Estimating in situ conservation costs of Zambian crop wild relatives under alternative conservation goals

Citation for published version:
Wainwright, W, Drucker, AG, Maxted, N, Brehm, JM, Ng'uni, D & Moran, D 2019, 'Estimating in situ conservation costs of Zambian crop wild relatives under alternative conservation goals', *Land Use Policy*, vol. 81, pp. 632-643. https://doi.org/10.1016/j.landusepol.2018.11.033

Digital Object Identifier (DOI):
10.1016/j.landusepol.2018.11.033

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Land Use Policy

Estimating *in situ* conservation costs of Zambian crop wild relatives under alternative conservation goals

Keywords: Crop wild relatives; Zambia; competitive tender; binary linear programming; payments for ecosystem services; social equity; payments for agrobiodiversity conservation services

Abstract

Crop wild relatives (CWR) are a globally threatened group of plants, harbouring valuable genes that are sometimes used to enhance commercial crop varieties and landraces. A lack of recognition in national planning for biodiversity conservation has resulted in inadequate CWR conservation strategies, particularly *in situ*. There is little information on *in situ* conservation costs, and this paper uses a payment for agrobiodiversity conservation services (PACS) approach to estimate the *in situ* costs of conserving CWR in Zambia, where 30 CWR have been prioritised for conservation (of which nine are present in our sample). Competitive tender bid offers were elicited from farmers willing to accept compensation for providing a CWR conservation service. Using data from 26 communities we determined the on-farm cost of conserving CWR, specifically in field margins/borders. Heterogeneity was evident in farmer bid offers, suggesting discriminatory price mechanisms can potentially deliver cost savings over uniform payment rules. Selection of bid offers under four different conservation goals using a binary linear programming (BLP) model reveals conservation costs ranging from US$ 23 to 91/ha per year. An untargeted area goal provided a least-cost procurement of conservation services ($ 2.3 k per year), followed by a targeted area goal ($ 5.9 k per year). The cost of selecting conservation sites increased when other constraints were added to the BLP model, including those concerning social equity ($ 6.4 k per year), and diversity ($ 9.2 k per year) goals. Overall, the findings suggest the use of competitive tenders, coupled with CWR data and BLP modelling, can potentially add much to improve the efficiency of *in situ* CWR conservation.

1. Introduction

Population growth and changing diets are expected to increase food demand above projected crop yield gains (Ray et al., 2013; Seto and Ramankutty, 2016). Climate change may reduce agricultural production by 2% each decade (Pachauri et al., 2014), yet demand for agricultural products is expected to increase by 50% between 2012 and 2050 (FAO, 2017). Advances in genotyping technologies and plant breeding to meet yield improvement goals offer one approach to increase global production using fewer inputs (Tester and Langridge, 2010). Such advances have increased the potential for using exotic genetic material, thereby heightening the importance of conserving and using CWR to deliver yield improvements, whilst also enhancing adaptive traits in crops (Dhariwal and Laroche, 2017). In this context, crop wild relatives (CWR), that is, the wild plant species that are genetically closely related to cultivated crops (Maxted et al., 2006) are an increasingly important genetic resource (Zhang et al., 2017). They have provided cultivars with pest and disease resistance, heat and drought tolerance, tolerance of salinity and abiotic stresses, and enhanced nutritional quality (Hajjar and Hodgkin, 2007; Maxted and Kell, 2009; Dempewolf et al., 2014).

Wild relatives are estimated to contribute US$ 120 billion to increased crop productivity per annum (PriceWaterhouseCoopers, 2013). Despite their importance, CWR have been depleted by agricultural intensification, habitat destruction and a range of other threats including land-use change (Kell et al., 2011). They are known to be a globally threatened group of plant species and efforts to improve conservation are therefore warranted to reduce further loss of diversity (Maxted et al., 2010).

CWR resources are sometimes found in disturbed anthropogenic habitats, e.g. around farms, which should be the focus of some conservation effort (Maxted et al., 2000). Moreover, there is no information on the costs of *in situ* CWR conservation at multiple scales, including the farm level. This constrains our understanding of farmers’ willingness to accept (WTA) conservation incentives and ultimately appreciation for heterogeneity in the per unit cost of selecting conservation service providers. This study seeks to demonstrate how the costs of conserving CWR *in situ* (through a measure that restricts farm activities in field margins) can be measured and analysed using a Zambian case study. The paper adds to the literature on the economics of *in situ* plant genetic resources (PGR) conservation and to the growing body of work addressing development of payment for ecosystem services (PES) schemes in developing countries, particularly payment for agrobiodiversity conservation services (PACS) (Narloch et al., 2011a, 2011b, 2013; Krishna et al., 2013). It makes a further contribution by considering distributional aspects of PES (e.g. social equity).

The paper is structured as follows. Section two provides background relating to CWR in Zambia, the use of incentives, conservation tenders and site selection models. Section three describes the research sites and outlines the methodological and modelling approach used. Section four provides an overview of the results and a discussion of these follows in section five, with the identification of further work necessary to improve future cost estimates. Section six presents conclusions.

2. Background

2.1 CWR conservation in Zambia

Zambia was chosen for this case study given its participation within a wider project in the South African Development Community (SADC) addressing *in situ* conservation and use of CWR (http://www.cropwildrelatives.org/sadc-cwr-project/). A previous exercise (see Ministry of Agriculture, 2016) identified 30 priority CWR species in Zambia for conservation to address food security. Using a sub-set of this priority list (see S1 for case study CWR species), we examine the cost of selecting farmer managed sites for conservation containing priority CWR. The nine CWR species were selected based on their verified presence in the sampling frame for the economic surveys. The need to conserve is driven by threats posed to CWR in sub-Saharan Africa primarily from climate change (Jarvis et al., 2008; Maxted and Kell, 2009) and land use change, including intensification of farming practices and alien invasive species (Burgess et al., 2006; Ford-Lloyd et al., 2011)

2.2 Payment for ecosystem services (PES) and competitive tender auctions

PES has emerged as a key voluntary incentive mechanism to reduce biodiversity loss by paying landowners for actions that sustain or enhance ecosystems (Börner et al., 2017). The introduction of PES type schemes for agrobiodiversity conservation has been limited but a growing body of work suggests this is becoming more widely applied, including in Bolivia, Peru, Ecuador, Guatemala and India (Narloch et al., 2011a, 2011b; Krishna et al., 2013; Midler et al., 2015; Drucker et al., 2017). This work provides an application of PES that compensates farmers for conserving CWR in field borders. A hypothetical competitive tender (CT) survey measured farmer WTA monetary rewards for conservation effort. CTs are a reverse auction mechanism, whereby agents submit a bid offer for a pre-defined conservation contract supplying, in this instance, CWR conservation services.

Relative to fixed price approaches CTs are incentive compatible in allowing participants to reveal their true opportunity costs (Stoneham et al., 2003), which is likely to include both market and non-market values and preferences. This allows identification of least-cost suppliers through the formulation of cost curves that reveal differences in agents' opportunity costs. CT mechanisms have been used to determine the costs of agrobiodiversity conservation (e.g. Bertke and Marggraf, 2005; Narloch et al., 2011a) though none have been applied to the case of CWR.

2.3 Binary linear programming (BLP)

This work combines CT cost elicitation with BLP modelling to optimise selection of farmer sites for CWR conservation under alternative conservation goals. BLP is a calculation process that finds the optimal solution to a problem with multiple attributes and constraints using a branch and bound algorithm (Messer, 2006). Many reserve selection problems are formulated as BLP problems because site selection decisions can be modelled with binary variables [0,1] which reflects the yes/no decision-making context associated with site selection (Beyer et al., 2016). Much previous work in reserve site selection has sought to solve the problem of maximising the expected number of species included in a reserve network subject to a restriction on network size or cost (Donaldson et al., 2017). BLP takes into account the benefits and costs of each site and evaluates all possible purchase combinations of sites, selecting sites that yield the highest possible aggregate conservation value (Williams et al., 2005). BLP thus facilitates determination of least-cost suppliers of conservation services under various objective functions (Haight and Snyder, 2009).

3. Methods

3.1 The study sites

The study regions were selected based on a review of records of populations for all 30 priority CWR species (held by the Zambia Agriculture Research Institute (ZARI)) (Ng'uni et al., 2016). After assessment of occurrence records we identified two study areas likely to contain the highest distribution of priority CWR species; Eastern Province and Northern Province (Figure 1). Historical records (obtained from herbarium collections varying in date) in these areas included wild relatives of melon and cucumber (*Cucumis* spp.), yams (*Dioscorea* spp.*)*, millets (*Echinochloa* spp.*, Eleusine* spp., *Pennisetum* spp.), sweet potato (*Ipomoea* spp.*)*, rice (*Oryza* spp.), eggplant (*Solanum* spp.), sorghum (*Sorghum* spp.), and cowpea (*Vigna* spp.) (Ng'uni et al., 2017).

