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VALUING ECOSYSTEM SERVICES IN SEMI-ARID RANGELANDS THROUGH STOCHASTIC SIMULATION

Short title: VALUING ECOSYSTEM SERVICES IN SEMI-ARID RANGELANDS

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ABSTRACT

Ecosystem services and economic returns from semi-arid rangelands are threatened by land degradation. Policies to improve ecosystem service delivery often fail to consider uncertainty in economic returns gained through different land uses and management practices. We apply an analytical framework using stochastic simulation to estimate the range of potential monetary outcomes of rangeland ecosystem services under different land uses, including consideration of the uncertainty and variability of model parameters. We assess monetary and non-monetary dimensions, including those ecosystem services with uncertain and missing information, for communal rangelands, commercial ranches, game farms and Wildlife Management Areas in southern Kgalagadi District, Botswana. Public land uses (communal grazing areas and protected conservation land in Wildlife Management Areas) provide higher economic value than private land uses (commercial ranches and game farms), despite private land uses being more profitable in their returns from meat production. Communal rangelands and protected areas are important for a broader range of ecosystem services (cultural / spiritual services, recreation, firewood, construction material and wild food), which play a key role in sustaining the livelihoods of the largest share of society. The full range of ecosystem services should therefore be considered in economic assessments, while policies targeting sustainable land management should value and support their provision and utilisation. By forecasting the range of plausible ecosystem values of different rangeland land uses in monetary terms, our analysis provides policy-makers with a tool to assess outcomes of land use and management decisions and policies.

KEY-WORDS. Monte Carlo simulation, Botswana Kalahari, economic valuation, land degradation, sustainable land management.

INTRODUCTION

The United Nations Convention to Combat Desertification (UNCCD) recognises that although land degradation occurs locally, undermining the livelihoods of natural resource dependent populations, it also reduces the quality and/or quantity of ecosystem services (ES) provided to society. International efforts towards land degradation neutrality (LDN) outlined in The Future We Want and the Sustainable Development Goals (SDGs) aim to ensure that at a global scale, land continues to support livelihoods whilst maintaining long-term productivity and ES (UN, 2015; UNCCD, 2015). LDN provides an opportunity to develop local solutions that balance unavoidable degradation with actions that sustain, restore and rehabilitate land and its ES, cumulatively resulting in zero net land degradation at a global scale. Achieving LDN requires analysis of the costs and benefits of different land uses, management strategies and action / inaction at different scales, as well as identifying uncertainties associated with policy outcomes (Keesstra *et al.*, 2016). Methodologies are needed that allow integrated assessment of a range of ES across different social and ecological dimensions, including their economic value. In this paper, we focus on land degradation and ES at the district scale in Botswana's Kalahari, within the context of national level policy decision-making.

Several monetary approaches have emerged for valuing ES and producing policy-relevant recommendations (TEEB, 2010; Bagstad *et al*., 2013; Costanza *et al.*, 2014). Many assess how the monetary value of ES contributes to land's Total Economic Value (TEV) which includes both current and future benefits that ES generate in terms of provisioning, regulating, cultural and habitat services, and encompasses use and non-use values (Ayele *et al.*, 2016; Giger *et al.*, 2015; Ligonja and Shrestha, 2015; Zhang *et al.*, 2013). The Economics of Land Degradation (ELD) initiative has developed methodologies that can highlight the potential benefits derived from the use of sustainable land management (SLM) practices (ELD Initiative, 2015). Within such economic approaches, challenges remain, in identifying appropriate ways to capture the shared values (*e.g.* cultural, spiritual and recreational) of ES to society (Fish *et al.*, 2011). The values of such services are important to those who depend upon the land for survival, but are often neglected in quantitative ES assessments partly because analysts hesitate to assign precise values to them. Where certain ES are only assessed qualitatively – or not at all – they risk being ignored altogether by decision-makers. This can lead decisions and policies to optimise delivery of only those ES that are easily quantifiable and which provide direct monetary returns. Efforts to integrate 'intangible' factors in ES valuation (*e.g.* non-use values) with hard economic evidence have used a range of methods that aim to quantify and value ES that are not traded on the market. These include stated preference methods based on ES demand, such as contingent valuation (*i.e.*, willingness to pay or accept compensation) and choice experiments (*i.e.* based on questionnaires, surveys and interviews) (Oleson *et al.*, 2015; Turner *et al.*, 2016), and Multi-Criteria Decision Analysis (MCDA) (Favretto *et al.*, 2016; Kenter *et al.*, 2015). However, significant knowledge gaps remain surrounding the total economic value of land under specific uses.

