Editorial Board of Antipode. Blackwell Publishers, Oxford.

Pimentel, D., Wilson, C., McCullum, C., Huang. R., Dwen, P., Flack, J., Tran, Q., Saltman, T. & Cliff. B. (1997). Economic and environmental benefits of biodiversity. *BioScience,* 47: 747–757.

Pirard, R., & Lapeyre, R. (2014). “Classifying market-based instruments for ecosystem services: A guide to the literature jungle.” *Ecosystem Services*, 9: 106–114.

Pirard, R. (2014). “From markets to payments to governance” Public lecture series, Bogor, Indonesia, November 20. Available online at http://blog.cifor.org/25291#.VJZSgsAOA

Prescott-Allen, R., Prescott-Allen, C. (1983). Genes from the Wild: Using Wild Genetic Resources for Food and Raw Materials. Earthscan, London.

Prescott-Allen, R., Prescott-Allen, C. (1986). The First Resource: wild species in the North American economy. Yale University Press, New Haven, CT.

PricewaterhouseCoopers LLD (2013). “A valuable resource for crop development.” Available at www.pwc.co.uk/valuations

Prudham, S. (2007). The Fictions of Autonomous Invention: Accumulation by Dispossession, Commodification and Life Patents in Canada. *Journal compilation Editorial Board of Antipode:* 406-429.

Rick, C.M., Chetelat, R.T. (1995). Utilization of related wild species for tomato improvement. In I International Symposium on Solanacea for Fresh Market, 412: 21-38.

Rodríguez-Labajos, B., Martínez-Alier, J. (2012). *Issues in the economics of ecosystems and biodiversity. Recent instances for debate*. EJOLT Report No. 5.

Schneider, A., Molnar, I., Molnar-Lang, M. (2008). Utilization of Aegilops (goatgrass) species to widen the genetic diversity of cultivated wheat. *Euphytica*, 163: 1-19.

Schwartz, M.W., Iverson, L.R., Prasad, A.M.; Matthews, S.N.; O’Connor, R.J. (2006). Predicting extinctions as a result of climate change. *Ecology,* 87: 1611-1615.

Semenov, M.A., Halford, N.G. (2009). Identifying target traits and molecular mechanisms for wheat breeding under and changing climate. *Journal of Experimental Botany*, 60: 2791-2804.

Sharratt, Lucy (2010). Public lecture: “Political Economy on Food.” Carleton University, November 12, 2010.

Smale, M. (Ed.) (2005). Valuing crop biodiversity: on-farm genetic resources and economic change. CABI Publishing, Wallingford, UK.

Stalker, H.T. (1980). Utilization of wild species for crop improvement. *Advances in Agronomy*, 33: 111-147.

Stem, C., Margoluis, R., Salafsky, N., & Brown, M. (2005). Monitoring and evaluation in conservation: a review of trends and approaches. *Conservation Biology*, 19(2): 295-309.

Stolton, S., Maxted, N., Ford-Lloyd, B., Kell, S.P., Iriondo, J.M., Dulloo, M.E., Turok, J. (2006). “Food Stores: Using Protected Areas to Secure Crop Genetic Diversity.” World Wide Fund for Nature (WWF) Arguments for protection series, WWF, Gland, Switzerland.

Sullivan, S. (2012). Financialisation, biodiversity conservation and equity: some currents and concerns. *Third World Network*, 16.

Swaminathan, M.S. (1996). ‘Compensating farmers and communities through a global fund for biodiversity conservation for sustainable food security.’ *Diversity*, 12: 73-75.

Swaminathan, M.S. (2011). In search of Biohappiness: Biodiversity and Food, Health and Livelihood Security. World Scientific Publishing Company.

Swanson, T., Göschl, T. (2000). Property rights issues involving plant genetic resources: implications of ownership for economic efficiency. *Ecological Economics*, 32(1): 75-92.

Tanksley, S.D., McCouch, S.R. (1997). Seed banks and molecular maps: unlocking genetic potential from the wild. *Science,* 277(5329): 1063–6.

TEEB (2010). *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*. Available at http://www.teebweb.org/

Thrupp, L. A. (2000). Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. *International affairs*, 76(2): 283-297.

Tittonell, P. (2014). Livelihood strategies, resilience and transformability in African agroecosystems. *Agricultural Systems*, 126: 3-14.

Turner, R.K., Daily, G.C. (2008). The ecosystem services framework and natural capital conservation. *Environment and Resource Economics*, 39: 25-35.

Upadhyaya, H.D., Pundir, R.P.S., Dwivedi, S.L., Gowda, C.L.L., Reddy, V.G., Singh, S. (2009). Developing a mini core collection of sorghum for diversified utilization of germplasm. *Crop Science*, 49(5): 1769-1780.