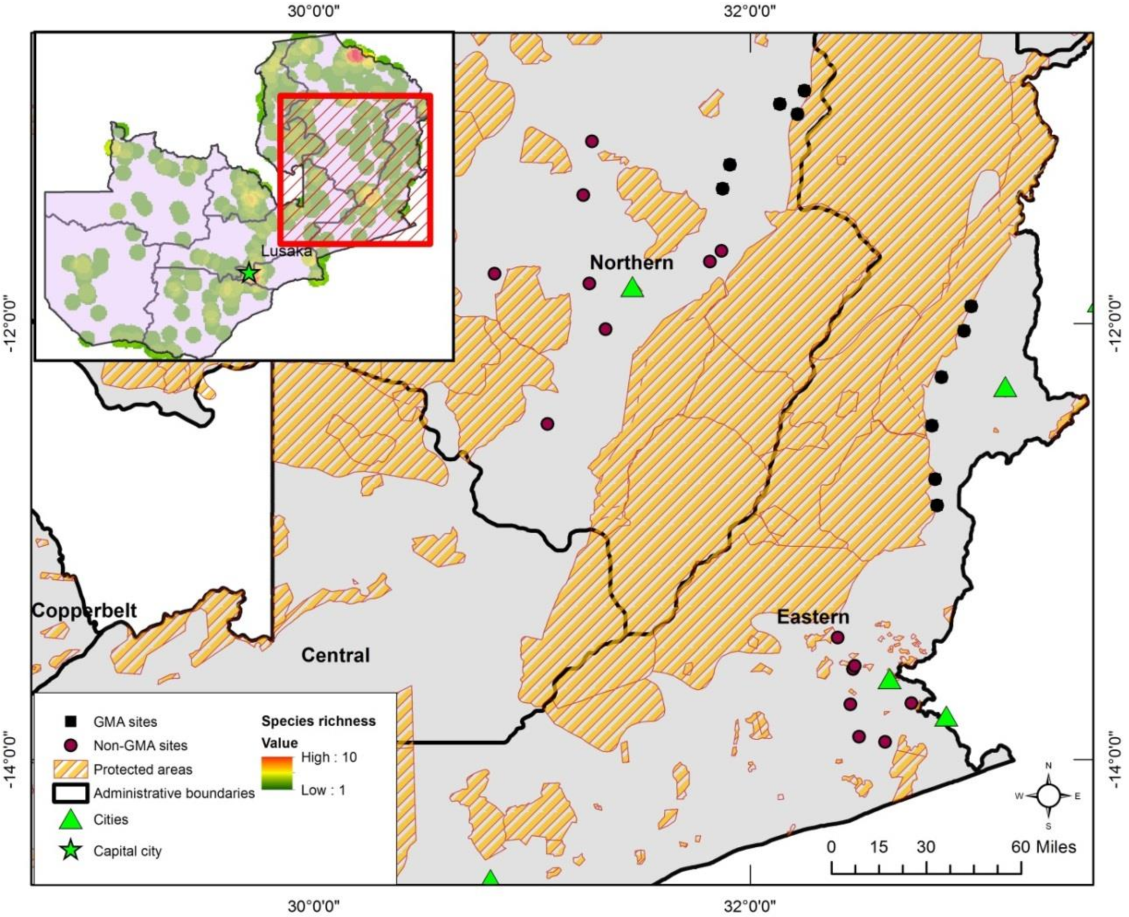
Eastern Province (herein referred to as Ecoregion 1[1]) has a population of 1.3 million and a land area of 51,476 km^2 (Ministry of Local Government and Housing, 2017). The province houses Zambia's most fertile land and consequently the majority of the country's large-scale commercial farms (Chikowo, 2018). The province has a higher human population and lower land availability than other areas in Zambia resulting in the application of more intensive farming practices that are impacting biodiversity (Eroarome, 2009). Northern Province (herein referred to as Ecoregion 2) occupies a land area of 87,806 km^2 and with a population of 712,000 people is sparsely populated

---

[1] Ecoregions were subsequently used in the site selection model outlined further in Section 3.6.

(Zamstats, 2010). The province sits on the Muchinga Escarpment and is characterised by large tracts of miombo woodland with predominantly small-scale agriculture. Land is relatively abundant and shifting cultivation (slash and burn) was widespread until recently (Grogan et al., 2013).

The areas selected for the CT exercise (within the study regions) were communities far from Game Management Areas[2] (herein referred to as 'non-GMA' sites) and communities adjacent to Game Management Areas (herein referred to as 'GMA' sites). People in GMAs are generally poorer and less educated than the national average, and these areas are associated with lower agricultural potential and fewer alternative livelihood opportunities (Manning, 2011). By contrast, non-GMA sites were considered better-off, with improved access to economic infrastructure. In both areas, agricultural production plays a crucial role in farmer livelihoods. An optimal conservation strategy may specify a combination of sites across both areas to ensure a diverse ecogeographic range of plant populations (e.g. those with restricted ranges and sub-populations) are captured for conservation (Rodrigues et al., 2004). Additionally, conservation in GMAs may enhance gene flow and dispersal from protected areas (PAs) whilst non-GMA sites may provide sanctuaries for species establishment outside formal designations. Both areas are therefore desirable for CWR conservation.



---

[2] Game Management Areas are transitional zones that serve as protected areas (Pas) for the management of wildlife adjacent to national parks.

Figure 1: Map of sample sites detailing protected areas (PAs). Inset map shows the location of the sample area (red hatch) and species richness of all 30 priority CWR species (red areas are CWR hotspots). Source data (Ng'uni et al., 2016).

3.2 Focus group discussions

Focus group discussions (FGDs) were held in selected farming communities and participants were invited by agricultural extension officers that regularly engage with community groups. Five FGDs were conducted with 10–15 participants in each encompassing a mix of genders, age groups, and wealth status. The FGDs sought to understand the degree of recognition of CWR within communities, CWR status and conservation management and community farm management practices. Specific activities (and associated costs, as perceived by community members) that would need to be implemented in order to attain a desirable (as determined by a conservation programme) level of CWR conservation management were discussed. Further information concerning the focus group discussions and cost estimates related to local farming practices and conservation activities are provided in S2.

3.3 Competitive tender design

Data from the FGDs and expert consultation informed the design of the area management option that would underpin the hypothetical tender. Expert consultation suggested that the tender should support CWR interventions through habitat-based conservation measures in field borders/margins – a habitat that has been shown to support CWR (Meilleur and Hodgkin, 2004; Maxted and Kell, 2009; Jarvis et al., 2015).

The area management option prohibited application of herbicides within 3m of the field perimeter or on the field border, and the field border was to be left undisturbed for the duration of the scheme. These activities are most likely to benefit CWR that may inhabit field borders as weeds (Jarvis et al., 2015). In addition, bids were also accepted for conservation in crop fields and on communal land areas but are beyond the scope of analysis of the current paper. The tender required farmers to detail the number of land plots and total area (in local land units) that they would be willing to enrol in the conservation programme, along with a monetary bid for providing the associated conservation service per annum. Additional information collected included gender, age and farm size (a proxy for wealth).

3.4 Competitive tender workshops

Farmers were invited to take part in the tenders by agricultural extension officers. Tender workshops were held at 26 different communities between April and May 2016, with a total attendance of 358 participants. This corresponded to 11 community GMA sites and 15 community non-GMA sites. The workshops used a format similar to the FGDs.

The first section of the workshop ‘Existence and Management’ prompted farmers to consider where CWR occur on their communal and farmed lands. Participants were asked to identify a set of CWR from photographs and describe where these occurred (if at all) on communal or farmed land. Respondents were then asked to consider how these might be managed and the implications of this management. The next section ‘Conservation Management’ asked farmers what activities might be required (on an annual basis) to maintain CWR on farmed lands, such as seed collecting, late burning of fields, selective weeding and training. The cost implications of these activities were discussed.

Next, a CT training exercise facilitated discussion and learning among the farmer groups regarding how a CT works in practice and what the rules and selection criteria of this particular tender were. For instance, the competitive nature of the tender was emphasised alongside other variables (not conveyed to participants) that would be considered in the selection process. All farmers were encouraged to participate in the exercise, including those not present at the workshops. An example of the CT bid offer form was then completed with participants, after which the actual bid offer forms were distributed and collected some days later to allow farmers time to deliberate.

3.5 CWR surveys

Alongside the CT workshops, 26 simple line transect surveys (Buckland et al., 2007) were undertaken at randomly selected communities in both the Eastern and Northern provinces. The aim was to develop a better understanding of CWR abundance and species richness across different community and farmer sites. A 100 meter line walking transect was undertaken through different habitats at selected communities. The habitats consisted of field borders, croplands and communal bush land. A ZARI staff member walking the transects identified most of the CWR found. Any CWR not identified on-site were photographed and reviewed later. These survey data was subsequently used, in conjunction with occurrence data obtained from Dickson et al. (2016) in the site selection model.

3.6 Site selection model

The model focuses on optimizing decisions for CWR conservation site selection while minimising cost subject to area, diversity and social equity constraints. The model accounts for a basic requirement to conserve at least 50 ha of field borders in each ecoregion, an area considered capable of capturing safe minimum populations for a range of CWR diversity (Maxted et al., 2008). The model was implemented in OpenSolver for MS Excel 2010 using a branch-and-bound procedure with the Simplex algorithm (Mason, 2012).

Initially, an untargeted area goal was developed to represent a simple method of site selection, based on procuring conservation sites at minimum cost, subject to the minimum area requirement per ecoregion. Three further conservation goals (different versions of the model) were then constructed: (i) a targeted area goal that uses a minimum CWR selection constraint[3] (ii) a social equity goal that ensures socially vulnerable groups are well represented and; (iii) a diversity goal that maximises the likelihood of capturing greater CWR diversity and species richness (Figure 2). Here, species richness refers to the number of priority CWR species (from the sub-list of nine CWR species) inhabiting each site.

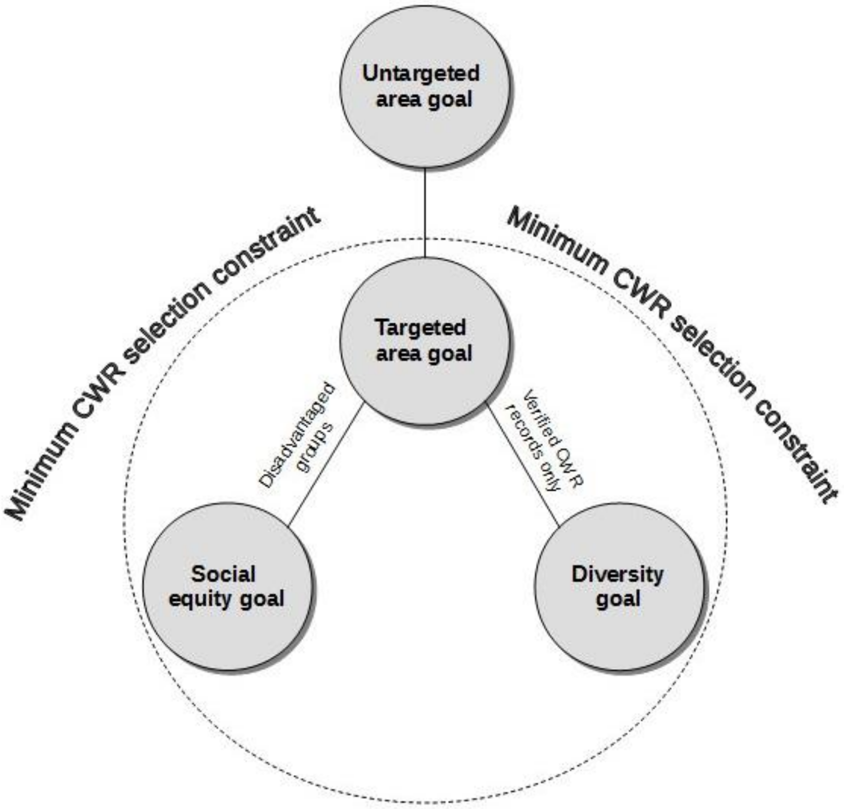


Figure 2: Schematic diagram of the different model goals

---

[3] The minimum CWR selection constraint ensures that each CWR is conserved in at least three different community sites per ecoregion and 5 farmer sub-sites per community, wherever possible.