This paper develops and applies a Monte Carlo-based decision model (*cf.* Rosenstock *et al.*, 2014; Luedeling *et al.*, 2015), providing empirical insight into the monetary valuation of ES in Botswana's arid and semi-arid Kalahari rangelands. These rangelands support diverse livelihoods by delivering a wide variety of ES, many of which are vital to the subsistence and survival of the poorest in society (Dougill *et al.*, 2010). Rangeland degradation in Botswana's Kalahari has led to widespread *Acacia mellifera* encroachment in semi-arid parts (Reed & Dougill, 2010; Thomas & Twyman, 2004), reducing grazing quality by replacing nutritious perennial grass cover with annual species of low-nutritional value, such as *Schmidtia kalaharensis* (Dougill *et al.*, 2016). In arid areas typified by linear dune fields, grass removal is leading to enhanced wind erosion and encroachment of the low-growing shrub *Rhigozum trichotomum* (Dougill *et al.*, 2016). These ecological changes directly affect pastoral livelihoods and exacerbate rural poverty (Chanda *et al.*, 2003), making land degradation an important national policy concern.

The Monte Carlo approach is based on the premise that the challenge to including intangible ES in monetary assessments stems partly from difficulties in assigning precise values to them. Such ES values can be quantified probabilistically, providing a confidence interval within which the value of a certain ES falls. Monte Carlo simulation allows quantification of total ES for a system even without precise values. It requires judgments to be made by analysts or experts on the study system, but avoids valuing at zero those ES that are difficult to quantify. Monte Carlo simulation offers an opportunity to integrate hard data with expert knowledge into a comprehensive assessment of the combined value of all ES, producing policy-relevant information that can be used to holistically appraise the value of different land use options (Rosenstock *et al.*, 2014).

This paper utilises stochastic simulation to estimate the range of potential monetary outcomes of rangeland ES under different land uses, including consideration of uncertainty and variability of model parameters. To achieve this, we: (i) quantify the overall monetary value of ES under four different land uses in Botswana's Kalahari, while considering uncertainty about the precise value of individual ES; and (ii) identify the ES that most limit our ability to assign precise values to total ES produced by a land use system, and the ES values for which uncertainty reduction would constitute the greatest progress towards valuation of total ES.

The Monte Carlo model is calibrated to available monetary data and integrates valuations of all relevant ES, including non-marketed ES that provide non-monetary values. This is the first study to apply a Monte Carlo approach in the valuation of semi-arid rangeland ES in the context of LDN. Our findings can facilitate economically and socially informed policy decisions that draw on holistic evaluations and comparison of the values of different land use options, informing investments in SLM and helping advance towards LDN.

METHODS

Study area

Data on monetary and non-monetary ES were collected during 2013-2014 across our study area, southern Kgalagadi District, Botswana. The District has an altitude ranging from 800 to 1200 m and extends *c.* 66,000 km^2 with a population of 30,000 people (GoB, 2012). It encompasses a semi-arid area characterised by a subtropical climate (with average annual temperature above 18°C) and lack of permanent surface water, which makes the area unfavourable for crop farming. Rainfall is scarce and erratic, with mean annual rainfall ranging between 186 and 360 mm and inter-annual variability ranging between 35% and 56% (Mogotsi *et al.*, 2011). It occurs mostly during the summer (October to April) in the form of thunderstorms. High variability in ecological cover is observed between wet and dry seasons, with exacerbated degradation levels reached during prolonged dry periods, when bare ground cover can reach up to 90% of the total land cover (Dougill *et al.*, 2016). Prolonged droughts, combined with high levels of bush encroachment resulting from rangeland degradation, are major drivers of reduced quality grazing, high livestock mortality peaks in summer, and increasing levels of rural poverty (Chanda *et al.*, 2003; Mogotsi *et al.*, 2011; Thomas & Twyman, 2004).