Ureta, C., Martinez-Meyer, E., Perales, H.R., Albarez-Buylla, E.R. (2012). Projecting the effects of climate change on the distributions of maize races and their wild relatives in Mexico. *Global Change Biology,* 18(3): 1073-1082.

van de Wiel, C., Schaart, J., Niks, R., & Visser, R. (2010). Traditional plant breeding methods. Wageningen, The Netherlands: Wageningen UR.

Vavilov, N.I. (1931). The Problem of the Origin of the World’s Agriculture in the Light of Latest Investigations. Science at the Crossroads: Papers Presented to the International Congress of the History of Science and Technology Held in London from June 29th to July3rd, 1931 by the delegates of the U.S.S.R, Frank Cass and Co., 1931. Available at formarxists.org.

Vincent, H., Wiersema, J., Kell, S., Fielder, H., Dobbie, S., Castañeda-Álvarez, N. P., … Maxted, N. (2013). A prioritized crop wild relative inventory to help underpin global food security. *Biological Conservation*, 167: 265–275.

Wale, E. (2008). A study on financial opportunity costs of growing local varieties of sorghum in Ethiopia: implications for farm conservation policy. *Ecological Economics*, 64 (3): 603–610.

Wale, E., Drucker, A.G., Zander, K.K. (Eds.). (2011). The economics of managing crop diversity on-farm: Case studies from the genetic resources policy initiative. Routledge.

Walker, B., Salt, D. (2006). Resilience thinking: sustaining ecosystems and people in a changing world. Island Press.

Weitzman, M.L. (1992). On diversity. *Quarterly Journal of Economics*, 107 (2): 363–405.

Weitzman, M.L. (1993). What to preserve? An application of diversity theory to crane conservation. *The Quarterly Journal of Economics,* 108: 157–184.

Weitzman, M.L. (1998). The Noah's Ark problem. *Econometrica*, 66 (6): 1279–1298.

Winkler, R. (2011). Why do ICDPs fail?: The relationship between agriculture, hunting and ecotourism in wildlife conservation. *Resource and Energy Economics*, 33(1): 55-78.

Witcombe, J.R., Hollington, P.A., Howarth, C.J., Reader, S., Steele, K.A. (2008) Breeding for abiotic stresses for sustainable agriculture. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 363: 703–716.

Wollenweber, B., Porter, J.R., Schellberg, J. (2003). Lack of integration between extreme high-temperature events at vegetative and reproductive growth stages in wheat. *Journal of Agronomy and Crop Science*, 189: 142-150.

World Food Summit (1996). Rome Declaration on World Food Security, Rome.

WWF (2004). *How Effective are Protected Areas? Preliminary analysis of forest protected areas by WWF: The largest ever global assessment of protected area management effectiveness*. Report prepared for the Seventh Conference of the Parties of the Convention on Biological Diversity, February 2004, World Wide Fund for Nature (WWF), Gland, Switzerland.

Wunder, S. (2007). The efficiency of payments for environmental services in tropical conservation. *Conservation Biology,* 21(1): 48–58.

Wünscher, T., Engel, S. (2012). International payments for biodiversity services: Review and evaluation of conservation targeting approaches. *Biological Conservation*, 152: 222-230.

Appendix I

Table 8 - Skype interviews

Name	Affiliation	Crop	Expert capacity	Expert ca-
Agrawal, Shiv Kumar	ICARDA	Lentil	Breeder	Mar 7
Amri, Ahmed	ICARDA	Wheat, barley	Gene bank manager	Feb 27
Bonierbale, Meredith	CIP	Potato	Breeder	Mar 14
Braun, Hans-Joachim	CIMMYT	Wheat	Breeder	Feb 13
Dempewolf, Hannes	GCDT		Conservation	Mar 12
Deshpande, Santosh	ICRISAT		Genomics	Mar 10
Diederichsen, Axel	AAFC	Oat	Gene bank manager	Mar 20
Drucker, Adam	Bioversity Int'l		Conservation	Apr 9
Dulloo, Eshan	Bioversity Int'l		Conservation	Mar 27
Eastwood, Ruth	KEW		Conservation	Apr 28
Fatokun, Christian	IITA	Cowpea	Breeder	Mar 12
de Haan, Stef	CIP	Potato	Breeder	Mar 14
Hamwieh, Aladdin	ICARDA	Chickpea	Breeder	Mar 13
Hanson, Peter	AVRDC	Tomato	Breeder	Feb 20
Hearne, Sarah	CIMMYT	Maize		Mar 6
Hershey, Clair	CIAT	Cassava	Breeder	Mar 14
Hole, David	Conservation International		Conservation	Apr 24
Jackson, Scott	University of Georgia	Soybean	Breeder	Mar 26
Jena, Kshirod	IRRI	Rice	Breeder	Mar 27
Khoury, Colin	CIAT		Conservation	Feb 21
Lopez-Montes, Antonio	IITA	Yam	Breeder	Mar 5
Maalouf, Fouad	ICARDA	Bean	Breeder	Mar 13
Maxted, Nigel	University of Birmingham		Conservation	Apr 1
Mohamed Hassan, Abdalla	ICRISAT	Sorghum	Breeder	Apr 12
Ojulong, Henry	ICRISAT	Finger millet	Breeder	Mar 20
Sackville Hamilton, Ruaraidh	IRRI	Rice	Gene bank manager	Jun 27
Steffenson, Brian	University of Minnesota	Barley	Breeder	Apr 14
Swennen, Rony	IITA	Banana	Breeder	Feb 25