Bid offers were selected using a discriminatory payment rule (Wünscher and Wunder, 2017), with a view to improving cost-effectiveness relative to using a uniform payment rule (Windle and Rolfe, 2008). For the untargeted area goal, the objective function (1.1) was to minimise the cost of selecting farmer sites for conservation, subject to a constraint (1.2) concerning the minimum area (50 ha) to be procured for conservation services from each ecoregion. The model notation is:

$$\boldsymbol{Min\ Z} = \sum_{\boldsymbol{i \in I}} \boldsymbol{c_i x_i} \tag{1.1}$$

Subject to

$$\sum_{i \in I} a_i e_i x_i \ \geq 50\ ha \tag{1.2}$$

$$\boldsymbol{x_i} \ \in \ \{\boldsymbol{0, 1}\} \qquad \textbf{for all i } \in \textbf{I} \tag{1.3}$$

Where a_i refers to the conservation area associated with site *i*, where $i \in I = \{1,2\ldots,448\}$, e_i is a binary variable that indicates whether site *i* is located in either ecoregion 1 or 2. The ecoregions were categorised based on a data set obtained from WWF (2004) and original work by Olson et al., (2001). The binary decision variable $X_i = \{0,1\}$ is used to determine selection of the parcels; 1 if the *ith* parcel is selected, 0 otherwise.

A set of additional constraints in the targeted goal (2.1) ensures that each priority CWR from the sub-set list[4] is conserved in at least three different community sites per ecoregion and five farmer sub-sites per community, wherever possible[5] (note not all CWR species were present at both ecoregions). Ideally, this genetic reserve design structure would be replicated across five distinct ecogeographic zones (Maxted et al., 2008) although data were only available for two (Ecoregion 1 and 2). The additional constraints are summarised below:

$$\text{for all n } \in \text{N} \quad \sum_{i \in I} n_i\, e_i\, d_i\, x_i \ \geq 3\, d_i\, x_i\ + 5\, f_i\, x_i \tag{2.1}$$

---

[4] A list of the priority CWR verified to be present at the sample sites and used in the modelling exercise is provided in S1.

[5] The proposed conservation design structure ensures CWR are conserved at different sub-plots per community (i.e. different farmers lands in each community) and per ecoregion, to capture different meta-populations and changes in local ecological conditions. Given limitations concerning the extent of our tender surveys, conservation to these requirements was not feasible for all CWR in the model.

$$\sum_{i \in I} m_i x_i \geq 0.4 \sum x_i \tag{3.1}$$

$$\sum_{i \in I} p_i x_i \geq 0.3 \sum x_i \tag{3.2}$$

$$\sum_{i \in I} v_i x_i = \sum x_i \tag{3.3}$$

$$\sum_{i \in I} q_i s_i y_i g_i x_i \geq 0.5 \sum x_i \tag{4.1}$$

The diversity goal (equations 3.1, 3.2 and 3.3) employs the same constraints as the targeted area goal plus ensures CWR should be conserved in GMA sites at least 40% of the time. This is to facilitate active management of CWR in areas close to PAs. An additional constraint (3.2) specifies at least 30 % of sites selected contain plots that are ≥ 0.8 ha in size (based on an assumption that larger sites are better suited to maintaining species and population genetic diversity) (Lindenmayer and Burgman, 2005). All sites selected (3.3) should have verified CWR populations present[6].

The social equity goal (equation 4.1) employs the same constraints as the targeted area goal plus ensures that vulnerable groups, such as women, younger farmers and the poor have a minimum representation of 50% across the total selected conservation area. The social equity parameters specifically relate to the following:

- Number of female farmers, recognising the important role women play in the management of genetic resources (Escobar et al., 2017) as well as women's empowerment being considered a prerequisite for global food security (Quisumbing et al., 2014).
- Number of farmers aged ≤ 35 years of age. This contributes to the objective of motivating younger farmers to remain in farming – where the average age of farmers in Zambia is increasing (Brooks et al., 2013).
- Number of farms ≤ 2 hectares in size (a proxy for poorer farmers).
- Number of sites that are located in GMA areas, where the population may be up to 30% poorer than the national average (World Bank, 2007).

---

[6] Note, the presence of CWR at all farmer sites had not been directly verified by botanical surveys or species occurrence records held by ZARI. Thus, procuring conservation sites solely based on farmer identification of CWR provides less certainty of ensuing the presence of CWR, despite training received at the project workshops.

A description of the decision variables and parameters is provided in Table 1.

Table 1: Description of model parameters and associated notation used for different model goals

Notation	Parameter description
	Decision variable
x_i	[0,1] variable, 1 if site i is selected for conservation services from I index of all sites, 0 otherwise (unknown)
	Untargeted area model
a_i	area (ha) associated with site *i* from index *I* of potential sites for conservation services
c_i	the cost of selecting site *i* for conservation services
e_i	[0,1] parameter: 1 if site i is located in ecoregion 1, 0 otherwise
Z	objective function value (unknown)
	Targeted area goal
d_i	community corresponding to farmer *f* at site *i* from index D of all communities
f_i	farmer *f* corresponding to site *i* from index *F* of all farmers
n_i	[0,1] parameter: 1 if site i is associated with species *n* from index *N* of all species, 0 otherwise
	Social equity goal
g_i	[0,1] parameter: 1 if site i is located in a GMA area 1, 0 otherwise
q_i	[0,1] parameter: 1 if farmer *f* is female, 0 otherwise
s_i	[0,1] parameter: 1 if the size of farm i is ≥ 2 hectares, 0 otherwise
v_i	[0,1] parameter: 1 if farmer *f* is <35 years old, 0 otherwise
	Diversity goal
m_i	[0,1] parameter: 1 if site i is located in a GMA area 1, 0 otherwise
p_i	[0,1] parameter: 1 if plot *p* associated with site i is >0.8 ha in size, 0 otherwise
v_i	[0,1] parameter: 1 if site i contains verified priority CWR, 0 otherwise

4. Results

4.1 Summary statistics and bid offers

A total of 132 male and 88 female farmers submitted bid offers at non-GMA sites; whilst 170 male and 58 female farmers submitted offers at GMA sites across the 26 communities visited. Bid offers totalled $110,154 (USD) and encompassed 632 hectares. A significant difference between GMA and non-GMA sites was found for a range of variables, using a two sample t-test (Table 2). The GMA sites had smaller farms and their socio-economic status index score[7] was lower, suggesting this group of farmers are indeed generally poorer. Mean number of plots included in bid offers at GMA sites and the mean size of plots was higher than non-GMA sites, suggesting such farmers were willing

---

[7] This refers to the FAO Richness Index (UN FAO, 2010) and represents the level of economic wellbeing associated with regions across Africa in 2010. This is measured from categories one (poorest areas) to six (wealthiest areas).

to enrol significantly more land. Bid offers at GMA sites were significantly higher in total, as well as per ha and per plot. No significant differences were found for age of famers and the proportion of lands enrolled. Additionally, bid offers were disaggregated by gender and age. Analysis by gender reveals a significant difference for total bid offer and bid offer per plot but not for bid offer per ha. For age, no significant differences were noted.

Table 2: Summary of descriptive statistics and t-tests for multiple parameters associated with farmer bid offers from GMA and non-GMA sites plus disaggregation by farmer gender and age.

	Mean	*Std*	*Mean*	*Std*	*T*wo sample *t*-test	
Variables	GMA		non-GMA		Obs	P value
Socio-economic status index[7]	4.4	1.0	4.9	0.8	427	***
Farm size (ha)	4.0	4.1	9.9	21.7	211	***
Age	42.4	12.0	43.2	12.5	422	ns
Number of plots bid	2.4	1.8	2.0	1.7	394	**
Average size of plot (ha)	1.0	1.2	0.3	0.3	216	***
Area bid (ha)	2.2	2.8	0.7	0.6	252	***
Proportion of land (%)	30.9	20.7	28.8	18.9	420	ns
Bid offer (USD)	396.7	560.1	96.5	73.3	237	***
Bid offer (USD per ha)	304.5	360.4	193.5	144.9	308	***
Bid offer (USD per plot)	213.0	205.3	64.2	56.1	223	***
	Male		Female			
Bid offer (USD)	302.6	506.3	160.1	209.0	421	***
Bid offer (USD per ha)	261.5	307.5	234.3	235.7	427	ns
Bid offer (USD per plot)	152.2	180.0	105.4	129.3	312	**
	Older farmers		Younger farmers			
Bid offer (USD)	263	475.3	240.1	320.6	427	ns
Bid offer (USD per ha)	241.8	268.3	282	329.5	177	ns
Bid offer (USD per plot)	129	158.2	163.3	188.8	155	ns

Note: 'Std' = standard deviation, 'Obs' = observations. *** = P<0.01, ** = P<0.05, NS = not significant. Welch's t-test was used where Fisher's F-test indicated heteroscedasticity (unequal variance).

A correlation matrix reports the strength and direction of relationships between variables that may explain bid offer characteristics (Figure 3). Price/ha is negatively correlated with plots, area (ha) and proportion of land enrolled in the tender, suggesting as area, plots and the proportion of farmer lands in bid offers increases, so the price/ha of bid offers decreases. Bid offer is positively correlated with area and, to a lesser extent plots, suggesting higher bid offers are likely to contain more area and plots. Price is positively correlated with GMA, suggesting GMA areas resulted in higher bid offers. The proportion of land enrolled was negatively correlated (albeit weakly) with age, suggesting older farmers were willing to enrol proportionately less of their farms. Farm size was negatively correlated with GMA and ecoregion 1, as might be expected given that these areas house smaller farms. Finally, plots were positively correlated with area, suggesting as the number of plots included increases, so the area enrolled also increases.