Within the study area our sampled sites encompassed the main land uses, (Figure 1): i) communal livestock grazing areas (unfenced cattle posts in non-private land) (*c.* 14,800 km^2), ii) privately owned (fenced) cattle ranches (*c.* 8,900 km^2), iii) privately owned (fenced) game farms (*c.* 800 km^2) and iv) Wildlife Management Areas (WMAs) (*c.* 14,800 km^2), designated as protected conservation areas around the Kgalagadi Transfrontier Park (which itself covers *c.* 26,700 km^2).

Analytical framework

We framed our analysis according to the ES classification by de Groot *et al.* (2010). Table 1 shows those ES we assessed, which are mapped in detail in Favretto *et al.* (2016). We identified provision of meat, wild food, firewood, construction material and groundwater as relevant provisioning ES (Madzwamuse *et al.*, 2007). The major regulating ES is climate regulation through carbon sequestration (Thomas, 2012). Kgalagadi District also provides habitat for a number of plant and animal species, thus contributing to genetic diversity. Local residents derive cultural and spiritual value, and tourists visit the region for recreational purposes. The total value of ES within each land use was calculated as the sum of all individual ES values.

Data collection and analysis

Interviews, secondary data and ecological assessments

Thirty-seven semi-structured interviews with stakeholders in each of the four land uses yielded quantitative data on the monetary costs and gains from land use activities linked to financial statements (see S1 and Favretto *et al.*, 2016, for details on the sampling criteria and data collection). Interviews also provided qualitative information on the land management strategies used and their implications for ES. Interviewees were selected purposively, based on their expertise in each type of land use and ownership and included: 20 communal livestock farmers, 10 private cattle ranchers, 3 private game ranchers, 3 government officers, 1 village development committee leader. Interview data were complemented with a comprehensive literature review, secondary data on rainfall patterns, land tenure, water management, population and national economic statistics, analysis of policy and strategic documents, application of the benefits transfer method for net amounts of total soil organic carbon sequestered per annum, and 12 ecological transect survey assessments. The ecological transects provided data on the links between land use and patterns of ecological change. They enabled a dual-scale assessment of both farm-scale patterns of ecological change and landscape-scale patterns of change in vegetation cover and animal distribution (for more details see Dougill *et al.* (2016)).

Data analysis

The array of information outlined in the section above allowed the key ES in the study area to be identified (See S2. For detailed descriptions of methods and data analysis techniques, see Favretto *et al.*, 2016). In the summation of total ES values, the ES identified were included as normally distributed variables, with distributions defined by the means and standard deviations obtained from primary data. While normal distributions did not match all distributions observed during data collection, they appropriately describe the uncertainty about the mean value for each ES. Since only the mean, and not the full distributions, are of interest in the Monte Carlo simulation, there was no need to consider more complex distributions for the ES value means. Distributions for all ES values were defined independently, because there were no compelling reasons for correlations. While some such correlations will exist and their knowledge would allow more precise valuation than can be obtained by not considering correlations, it is safer to simulate a scenario with no correlations than to assume correlated ES without being certain about this, because if this assumption does not hold, the latter might lead to confidence intervals that do not include the true TEV to be estimated. Data gaps pertaining to the remaining ES found to be of high importance during interviews (*i.e.* spiritual value and habitat) were filled by probabilistic estimates based on our uncertainty about these ES values. This means that we expressed all ES values through probability distributions, based on estimated 90% confidence intervals, that we considered reasonable Bayesian priors for the model, *i.e.* intervals that represented the best of our knowledge in the absence of actual measurements. Where little information was available on the value of an ES, the corresponding confidence interval was relatively wide. To avoid cognitive biases in making estimates (Tversky & Kahnemann, 1974), we followed procedures recommended by Hubbard (2014) to improve accuracy. Probability distributions were scrutinised by Klein's premortem analysis (Klein, 2007) and improved by iteratively excluding unrealistically high or low values. We also used the 'equivalent bet' approach (Hubbard, 2014), based on estimators comparing the clearly defined odds of monetary bets with the chance of the true value for a variable being within the confidence intervals they specified. Application of these techniques has measurably improved the accuracy of estimated probability distributions (Hubbard, 2014; Lichtenstein *et al.*, 1977). By using Monte Carlo simulation to sum all ES values, TEVs can consider the aggregate uncertainty of all input values.