Table 8 - Skype interviews

Name	Affiliation	Crop	Expert capacity	Expert ca-
Tyack, Nik	Pier researcher		Conservation	Mar 19
Weltzien-Rattunde, Eva	ICRISAT	Sorghum	Breeder	Mar 12
Yencho, Craig	North Carolina State University	Sweet potato	Breeder	Mar 26

Table 9 - Email correspondences

Name	Affiliation	Crop	Expert capacity	Date (2014)
Agrama, Hesham	IITA	Soybean	Breeder	Mar 3
Banziger, Marianne	CIMMYT	Maize	Breeder	Feb 17
Hash, Tom	CIMMYT	Pearl millet	Breeder	Feb 27
Raatz, Bodo	CIAT	Bean	Breeder	Feb 17

Appendix II

I - General information

1. What is your current job title?
2. What is the focus on your current research?
3. Is breeding with crop wild relatives a significant part of your current research?

II - Quantitative data collection (CGIAR gene bank managers and breeders)

1. How many cultivars bred using wild species have been released from your centre since 2007?
    - Is this information well documented?
    - Is there a dataset of these varieties available?
    - Are there significant challenges in determining the genetic history of cultivars released, or other challenges that would limit quantitative data collection?
2. How many cultivars bred using wild species are currently in the pipeline?
    - How far along in the development process are these varieties, i.e., how close are they to being publicly released?
3. How many of these cultivars (both released and close to being released) have improved abiotic stress tolerances relevant to climate change introgressed from wild species, such as resistance to drought, soil salinity and extreme temperature variation?
4. How many of these cultivars (both released and close to being released) have other trait improvements introgressed from wild species, such as pest and disease resistance, other yield characteristics and other quality characteristics?

III - Qualitative data collection (CGIAR gene bank managers and breeders)

1. In your professional opinion, are crop wild relatives being used significantly more in breeding programs now than they were 5, 10, 20 years ago?
    - Is there a distinct trend in the use of wild species?
2. If there is an upward trend in the use, how has this been achieved?
    - Recent scientific advancements in the field of molecular biology?
    - Improved access to pre-breeding materials among public breeding centres?
    - Increased numbers of wild species accessions held in genebank facilities?
    - Increased funding for breeding with wild species for developing ‘climate ready’ crops?
    - Other important factors?
3. If there is no discernible trend in the use of wild species, why has more success not yet been achieved?
    - What are the prevailing constraints to using wild germplasm in crop improvement programs?
4. In your professional opinion, has there been a notable change in the *types of traits* borrowed from crop wild relatives, i.e. the numbers of cultivars released with im-

proved yield, improved quality characteristics, environmental stress tolerance, pest and disease resistance and other traits borrowed from wild species?

- Has the greater push to develop ‘climate ready’ crops resulted in the release of more cultivars with improved tolerance to drought conditions, soil salinity or extreme temperature variation?

IV - Implications for conservation (Conservationists)

1. Are CWR are being used more in breeding programs (trends), and why (scientific advancements; improved accessibility to pre-breeding materials, increased number of wild accessions held in genebanks, increased funding for breeding with wild species, etc.)?
2. The impact of the climate change mitigation discourse employed by conservationists to justify wild species conservation;
3. Potential implications of increased use in wild species status in conservation planning and increased investment in genetic diversity conservation (*in situ* and *ex situ)*;
4. Potential for wild species’ inclusion in market-based mechanisms for biodiversity conservation;
5. Potential positive implications of the value of wild species being more widely recognised (ex. increased conservation investment internationally);
6. Potential negative implications of the value of wild species being more widely recognised (social and ecological concerns relating to payment for ecosystem services schemes such as REDD/REDD+, indigenous rights to plant genetic resources, threats to biocultural heritage, etc.) Language used tailored to specific expertise of contact;
7. Any knowledge of pilot projects, past or present, providing economic incentives to landowners within agricultural biodiversity hotspots / centres of origin, i.e. areas with the highest concentrations of crop wild relative diversity.