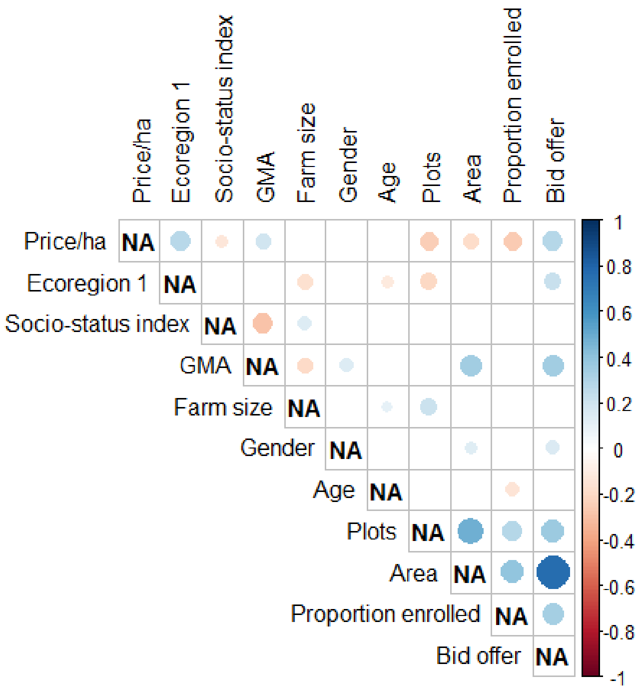


Figure 3: Correlation matrix demonstrating strength and direction of correlation for multiple explanatory variables for farmer bid offers. All populated variable cells were significant (P <0.05) in the analysis. Positive correlations are displayed in red, negative in blue. Colour intensity and the size of the circle are proportional to the correlation coefficients. For a full description of the variables, see S3.

4.2 Site selection under multiple conservation goals

The construction of a supply curve allows the marginal cost for procuring an additional unit of conservation area to be estimated (Figure 4). The different model goals are shown through the varying supply curves, all of which are non-linear (i.e. price increments to procure more area vary along the curves). The supply curves show the minimum bid offer values to achieve a desired conservation area under the different selection goals. The untargeted area goal provided least-cost selection of conservation sites, followed by the targeted area and equity goals while the diversity goal was most expensive. The trade-offs between the different goals become more pronounced as selection of bid offers continues up the supply curve.

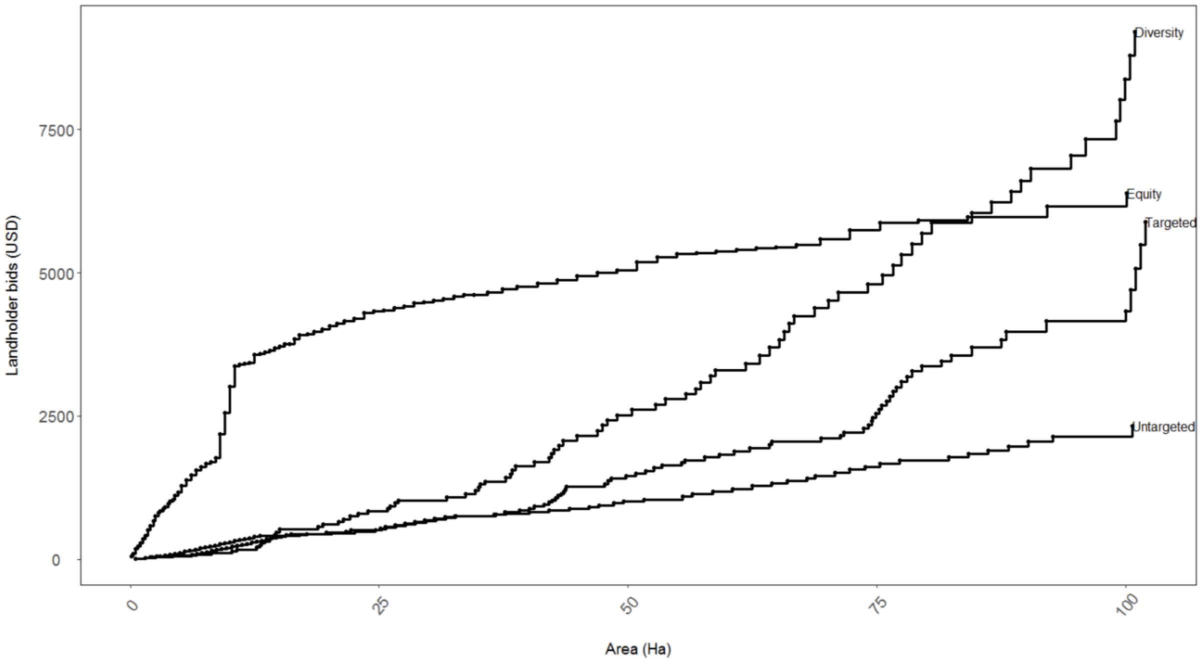


Figure 4: Supply curve of farmer bid offers (USD per annum) and area (ha) procured for conservation under the different conservation goals.

A range of diversity and social equity parameters varied depending on the goal employed (i.e. no. of younger farmers, no. larger plots, no. of female farmers, no. of GMA sites, no. of small farms and no. of communities). The untargeted area goal includes the highest proportion of larger plots of any goal, suggesting some farms with larger plots also sell cheapest (Figure 5). The targeted area goal selects more communities, verified CWR sites and female farmers relative to the untargeted goal. The diversity goal selected the highest proportion of sites with verified CWR records though not the highest number of larger plots. The social equity goal selected a higher proportion of younger farmers, female farmers, GMA sites and communities but with less emphasis on selecting sites with verified CWR.

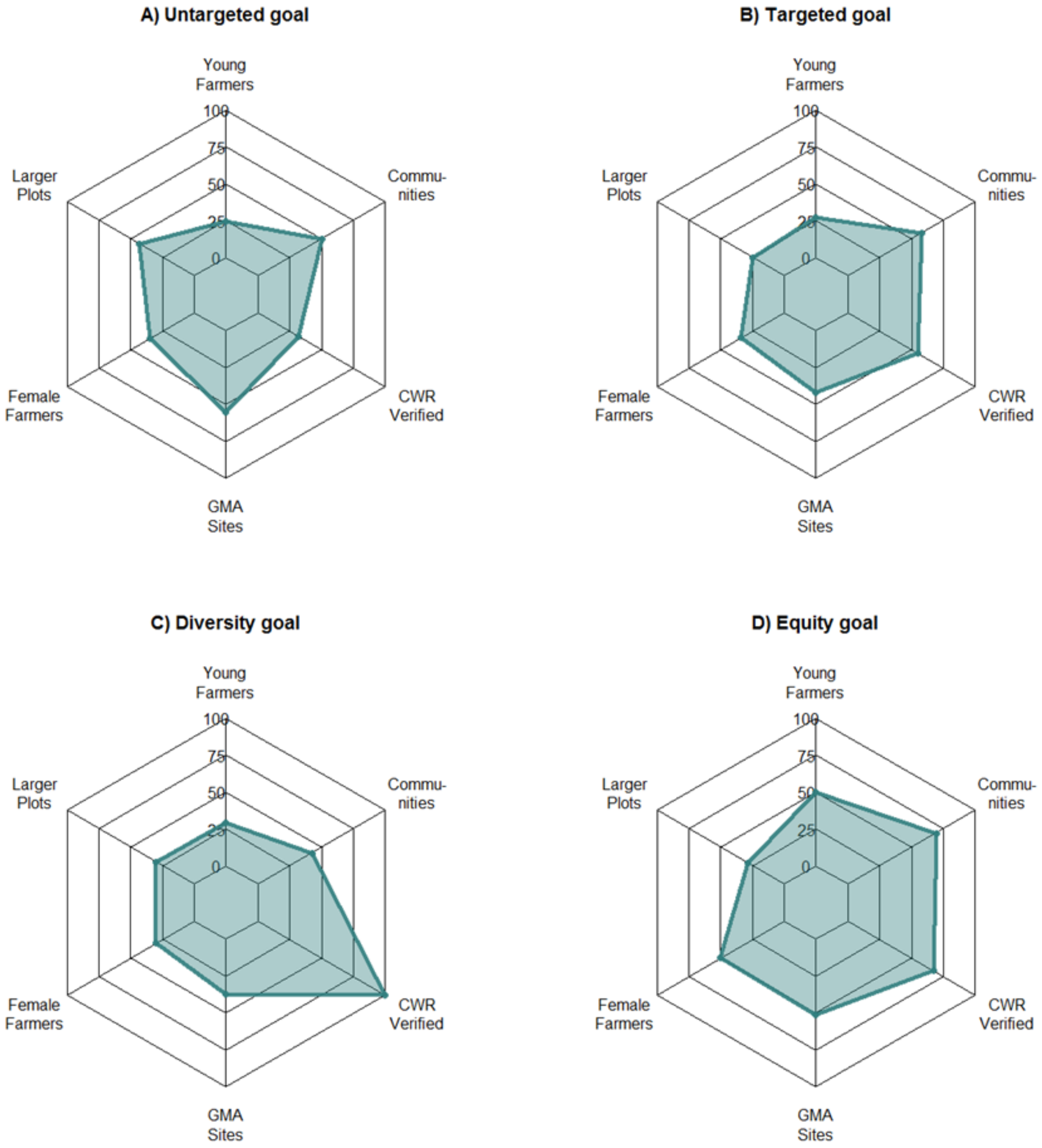


Figure 5: Panel of radar plots corresponding to farmer selection under the ‘untargeted area’, ‘targeted area’, ‘diversity’ and ‘equity’ goals. The 0–100 scale shows the proportion (%) of each parameter in site selection under the different goals.

Overall, the untargeted area goal provided least-cost procurement of conservation services ($2.3 k), followed by targeted area ($5.9 k), social equity ($6.4k) and diversity ($ 9.2k) goals (Table 3). Compared to using a uniform payment rule[8], the various model goals provided cost reductions of 87%, 66%, 63% and 48% per hectare, respectively; although these cost reductions would be reduced the further along the supply curve bid offers were selected. The equity goal selected the most GMA sites (45), female farmers (44), smaller farms (45) and young farmers (44) of all the model goals. The social equity goal therefore provides a basis to improve social equity outcomes but also has the

---

[8] The uniform payment was calculated as the average price per hectare across all bid offers.

second highest cost. Compared to the most expensive goal (diversity), social equity costs $27/ha or $2.8k per annum less. The diversity goal selected the largest farms and had a mean species richness of 2.66 – the highest species richness of any model goal. The cost per unit species richness[9] ranged from between $3k (untargeted area) to $4.4 k (targeted area) under all model goals. In terms of per unit of species richness, the diversity goal was 18% cheaper than the equity goal.