Provision of many ES was not homogeneously distributed throughout the study area under the different land uses (Favretto *et al.*, 2016). For instance, construction material is not collected in remote parts of WMAs. In these cases, we estimated the percentage of the area that provided the service and the amount of products or services based on published reports (*e.g.* Arntzen *et al.*, 2010; Madzwamuse *et al.*, 2007). The product of these figures was multiplied by the value per unit of product / service. In this calculation, we distinguished between marketed and non-marketed portions of the product or service, which received different price estimates. Due to time constraints we were not able to collect data that would allow these products and services to be valued through alternative methods, *e.g.* based on the willingness to pay or the labour or time used for collection (Oleson *et al*., 2015). For recreational and spiritual ES, we estimated the value of the ES per person, rather than per area, and multiplied by the number of residents of the respective land use types (GoB, 2012). For carbon sequestration, we reduced the ES value computed from per-area sequestration and area by estimates of the cost of monitoring, reporting and verifying (MRV) the amount of sequestered carbon. Inclusion of MRV costs was necessary, because all relevant pathways through which local residents could reap benefits from carbon sequestration would require expenses for MRV. Wide ranges were assumed for these, since MRV by external consultants, which might be necessary for carbon sales to established international mechanisms, would incur substantially greater costs than MRV by local residents, which has been acceptable for certain voluntary carbon sequestration schemes (Kollmuss *et al.*, 2008). Given both the MRV difficulties and the limited institutional capacity for climate finance payments for rangeland systems (Dougill *et al.*, 2012) low probabilities of C payment benefits are assumed.

Once probability distributions had been estimated for all variables, the overall ES value of the system was computed by Monte Carlo simulation, whereby 10,000 sets of random samples were drawn for all variables, and the sum of all individual ES computed. The smooth probability distributions resulting from the calculations indicated 10,000 model runs were sufficient to cover the range of plausible outcomes. These outcomes were expressed by 10,000 estimates of total system ES, which together constituted a probability distribution of the value of ES provided by ecosystems. A sensitivity analysis elucidated which study variables most constrained our ability to provide precise ES value estimates. This calculation was based on the Variable Importance in the Projection (VIP) metric of Partial Least Squares (PLS) regression (Luedeling & Gassner, 2012; Luedeling *et al.*, 2015). The PLS procedure relates all dependent variables (the total ES value of the system) to all input variables. It then identifies, via the VIP, those independent variables whose variation has the greatest impact on the value of the dependent variable. These variables were interpreted as major sources of uncertainty and therefore as priorities for measurement. All calculations were implemented as automated procedures in R programming language (Luedeling & Göhring, 2016; R Core Team, 2014).

RESULTS

Figure 2 shows the overall ES values (USD / km^2) and their probability distributions estimated through a Monte Carlo simulation with 10,000 model runs under the four land uses analysed. According to the median values of the distributions, WMAs and communal grazing have almost identical ES values (USD3.98 / km^2). Median ES provided by private cattle ranches (USD3.68 / km^2) and private game ranches (USD1.13 / km^2) are lower than for the public land uses (Figure 2). A higher median value for a given system does not necessarily mean that this system would also have a higher value, if all uncertainties could be eliminated. However, this is more likely if median values differ greatly and distribution shapes are generally similar. Among public land uses, ES values provided by WMAs were more uncertain than for communal grazing, as indicated by wider 90% confidence intervals (USD1.49 – 6.57, as opposed to USD2.14 – 6.01). This mostly reflected greater uncertainty about the spiritual and recreational value of the land for WMAs than for communal grazing. Game ranching was most risky (*i.e.* projected outcomes were highly uncertain given available information) among the private land uses, with a wide 90% confidence interval of USD-5.07 – 7.26 (including negative outcomes), compared to USD2.08 – 5.56 for private cattle ranching (Figure 2). ES values differed only slightly between private cattle ranching and the two public land uses, with private game ranching appearing substantially more risky and less profitable from an ES perspective. The possibility of negative outcomes for this land use reflected observations that meat production was often unprofitable, translating to a negative contribution to total ES value.

When we related variation in the total value of ES provided by the four systems to uncertainty about the values of individual ES via PLS regression, a small number of ES emerged as most limiting for our ability to provide precise estimates of total ES (Figure 3). High VIP values indicate the major knowledge gaps that should be addressed to increase precision about the total value of all ES provided by the different land uses. Under communal grazing, uncertainty about total ES values mainly stemmed from uncertainty about values of profit of meat production, plant / livestock diversity, recreation and cultural / spiritual inspiration. Variation in the total value of ES in WMAs was principally due to uncertainty about the value of recreation, cultural / spiritual inspiration and plant / livestock diversity. Key ES identified under private cattle ranches included plant / livestock diversity, groundwater extraction and profit from meat production. Under private game ranches, total ES value uncertainty mainly derived from poorly constrained estimates for the profit of meat production, and the values of recreation and plant / livestock diversity.