The targeted area goal selected the most non-GMA and ecoregion 1 sites. Non-GMA sites are associated with lower bid offers (on average) than GMA sites; hence their selection. In addition, the targeted area goal procured more plots than any other selection goal (192) and these plots were on-average 17% smaller than for the untargeted and social equity goal – reporting the highest mean plot size. The untargeted area goal was 75% cheaper on a per hectare basis than the most expensive goal (diversity). If expenditure under the targeted area goal mirrored that of the social equity goal then a further 20% of conservation area, or 17% more sites, could be procured. Similarly, trade-offs between the diversity and equity goal suggest the latter could conserve an additional 50% more conservation area or 40% more sites (with mirrored budgets) but with a 48% reduction in species richness across sites (i.e. the selected sites contained less priority CWR).

Table 3: Summary of parameters associated with individual farmer bid offer selection under different model goals

Parameter	**Untargeted**	**Targeted**	**Equity**	**Diversity**
Cost per hectare (ha)	23	58	64	91
Total GMA sites	38	40	45	27
Total non-GMA sites	31	56	43	59
Total ecoregion 1 sites	23	59	50	44
Total ecoregion 2 sites	46	37	38	42
Total farmers	69	96	88	86
Total female farmers	24	33	44	26
Total young farmers	17	26	44	25
Mean farm size (ha)	5	8	8	11
Total smaller farms (< 2 ha)	31	43	45	27
Total number of plots	156	192	166	162
Mean plot size (ha)	0.64	0.53	0.64	0.62
Total large plots (≥ 0.8 ha)	30	24	25	26
Total communities	13	15	18	12
Mean CWR species richness[1]	0.77	1.34	1.51	2.66
Cost per unit (USD) species richness	$ 3,022	$ 4,398	$ 4,232	$ 3,461

---

[9] A unit cost of species richness is taken by dividing the mean species richness (i.e. mean number of priority CWR from the sub-list present at each site) by the total cost for each selection goal.

Total area (ha)[2]	**100**	**101**	**100**	**101**
Total Cost (USD per annum)	$ 2,327	$ 5,893	$ 6,390	$ 9,206

[1]Mean species richness was calculated based on the number of verified CWR species records (from the sub-set list of nine CWR species) associated with each site selected under that specific selection goal. [2]The model goals were constrained to select between 50 and 51 ha per ecoregion, to allow adequate flexibility to meet all other constraints in the model.

4.3 CWR conservation outcomes

An upward sloping supply curve reveals different cost estimates for procuring conservation land for each of the nine priority CWR species[10] (Figure 6). While the supply curve does not consider overlap in species richness, it is clear sites with higher species diversity would result in lower cost per CWR. Five wild relatives have relatively comparable supply curves: *Vigna dekindtiana*, *Sorghum bicolor*, *Eleusine indica*, *E. coracana* and *Solanum incanum*. The most abundantly conserved CWR by area was *E. coracana* (54 ha) and the least conserved CWR was *Cucumis zeyheri* (3 ha). The rarer CWR tend to feature in less conservation sites and are therefore conserved across less area, suggesting the need for a more targeted approach to capture rare species adequately.

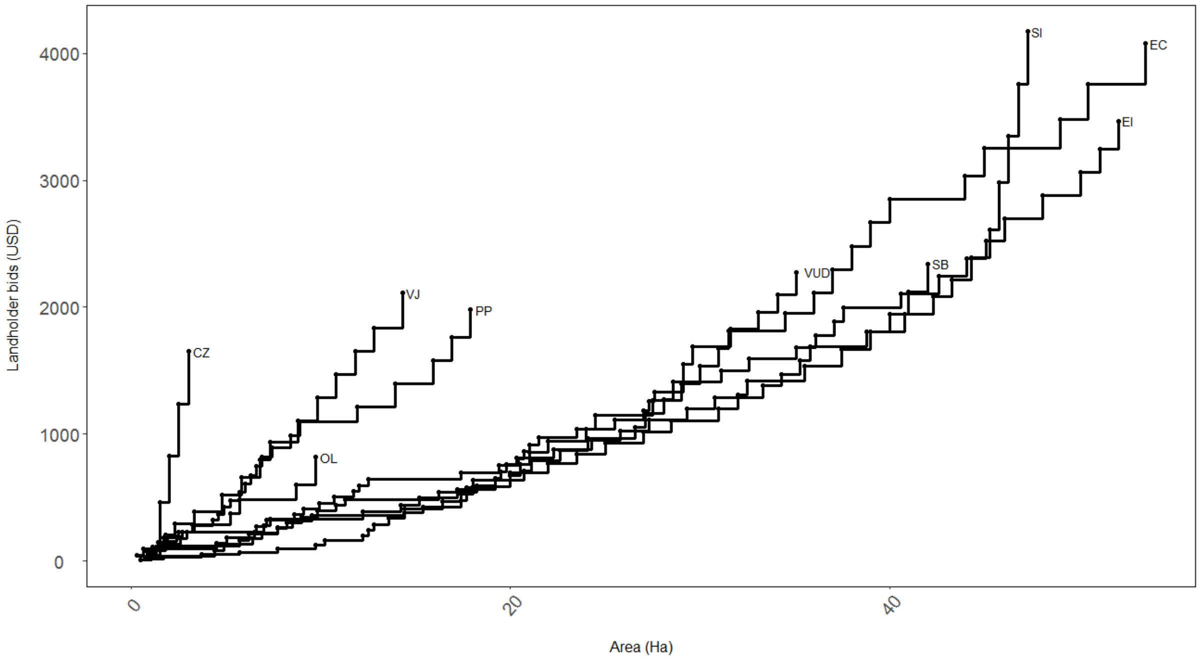


Figure 6: Supply curve revealing the cost of procuring conservation area (ha) thought to be inhabited by specific CWR in the diversity goal.

Key: VUD (*Vigna unguiculata* subsp. *dekindtiana*), VJ (*Vigna juncea*), EC (*Eleusine coracana*), SB (*Sorghum*

---

[10] Although 30 CWR were prioritised for conservation in Zambia, only nine priority CWR were verified to be present at our sample sites.

bicolor), SI (*Solanum incanum*), EI (*Eleusine indica*), PP (*Pennisetum purpureum*), CZ (*Cucumis zeyheri*), OL (*Oryza longistaminata*).

Only four priority CWR were found across both ecoregions surveyed (Table 4) suggesting the need for more wide-ranging CT surveys. The two most expensive CWR to conserve (under the diversity goal) were *C. zeyheri* ($550 per ha) and *V. juncea* ($148 per ha). Both *C. zeyheri* and *V. juncea* were also the rarest CWR in our sample. The cheapest CWR were *S. bicolor* ($56 per ha) and *V. unguiculata* subsp. *dekindtiana* ($65 per ha). However, these were not the most abundant CWR across our sample, suggesting other factors (beyond rarity) are also driving changes in cost.

The most prolifically conserved CWR for the diversity goal (by number of sites) was *E. indica* (43) while the most sparsely conserved was *C. zeyheri* (5). These correspond to the most, and least, prolific CWR across all farmer sites featuring in our sample, respectively. *E. indica* was conserved across more plots than any other CWR but not the highest area. *E. coracana* was conserved across the highest area (54 hectares) of any wild relative but not the most farmers or plots (this being *E. indica).* This suggests a further potential trade-off between conserving across larger geographical ranges (using farmer numbers as a proxy) and ensuring a greater extent of hectares. Decision makers should be aware of such potential trade-offs when setting conservation goals.

Table 4: Summary of conservation parameters according to each CWR for the diversity goal

CWR	**No. eco-regions**	**No. comm-unities**	**No. Farmers**	**Total area (ha)**	**Total plots**	**Cost/ha ($)**	**Total annual cost ($)**
Oryza longistaminata	1	1	10	10.2	17	80	817
Cucumis zeyheri	1	1	5	3	5	550	1,651
Pennisetum purpureum	1	3	24	17.9	38	111	1,981
Vigna juncea	1	2	16	14.3	28	148	2,109
Vigna unguiculata subsp. *dekindtiana*	1	3	26	35.1	59	65	2,275
Sorghum bicolor	2	4	28	42	63	56	2,340
Eleusine indica	2	5	43	52.1	85	67	3,466
Eleusine coracana	2	5	38	53.5	68	76	4,078
Solanum incanum	2	4	38	47.3	78	88	4,172

Compared to using a uniform payment rule, the diversity goal resulted in cost improvements of 120% per hectare across each CWR, excluding *C. zeyheri* where a uniform payment rule would actually result in a cost reduction of 68%. Cost improvements ranged from 18% for *V. juncea* to 213% for *S. bicolor*, although these cost reductions may be lower if the area goal was increased (i.e. as the model moves up the supply curve).

5. Discussion

5.1 Working with different types of farmer

The cost-effectiveness gains from optimised site selection reflect the heterogeneity in opportunity costs of different farmers, as revealed in bid offers (Engel, 2016). While selecting at the lower end of the supply curve may reduce cost, the advantages must be weighed against increased transaction costs associated with differentiating payments, as well as fairness and welfare implications (Börner et al., 2017).

Across our sample, farms inputting bid offers comprising greater area and plots were found to be cheaper on a price/ha basis. Male farmers input significantly higher bid offers than female farmers (both in total and on a per plot basic), possibly as a result of the fact that women are often paid less than men for undertaking similar work in rural labour markets (e.g. FAO, 2011). The proportion of land enrolled in bid offers as a percent of total land ownership was not correlated with farm size, suggesting poorer households (i.e. GMA sites) are able to participate in this PACS scheme at levels similar to those of better-off households – a finding mirrored in work by Pagiola et al. (2010).

Bid offers in GMAs were higher in absolute terms as well as per ha and per plot, suggesting poorer members of society do not necessarily “sell cheapest” (Pascual et al., 2014; Narloch et al., 2017). Importantly, these cost differences were not driven by changes in sample sizes between GMA and non-GMA sites, suggesting farmers from GMAs face higher shadow opportunity costs, possibly as a result of greater reliance on agri-production for livelihoods and survival. Additionally, these farmer groups may be aware of the financial benefits that can arise from working with conservationists. Despite the potentially higher cost of working with poorer farmers it may nonetheless be desirable to engage poorer actors in conservation activities. Working with GMA farmers may strengthen existing relationships between farmers and concurrent conservation programmes (Lindsey et al., 2014). Additionally, farmers living in the GMA may harbour pro-environmental attitudes given their proximity to protected areas (Allendorf et al., 2006) and these benefits may offset the additional cost of working with these groups.

Paying farmers for environmental services provision can itself either reinforce or erode pre-existing intrinsic motivation for conservation (often termed ‘‘crowding-in” and ‘‘crowding-out”, respectively) (Narloch et al., 2013; Midler et al., 2015; Börner et al., 2017). There are many reasons for crowding-in or out, including satisfaction or demotivation with a contractual scheme (Nordén et al., 2013). Consideration regarding such potential impacts should be undertaken with a view to considering how crowding-in positive behaviours could be actively encouraged through scheme design and targeting. A complimentary approach may be to reward farmers by forging public private breeding initiatives to improve their crop landraces and ultimately farmer yields.

5.2 Trade-offs in PES

The cost of site selection ranged from \$23/ha to \$91/ha across all selection goals. Similar work on conservation tenders for the maintenance of landraces has obtained estimates of US \$300/ha to \$400/ha in Ecuador and \$835/ha in Guatemala (Drucker et al., 2017), \$1,323/ha in Bolivia (conservation area of 2.8 ha) and \$3,636/ha in Peru (conservation area of 0.32 ha) (Narloch et al., 2017). The lower Zambia costs may reflect the reduced opportunity costs associated with conservation in field margins (as opposed to the need for active cultivation when considering landraces) and lower labour costs (Rapsomanikis, 2015).

Using a discriminatory payment rule to select bid offers yielded cost-effectiveness improvements of 87% to 48% per hectare across the various model iterations, compared to a uniform payment rule. Sensitivity analysis indicates these gains in cost-effectiveness persist, albeit at a somewhat reduced level, even when procuring larger conservation areas (i.e. 100 ha. per ecoregion, rather than just 50 ha.) suggesting these findings are robust with regard to the area constraint imposed. The different constraints employed also impact cost effectiveness. The diversity goal yielded the best conservation performance (i.e. a 76% increase in mean CWR species richness, compared to the equity goal) but the social equity goal resulted in 69% more female farmers, 76% more younger farmers and 67% more smaller farmers being selected in bid offers. These factors suggest a trade-off between cost-effectiveness, diversity and other socially desirable attributes. Similar work has found comparable trade-offs persist for landrace conservation (Narloch et al., 2011b) and biodiversity conservation in the tropics (Calvet-Mir et al., 2015).

It is therefore of interest to explore the relationship between social equity and the cost-effectiveness of conservation schemes. Factors such as perceived distributional fairness may influence an individual’s motivation to engage in conservation programmes (Vatn, 2010; Narloch et al., 2013; Midler et al., 2015) and perceptions of unfairness can undermine the effectiveness of incentives (Sommerville et al., 2010). Debate in the literature has raised questions regarding the appropriateness of using PES programmes to tackle factors such as poverty reduction at the expense of ecological outcomes (Kinzig et al., 2011; Jack et al., 2008). While there are strong arguments for including equity considerations in PES (Wunder, 2007), it can be argued that allocating funds to service providers that are not the most competitive may undermine conservation effort (Börner et al., 2017).

Our work demonstrates imposing fairness considerations would result in additional scheme cost of a relatively modest 8% when compared to the targeted area goal. Although the diversity goal cost an additional 44% more to procure land than the social equity, it was actually cheaper per unit of species richness than the equity and targeted area goal. In other words, the diversity goal is the cheapest approach to maximising species richness out of the selection goals where a minimum diversity constraint is imposed. Multi-criteria approaches may be required to balance environmental effectiveness and fairness considerations and there are strong arguments for not treating environmental and social equity goals as fully separate objectives in PES schemes (Pascual et al., 2014). Good conservation outcomes are often contingent on developing positive local attitudes (Struhsaker et al., 2005) and pro-social behaviour that can improve compliance (Narloch et al., 2017). Our results show it is possible to combine social equity and diversity criteria and the cost implications resulted in a 15% increase. Ultimately, there is a need for such considerations to form part of the establishment of a consensus around the definition of conservation goals and how trade-offs are considered (Zumaran, 2018).

5.3 National scale CWR conservation

Establishment of national, regional and global genetic reserves has been identified as a key challenge for CWR conservation (Maxted et al., 1997, 2010). Costs for establishing an on-farm conservation site for CWR have been estimated by Maxted (2015, unpublished) at $10k per ecoregion per year . While the total cost of conservation under the diversity maximising goal was estimated at $9.2k per year across two ecoregions, if this estimate were extrapolated to cover all ten ecoregions in Zambia (upper bound) or five ecoregions (lower bound) then the costs for establishing a national (on-farm) conservation network would range from $41,250 to $82,500 per year[11]. The latter is likely an overestimate since Brown and Briggs (1991) and Fielder et al. (2016) note conserving each CWR at a minimum of five different ecoregions should suffice. In any case we suggest this is a relatively modest sum as it only amounts to between 0.5% and 0.9% of income generated by the Zambian Wildlife Authority (Lindsey et al., 2014).

Eight of the nine priority CWR modelled in this exercise were present in existing PAs (Ministry of Agriculture, 2016). Yet, many populations in PAs receive no active management highlighting the need to establish their management on-farm (Maxted et al., 1997; Lawson et al., 2014). While only *C. zeyheri* was not present within existing PAs, *Sorghum bicolor* and *Solanum incanum* were found to be present in only 20% and 25% of PA sites, respectively (see S4). In addition, *C. zeyheri* was not present in any *ex situ* collections while *Sol. incanum* and *S. bicolor* was scarcely stored *ex situ*. This suggests rationalisation is needed and raises broader questions concerning

---

[11] Based on procuring 50 hectares per ecoregion at the mean cost of $150/ha (this cost is based on the price/ha of individual farmer bid offers in the diversity goal). The cost estimate includes an additional 10% monitoring and management cost (as per Lindenmayer et al., 2012).

how best to allocate funds across integrated *in situ* and *ex situ* strategies. The high cost of conserving *C. zeyheri*, suggests it may be more cost-effective to prioritise *ex situ* approaches to enable a higher proportion of funds to be allocated to the *in situ* management of other CWR where the cost of conserving is much lower. Alternative *in situ* strategies (e.g. protected areas designations) may also be more appropriate where farmer led conservation is cost prohibitive.

5.4 Limitations and further work

In this study, agricultural extension officers were used to promote the conservation tender and recruit workshop participants, with bid offers ultimately being received from a wider range of community members. However this approach could potentially introduce a self-selection bias that lowers the bid costs we observed relative to the mean of the broader population. This tendency is however potentially offset by another possible bias that can arise from the use of an open-ended tender question, which in some circumstance has been shown to lead to higher WTP estimates relative to a closed format. There is an extensive debate regarding the use of open versus closed formats, which is arguably unresolved. In our particular context the open-ended format was considered to be appropriate given the unusual nature of the conservation service contract being solicited.

Nevertheless, the cost figures generated are likely to reflect only a lower-bound estimate of the total costs, given that a range of transaction costs have not been accounted for, falling outside of the scope of this study. Such additional costs would include farmer CWR management training, as well as the administration costs of the scheme and associated monitoring and verification. In other studies, such transaction costs have been found to range from 6% to 87% of total costs paid to landholders (Latacz-Lohmann and Schilizzi, 2005); while monitoring necessary to ensure site management is maintaining or enhancing target CWR populations (Maxted et al., 1997, 2008) may be differentiated based on demographic counting with costs in the range of CWR (US$1 k per monitoring event) and genetic characterisation (required every 25–30 years costing ~ $50 k per monitoring event) per ecoregion (Maxted, 2017, *personal communication*)

An additional constraint was our reliance on CWR records that varied in date, raising questions over their reliability and the potential need for additional field surveying to establish renewed population baselines. Furthermore, the limited number of CWR species used to inform the site selection model may have affected outcomes under each selection goal. Further validation of the results could be achieved through applying the approach developed at the national scale (with associated sample sizes). Ecological metrics such as habitat connectivity and sub-populations were not considered but have been shown to be important in other work (Beyer et al., 2016) and incorporating such metrics into future model iterations may lead to more integrated conservation approaches. Finally, the implications of climate change need to be made more explicit in decisions concerning optimal site selection given range shifts that are likely to occur which threaten the protection of CWR in static protected areas (Phillips et al., 2017).

6. Conclusion

Advances in genotyping technologies and plant breeding to meet yield improvement goals have increased the potential for using exotic genetic material, thereby increasing the importance of conserving and using CWR. In the Zambian context, we demonstrated that *in situ* conservation costs ranges from \$23-\$91/ha. Including social equity goals in site selection results in a cost increase of 8% relative to the targeted area goal. The diversity goal was most expensive, with an additional 42% cost per ha compared to the social equity goal, but 18% cheaper per unit species richness. This implies a potential trade-off between conservation area, species richness and more equitable distribution of conservation funds to disadvantaged groups. Any such trade-offs should be made transparent and brought to the attention of the relevant decision-makers responsible for CWR conservation strategies; as should the fact that the inclusion of some rare CWR were found to disproportionately increase on farm conservation costs, suggesting alternative conservation approaches (e.g. *ex situ* or *in situ* within protected areas) may be more appropriate in some cases.

Despite data gaps, these findings reveal clear opportunities to improve the cost-effectiveness of incipient conservation approaches based on existing data and the use of tender instruments that are capable of identifying least-cost conservation service providers. Although this work has focused on CWR conservation in Zambia, the selection model developed could be applied more widely, thereby supporting national and global CWR conservation strategy design and implementation.

Acknowledgements

We thank ZARI colleagues Graybill Munkombwe and Masiye Tembo for their assistance during the fieldwork visits. We also thank Ehsan Dulloo and Imke Thormann for their assistance in supporting the survey design and sampling strategy, plus Rafael Silva for reviewing the model notation. We acknowledge funding from the Natural Environment Research Council (NERC) E3 Doctoral Training Programme (DTP) studentship (NE/L002558/1). This work was carried out within the project '*In situ* conservation and use of crop wild relatives in three ACP countries of the SADC region' (SADC Crop Wild Relatives project) (http://www.cropwildrelatives.org/sadc-cwr-project/) co-funded by the European Union and implemented through the ACP-EU Co-operation Programme in Science and

Technology (S&T) II by the African, Caribbean and Pacific (ACP) Group of States (grant agreement no. FED/2013/330-210).

References

Allendorf, T., Swe, K.K., Oo, T., Htut, Y., Aung, M., Allendorf, K., Hayek, L.-A., Leimgruber, P., Wemmer, C., 2006. Community attitudes toward three protected areas in Upper Myanmar (Burma). Environ. Conserv. 33, 344–352.