DISCUSSION

Monte Carlo simulations indicate that rangeland used for communal grazing and WMAs are likely to provide the highest ES value and deliver the broadest ranges of ES. Uncertainty in terms of monetary outcomes under land uses where commercial meat is produced (all land uses excluding WMAs) is mainly due to variations in meat production profitability and the value associated with plant / livestock diversity (Figure 3). Availability of the latter is important for profit to be generated (Mace *et al.*, 2012), where the nutritional status of cattle depends greatly on the diversity of forage species and livestock breeds (Scherf *et al.*, 2008).

Favretto *et al.* (2016) show that the mean net profit of meat production generated under private cattle ranches is greater than the one generated under communal grazing. However, the latter achieves a higher overall value in the Monte Carlo simulations due to the role played by non-marketed ES (Figure 2). Figure 3 indicates that cultural / spiritual inspiration and recreation impact significantly on the value variability of communal and WMA land uses. Cultural and spiritual values, both individual and shared, are deeply grounded in the cultural heritage and practices of public land users (Kenter *et al.*, 2015).

The monetary value of a land use links to availability of an ES, but also its relative importance to society. Of 30,000 inhabitants in the study area, *c.* 98% are public land users (GoB, 2012). Understanding and preserving individual and shared cultural / spiritual values and recreation (key ES in communal grazing areas and WMAs in the VIP analysis, Figure 3) is therefore vital for decision-makers developing SLM policies to enhance social equity and deliver positive societal impacts (Fish *et al.*, 2011; Kenter *et al.*, 2015).

Recreation – including hunting and photographic safari – can generate substantial economic benefits under communal and WMA land uses (Arntzen *et al.*, 2010). Since the 1990s, Community Based Natural Resource Management (CBNRM) approaches have been developed in Botswana to promote recreation activities that benefit communal land users (Mulale and Mbaiwa, 2012). A CBNRM Policy was formally adopted in 2007. However, capacity to develop CBNRM activities remains constrained by strong policy and market incentives in the livestock sector (*ibid*). Uncertainty in revenues from CBNRM through trophy hunting, photographic safari and ecotourism results in high variation of the final ES value achieved from communal and WMA land uses (see 'recreation', Figure 3). The Monte Carlo simulations indicate a need to reduce uncertainty surrounding these ES, in order to quantify TEV values more precisely. Future policy measures need to be placed within the cultural and recreational contexts of ES values, so that economic incentives to invest in rangeland resources are generated for land users.

Other non-marketed ES important to communal and WMA farming communities include firewood, construction material and wild food (Favretto *et al.*, 2016). Thatching grass and poles for fencing are widely collected and used as construction materials, while wild food provides supplementary nutrition (and water), particularly in the dry season. Some wild plants are also used as medicines. These non-marketed ES are currently underestimated by decision makers from an economic perspective as they lack a functioning market and because policy incentives focus primarily on meat production (Madzwamuse *et al.*, 2007). Figure 3 suggests the value of these ES is substantial, and even if beneficiary communities do not pay for these services, there is a need to sustain them. These ES need careful consideration in decision-making too, ensuring the land management practices promoted by policy do not reduce or restrict access to these ES.

Fresh water is scarce in the Kalahari and costs linked to groundwater extraction through boreholes highly influenced the TEV generated under private cattle ranches, where revenue generation focuses on meat production (Figure 3). Borehole technology is expensive, and on average a single private cattle rancher has an extraction capacity 3 times higher than a communal farmer (Favretto *et al.*, 2016). Consequently, water extraction investments, and related profits derived by meat production, vary widely (Figure 2).