Bertke, E., Marggraf, R., 2005. An incentive based tool for ecologically and economically efficient provision of agrobiodiversity. Sustainable agricutural and natural resource management knowledge base. Available from: https://vtechworks.lib.vt.edu/handle/10919/67255

Beyer, H.L., Dujardin, Y., Watts, M.E., Possingham, H.P., 2016. Solving conservation planning problems with integer linear programming. Ecol. Modell. 328, 14–22.

Börner, J., Baylis, K., Corbera, E., Ezzine-de-Blas, D., Honey-Rosés, J., Persson, U.M., Wunder, S., 2017. The effectiveness of payments for environmental services. World Dev. 96, 359–374.

Brooks, K., Zorya, S., Gautam, A., Goyal, A., 2013. Agriculture as a sector of opportunity for young people in Africa. World Bank. Report number WPS6473.

Brown, A.H.., Briggs, J.D., 1991. Sampling strategies for genetic variation in ex situ collections of endangered plant species, in: Falk, D.A., Holsinger, K.. (Eds.), Genetics and Conservation of Rare Plants. Oxford University Press., pp. 99–119.

Buckland, S.T., Borchers, D.L., Johnston, A., Henrys, P.A., Marques, T.A., 2007. Line transect methods for plant surveys. Biometrics 63, 989–998.

Burgess, N.D., Hales, J.D., Ricketts, T.H., Dinerstein, E., 2006. Factoring species, non-species values and threats into biodiversity prioritisation across the ecoregions of Africa and its islands. Biol. Conserv. 127, 383–401.

Calvet-Mir, L., Corbera, E., Martin, A., Fisher, J., Gross-Camp, N., 2015. Payments for ecosystem services in the tropics: a closer look at effectiveness and equity. Curr. Opin. Environ. Sustain. 14, 150–162.

Chikowo, R., 2018. Description of cropping systems, climate, and soils in Zambia [WWW Document]. URL http://www.yieldgap.org/zambia (accessed 2.9.18).

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. Agroecol. Sustain. Food Syst. 38, 369–377.

Dhariwal, G.K., Laroche, A., 2017. The future of genetically engineered plants to stabilize yield and improve feed. Anim. Front. 7, 5–8.

Donaldson, L., Wilson, R.J., Maclean, I.M.D., 2017. Old concepts, new challenges: adapting landscape-scale conservation to the twenty-first century. Biodivers. Conserv. 1–26.

Drucker, A. g., Ramirex, M., Medina, T., 2017. Incentivos costo-efectivos parala conservaciony uso in situ/en finca dela agrobiodiversidad avances del programa resca en America Latina. Sirgealc, Guadalajara, Mexico.

Engel, S., 2016. The devil in the detail: a practical guide on designing payments for environmental services. Int. Rev. Environ. Resour. Econ. 9, 131–177.

Eroarome, A.M., 2009. Country Pasture/Forage Resource Profiles: Zambia. Rome, Italy.

Escobar, S.S., Odame, H.H., Tegbaru, A., 2017. 21 Gender transformative approaches in agricultural innovation. Sustain. Intensif. Smallhold. Agric. 304.

FAO, 2017. The future of food and agriculture – Trends and challenges. Rome, Italy.

FAO, 2011. The role of women in agriculture. ESA Working Paper No. 11-02.

Fielder, H., Smith, C., Ford-Lloyd, B., Maxted, N., 2016. Enhancing the conservation of crop wild relatives in Scotland. J. Nat. Conserv. 29, 51–61.

Ford-Lloyd, B. V, Schmidt, M., Armstrong, S.J., Barazani, O., Engels, J., Hadas, R., Hammer, K., Kell, S.P., Kang, D., Khoshbakht, K., 2011. Crop wild relatives—undervalued, underutilized and under threat? Bioscience 61, 559–565.

Grogan, K., Birch-Thomsen, T., Lyimo, J., 2013. Transition of shifting cultivation and its impact on people's livelihoods in the Miombo woodlands of northern Zambia and south-western Tanzania. Hum. Ecol. 41, 77–92.

Haight, R.G., Snyder, S.A., 2009. Integer programming methods for reserve selection and design. Spat. Conserv. prioritization Quant. methods Comput. tools.(A Moilanen, KA Wilson, HP Possingham, eds.). Oxford Univ. Press. New York, NY 43–57.

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

Jarvis, A., Lane, A., Hijmans, R.J., 2008. The effect of climate change on crop wild relatives. Agric. Ecosyst. Environ. 126, 13–23.

Jarvis, S., Fielder, H., Hopkins, J., Maxted, N., Smart, S., 2015. Distribution of crop wild relatives of conservation priority in the UK landscape. Biol. Conserv. 191, 444–451.

Kell, S.P., Maxted, N., Bilz, M., 2011. 28 European Crop Wild Relative Threat Assessment: Knowledge Gained and Lessons Learnt, in: Maxted, N., Dulloo, M.E., Ford-Lloyd, B.., Frese, L., Iriondo, J.., Pinheiro de Carvalho, M.A.. (Eds.), Agrobiodiversity Conservation Securing the Diversity of Crop Wild Relatives and Landraces. CABI International, Wallingford., pp. 218–242.

Kinzig, A.P., Perrings, C., Chapin, F.S., Polasky, S., Smith, V.K., Tilman, D., Turner, B.L., 2011. Paying for ecosystem services—promise and peril. Science (80-.). 334, 603–604.

Krishna, V. V, Drucker, A.G., Pascual, U., Raghu, P.T., King, E.D.I.O., 2013. Estimating compensation payments for on-farm conservation of agricultural biodiversity in developing countries. Ecol. Econ. 87, 110–123.

Latacz-Lohmann, U., Schilizzi, S., 2005. Auctions for conservation contracts: a review of the theoretical and empirical literature. Rep. to Scottish Exec. Environ. Rural Aff. Dep. 15.

Lawson, C.R., Bennie, J.J., Thomas, C.D., Hodgson, J.A., Wilson, R.J., 2014. Active management of protected areas enhances metapopulation expansion under climate change. Conserv. Lett. 7, 111–118.

Lindenmayer, D., Burgman, M., 2005. Practical conservation biology. Csiro Publishing.

Lindenmayer, D.B., Zammit, C., Attwood, S.J., Burns, E., Shepherd, C.L., Kay, G., Wood, J., 2012. A novel and cost-effective monitoring approach for outcomes in an Australian biodiversity conservation incentive program. PLoS One 7, e50872.

Lindsey, P.A., Nyirenda, V.R., Barnes, J.I., Becker, M.S., McRobb, R., Tambling, C.J., Taylor, W.A., Watson, F.G., t'Sas-Rolfes, M., 2014. Underperformance of African protected area networks and the case for new conservation models: insights from Zambia. PLoS One 9, e94109.

Manning, I., 2011. Wildlife conservation in Zambia and the Landsafe customary commons. Nat. Resour. J. 52, 195–214.

Mason, A.J., 2012. Opensolver-an open source add-in to solve linear and integer progammes in excel, in: Operations Research Proceedings 2011. Springer, pp. 401–406.

Maxted, N., 2017. Personal Communication. Discussions concerning the appropriate scale of a CWR conservation programme.

Maxted, N., 2015. Global network options for in situ conservation and on-farm management of plant genetic resources. A concept note (unpublished).

Maxted, N., Ford-Lloyd, B. V, Hawkes, J.G., 1997. Complementary conservation strategies, in: Maxted, N., Ford-Lloyd, B.V., Hawkes, J.G. (Eds.), Plant Genetic Conservation: The in Situ Approach. Chapman & Hall, London., pp. 20–55.

Maxted, N., Ford-Lloyd, B. V, Jury, S., Kell, S., Scholten, M., 2006. Towards a definition of a crop wild relative. Biodivers. Conserv. 15, 2673–2685.

Maxted, N., Hawkes, J.G., Ford-Lloyd, B. V, Williams, J.T., 2000. A practical model for in situ genetic conservation, in: Plant Genetic Conservation. Springer, pp. 339–367.

Maxted, N., Iriondo, J.M., De Hond, L., Dulloo, E., Lefèvre, F., Asdal, A., Kell, S.P., Guarino, L., 2008. Genetic reserve management, Plant Genetic Population Management. CAB International, Wallingford.

Maxted, N., Kell, S.., 2009. Establishment of a Global Network for the In Situ Conservation of Crop Wild Relatives: Status and Needs. Rome, Italy.

Maxted, N., Kell, S., Toledo, Á., Dulloo, E., Heywood, V., Hodgkin, T., Hunter, D., Guarino, L., Jarvis, A., Ford-Lloyd, B., 2010. A global approach to crop wild relative conservation: securing the gene pool for food and agriculture. Kew Bull. 65, 561–576.

Meilleur, B.A., Hodgkin, T., 2004. In situ conservation of crop wild relatives: status and trends. Biodivers. Conserv. 13, 663–684.

Messer, K.D., 2006. The conservation benefits of cost-effective land acquisition: A case study in Maryland. J. Environ. Manage. 79, 305–315.

Midler, E., Pascual, U., Drucker, A.G., Narloch, U., Soto, J.L., 2015. Unraveling the effects of payments for ecosystem services on motivations for collective action. Ecol. Econ. 120, 394–405.

Ministry of Agriculture, 2016. National strategic action plan for the conservation and sustainable use of crop wild relatives in Zambia. Lusaka, Zambia.

Ministry of Local Government and Housing., 2017. Eastern Province [WWW Document]. URL http://www.mlgh.gov.zm/?page_id=666 (accessed 6.1.17).

Narloch, U., Drucker, A.G., Pascual, U., 2017. What role for cooperation in conservation tenders? Paying farmer groups in the High Andes. Land use policy 63, 659–671.

Narloch, U., Drucker, A.G., Pascual, U., 2011a. Payments for agrobiodiversity conservation services for sustained on-farm utilization of plant and animal genetic resources. Ecol. Econ. 70, 1837–1845. https://doi.org/10.1016/j.ecolecon.2011.05.018

Narloch, U., Pascual, U., Drucker, A.G., 2013. How to achieve fairness in payments for ecosystem services? Insights from agrobiodiversity conservation auctions. Land use policy 35, 107–118.

Narloch, U., Pascual, U., Drucker, A.G., 2011b. Cost-effectiveness targeting under multiple conservation goals and equity considerations in the Andes. Environ. Conserv. 38, 417–425.

Ng'uni, D., Munkombwe, G., Mwile, G., Dulloo, E., Thormann, I., Gaisberger, H., Maxted, N., Magos Brehm, J., Kell, S., 2017. Technical Background Document to the National Strategic Action Plan for the Conservation and Sustainable Use of Cop Wild Relatives in Zambia. https://doi.org/doi/10.7910/DVN/VYZZFF

Ng'uni, D., Munkombwe, G., Tembo, M., 2016. Occurrence data for priority CWR of Zambia. https://doi.org/doi/10.7910/DVN/Z5XN1F

Nordén, A., Persson, U.M., Alpizar, F., 2013. 8 Incentives, impacts and behavioural issues in the context of payment for ecosystem services programmes. Glob. Dev. Rethink. Interv. Gov. 102, 147–168.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. Bioscience 51, 933–938.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC.

Pagiola, S., Rios, A.R., Arcenas, A., 2010. Poor household participation in payments for environmental services: Lessons from the Silvopastoral Project in Quindío, Colombia. Environ. Resour. Econ. 47, 371–394.

Pascual, U., Phelps, J., Garmendia, E., Brown, K., Corbera, E., Martin, A., Gomez-Baggethun, E., Muradian, R., 2014. Social equity matters in payments for ecosystem services. Bioscience 64, 1027–1036.

Phillips, J., Brehm, J.M., van Oort, B., Asdal, Å., Rasmussen, M., Maxted, N., 2017. Climate change and national crop wild relative conservation planning. Ambio 1–14.

PriceWaterhouseCoopers, 2013. Crop wild relatives: a valuable resource for crop development. Available http://pwc.blogs.com/files/pwc-seed-bank-analysis-for-msb-0713.pdf

Quisumbing, A.R., Meinzen-Dick, R., Raney, T.L., Croppenstedt, A., Behrman, J.A., Peterman, A., 2014. Closing the knowledge gap on gender in agriculture, in: Gender in Agriculture. Springer, pp. 3–27.

Rapsomanikis, G., 2015. The economic lives of smallholder farmers: an analysis based on household data from nine countries. Food and Agricultural Organisation of the United Nations.

Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield trends are insufficient to double global crop production by 2050. PLoS One 8, e66428.

Rodrigues, A.S.L., Andelman, S.J., Bakarr, M.I., Boitani, L., Brooks, T.M., Cowling, R.M., Fishpool, L.D.C., da Fonseca, G.A.B., Gaston, K.J., Hoffmann, M., 2004. Effectiveness of the global protected area network in representing species diversity. Nature 428, 640.

Seto, K.C., Ramankutty, N., 2016. Hidden linkages between urbanization and food systems. Science (80-.). 352, 943–945.

Sommerville, M., Jones, J.P.G., Rahajaharison, M., Milner-Gulland, E.J., 2010. The role of fairness and benefit distribution in community-based Payment for Environmental Services interventions: A case study from Menabe, Madagascar. Ecol. Econ. 69, 1262–1271.

Stoneham, G., Chaudhri, V., Ha, A., Strappazzon, L., 2003. Auctions for conservation contracts: an empirical examination of Victoria's BushTender trial. Aust. J. Agric. Resour. Econ. 47, 477–500. https://doi.org/10.1111/j.1467-8489.2003.t01-1-00224.x

Struhsaker, T.T., Struhsaker, P.J., Siex, K.S., 2005. Conserving Africa's rain forests: problems in protected areas and possible solutions. Biol. Conserv. 123, 45–54.

Tester, M., Langridge, P., 2010. Breeding technologies to increase crop production in a changing world. Science (80-.). 327, 818–822.

UN FAO, 2010. FAO Geonetwork Richness Index [WWW Document]. Available from: http://ref.data.fao.org/map?entryId=5d112b2b-9793-4484-808c-4a6172c5d4d0

Vatn, A., 2010. An institutional analysis of payments for environmental services. Ecol. Econ. 69, 1245–1252.

Williams, J.C., ReVelle, C.S., Levin, S.A., 2005. Spatial attributes and reserve design models: a review. Environ. Model. Assess. 10, 163–181.

Windle, J., Rolfe, J., 2008. Exploring the efficiencies of using competitive tenders over fixed price grants to protect biodiversity in Australian rangelands. Land use policy 25, 388–398. https://doi.org/10.1016/j.landusepol.2007.09.005

World Bank, 2007. Economic and poverty impact of nature-based tourism. Lusaka, Zambia.

Wunder, S., 2007. The efficiency of payments for environmental services in tropical conservation. Conserv. Biol. 21, 48–58.

Wünscher, T., Wunder, S., 2017. Conservation tenders in low-income countries: Opportunities and challenges. Land use policy 63, 672–678.

WWF, 2004. Terrestrial Ecoregions of the World. USA. Available from: https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world

Zamstats, 2010. Muchinga Province 2010 Census Final Population and Electoral population. Lusaka, Zambia.

Zhang, H., Mittal, N., Leamy, L.J., Barazani, O., Song, B., 2017. Back into the wild—Apply untapped genetic diversity of wild relatives for crop improvement. Evol. Appl. 10, 5–24.

Zumaran, R., 2018. Lineamientos metodológicos para identificar la diversidad de los cultivos en riesgo de erosión genética y su recuperación. Informe Final. Industrias Forestales QIRI S.A.C., Lima, Peru.

Supplementary information

S1: List of priority CWR used in the modelling exercise and distribution across community and farmer sites.

CWR	**Related crop**	**No. of community locations**	**No. of sites**
Cucumis zeyheri	Cucumber	1	20
Eleusine coracana	Finger millet	5	78
Eleusine indica	Finger millet	5	87
Oryza longistaminata	Rice	1	30
Pennisetum purpureum	Pearl millet	4	65
Solanum incanum	Egg plant	4	80
Sorghum bicolor	Sorghum	2	50
Vigna juncea	Cowpea	2	20
Vigna unguiculata subsp. *dekindtiana*	Cowpea	3	43

S2*:* Information arising from focus group discussions (FGDs) with Zambian farmers concerning CWR conservation and local farming practices

Five FGDs were undertaken across Northern and Eastern province with a total of 55 participants. On average, 61% of CWR from a picture list of CWR shown to participants (though to inhabit the region) were identified. A range of other plant species thought to be wild relatives were also mentioned by participants and a small number of species thought to be CWR but now extinct were also noted.

Multiple uses of CWR were identified by participants including animal feed, medicine, thatch and human food (particularly when crop harvests are poor). Wild relatives were identified as occupying a range of different habitat types including adjacent to water sources (i.e. streams and marshland); adjacent to dwellings; roadside verges; field margins; in croplands; hilly ground and near termite mounds.

Participants were also asked whether the CWR identified had either declined, remained stable, or increased over time. Some 35% of wild relatives were identified as declining; 54% had remained the same and 11% had increased. The decline of some CWR populations had largely been attributed to over-harvesting, human induced bush fires, weeding and increased pressure from game animals (at GMA sites). In contrast, increases of some CWR noted by communities had been driven by an increase in farm animals that resulted in greater seed dispersal. Most CWR populations were unmanaged by communities, although some were harvested if edible by farm animals or humans. Those growing on crop lands were managed as weeds unless edible.

Community participants identified a number of activities they believe would enhance CWR populations including wild seed harvesting; selective weeding in crop lands; increased provision of fallow lands; reduced fire burning (particularly early in agricultural season to allow plants to seed) and creating awareness as to the importance of CWR. Resources required for these activities included agricultural tools; subsides; access to transport and training.

Farmers were also asked questions concerning activities required for cultivating a hectare of land and the estimated costs associated with these activities. Additionally, they were asked the estimated costs for sympathetically managing a hectare of land to not de-weed CWR. An example of the activities and associated costs mentioned are given below. These figures compare well to cost per hectare estimates derived from the tender workshops.

Activity	Estimated cost (US$ per hectare)
Ploughing and land preparation	15 – 55
Planting	16 – 37
Weeding*	22 – 73
Harvesting	18 – 138
Sympathetic weeding (i.e. not removing weed CWR from croplands)	37 – 110
Average value of crop yield per ha**	344 – 688

* Usually smallholder farmers, who account for large number of farmers in the two regions, do not use herbicides in their farming activities. In most cases, it is either they use hand hoe or ox drawn implements to control weeds in their fields. However, if herbicides are used, which normally is sourced through farmer input subsidies, they normally use pre emergence herbicides before planting of their main crop such as maize. ** The average farmer yield per ha for a maize crop in Northern and Eastern Provinces ranges from 1.95 - 2.2 tons/ha (Indaba Agricultural Policy Research Institute, 2017).

S3: Full description of the parameters used in the correlation matrix

Parameter	**Description**
Price/ha	The farmer bid offer for supplying conservation services in costs per hectare..
Ecoregion 1	Whether the conservation site was located in Ecoregion 1 or 2.
Socio-status index	The FAO Richness Index (UN FAO, 2010) represents the level of economic wellbeing associated with regions across Africa in 2010. This is measured from categories one (poorest areas) to six (wealthiest areas).
GMA	Whether the conservation site was located in a game management area.
Farm size	Total size of the farm bidding to supply conservation services.
Gender	The gender of the farmer.
Age	The age of the farmer.
Plots	The total number of plots bid in the conservation tender.
Area (ha)	The total conservation area bid in the conservation tender.
Proportion enrolled	The proportion of farmers lands bid in the conservation tender.
Bid offer (USD)	The total bid offer (per annum) for supplying conservation services.

S4: *In situ* and *ex situ* coverage of priority CWR in existing Zambian PAs and genebank collections.

CWR	**Populations covered in PAs**	**% of populations covered in PAs**	**Accessions in national genebank**	**Accessions in international genebank**
Cucumis zeyheri	0	0	0	0
Eleusine coracana	34	23	0	137
Eleusine indica	4	36	3	3
Oryza longistaminata	102	51	56	112
Pennisetum purpureum	4	50	0	5
Solanum incanum	1	25	0	1
Sorghum bicolor	1	20	0	2
Vigna juncea	6	19	0	13
Vigna unguiculata subsp. *dekindtiana*	30	32	20	86

Data from (Ministry of Agriculture, 2016).

References:

Indaba Agricultural Policy Research Institute, 2017. Zambia agriculture status report 2017. Lusaka, Zambia.

Ministry of Agriculture, 2016. National strategic action plan for the conservation and sustainable use of crop wild relatives in Zambia. Lusaka, Zambia.