The Kalahari also provides other values through carbon storage and climate regulation (Thomas, 2012). However, low global carbon prices, uncertainty over markets and standards, and poorly developed methodologies, particularly for MRV, raise concerns for the profitability of carbon sequestration (Stringer *et al.*, 2012). Due to market regulations, entry into carbon marketing schemes may not be an option for many, especially land users without formal land tenure (Dougill *et al.*, 2012, Howard *et al.*, 2015). Limited data were available on MRV costs, suggesting an urgent need for further study to gather more consistent data on these. Ecological concerns also require consideration. While establishing carbon credit schemes in the Kalahari might generate new potential income streams linked to one particular ES, increased woody biomass could most easily be achieved through allowing bush encroachment, which will impact negatively on the future provision of other ES (Reed *et al.*, 2015).

While high economic values can be generated under private land uses by ES linked to meat production in game farms and cattle ranches, our analysis highlights the value of other ES (*i.e.* cultural / spiritual, recreation, as well as firewood, construction material and wild food) that are not recognised in land management and land policy. The high VIP variables in Figure 3 identify the need to consider these ES in the development of policy, to prevent future policy from strengthening some ES (*e.g.* commercial meat production) at the expense of others that are valuable from a wider socio-economic perspective. Alternative land management strategies focused on economic and livelihood diversification would improve SLM, advance local-scale contributions towards LDN and provide positive equity impacts on the welfare of Kalahari communities. Successful socio-economic and environmental outcomes will depend on the type of land use promoted and the different management strategies adopted under each.

These findings reinforce similar considerations raised by other rangeland studies globally, which stress the need to look beyond the economic value of marketed ES and take into account environmental and conservation perspectives in land decision making. Through application of the residual value method, Campos *et al.* (2016) assessed private livestock grazing environmental income across silvopastoral ecosystems in Spain, identifying maintenance of livestock grazing as a key policy challenge, particularly when multiple ES and an increased supply of public goods and services are considered. Our Monte Carlo simulations combined with MCDA analysis (Favretto *et al.*, 2016) add to this discussion, suggesting that despite the high profitability of cattle production, the multi-faceted effects of land degradation must be considered in the development of interventions aimed at compensating graziers for the value of their livestock. Incentives that might encourage over-grazing must be avoided, particularly in degraded areas (both communal and private) characterised by high levels of bush encroachment, which result in lower primary production of grass species needed to maintain cattle production (Favretto *et al.*, 2016; Reed *et al.*, 2015). As described through a stochastic best response dynamics model which coupled "social" and "grass biomass" dynamics in the study of Mongolian rangelands, grazing pressure is correlated to grass biomass depletion (Lee *et al.*, 2015). Herders' decisions on foraging sites depend on the variability in their payoff rates, which is inversely correlated to the levels of degradation (*i.e.*, higher grass depletion / lower payoffs). Similarly, an assessment of the impacts of stocking rates on soil quality and pasture production in privately owned rangelands in southwestern Spain, based on statistical analysis and structural equation models, indicated that heavy grazing can produce large surface areas of bare soil (Pulido *et al.*, 2016).

The outcomes of major rangeland management policies have been assessed through a systematic literature review in China (Gongbuzeren *et al.*, 2015) highlighting the need for more flexible and inclusive land policies, with a view to fostering coadaptation between social and ecological systems under varied local institutional arrangements. Addressing these considerations, and the implications of land use decisions for social equity, across multiple continents and rangeland systems is also important in the Kalahari, and will be crucial in the promotion of LDN.

Expressing the range of monetary and non-monetary values underpinning the Kalahari rangelands in economic terms, Monte Carlo simulations provide an effective tool for identifying ES values that support wider dryland populations who depend on ES under different land uses. Consequently, its results may provide useful guidance to policy-makers who still often operate in silos and without considering knock-on implications of their decisions for ES in sectors beyond their own (Martinez-Harms *et al.*, 2015). It provides an intuitive way to expand initial mixed-method analysis to better capture uncertainties surrounding ES within multi-functional landscapes. By enabling the combination of all ES into the TEV of ES provision, our approach goes beyond the capability of MCDA, which typically delivers both qualitative and quantitative information, making it difficult for policy-makers to appreciate the implications of their actions for total ES values. Monte Carlo simulation provides a useful 'first stab' at calculating total ES values. If more detailed considerations are needed, results can be refined with more elaborate approaches that better represent causal system mechanisms, such as Dynamic Systems modelling (*e.g.* Dougill *et al.*, 2010) or Bayesian Belief Networks (*e.g.* Fenton & Neil, 2013; Yet *et al.*, 2016). Such approaches, however, require more expertise, analytical effort and, in many cases, far-reaching assumptions. In this context, Monte Carlo simulation is more likely to find widespread application and should be considered more widely for valuing ES provision within multi-functional land use systems.

CONCLUSIONS

This paper provides an empirical contribution to our understanding of how the range of (monetary and non-monetary) values generated by ES under varied land uses, can be quantified in monetary terms. It applies stochastic simulation through a Monte Carlo-based approach to advance estimation of the value of ES under different land uses. It highlights the uncertainty of ES value distributions under each land use in Botswana's Kalahari rangelands and identifies the ES with the greatest impact on the variation of such distributions. Sensitivity analysis using the

PLS procedure indicates that variability of monetary outcomes under cattle and game ranch land uses is strongly correlated to the value produced by key ES linked to meat production, including plant / livestock diversity, groundwater extraction and profit of meat production. Given the focus of tourist and recreational activities pursued by private game ranches, recreation was identified as a key ES with high impacts on value variability under this land use. Uncertainty about variability in value distributions across communal grazing and WMAs is closely tied to problems in valuing cultural / spiritual inspiration, recreation, as well as firewood, construction material and wild food. It is vital that sustainable land management policies support the provision and utilisation of non-monetary ES, with a view to enhancing livelihood diversification, reducing land degradation and fostering positive equity impacts on the welfare of Kalahari communities. Identifying policy mixes that support multifunctional landscapes will be vital in both promoting sustainable land management and moving towards LDN.

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Supporting information

S1: Checklist of questions assessed through semi-structured interviews in Kgalagadi District, southern Botswana

S2: Bibliography of secondary data, policy and strategic documents, benefits transfer and ecological assessments

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FIGURES

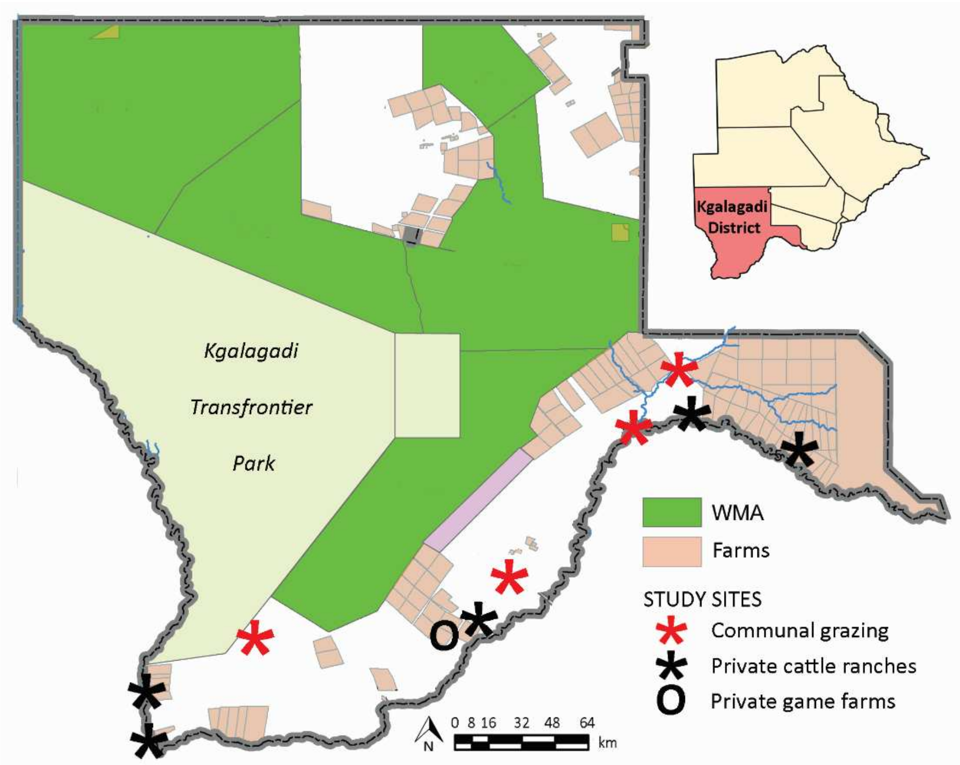

Figure 1. Land use of Kgalagadi District, southern Botswana and sample point within the study site. Source: modified from Favretto *et al.*, 2016.

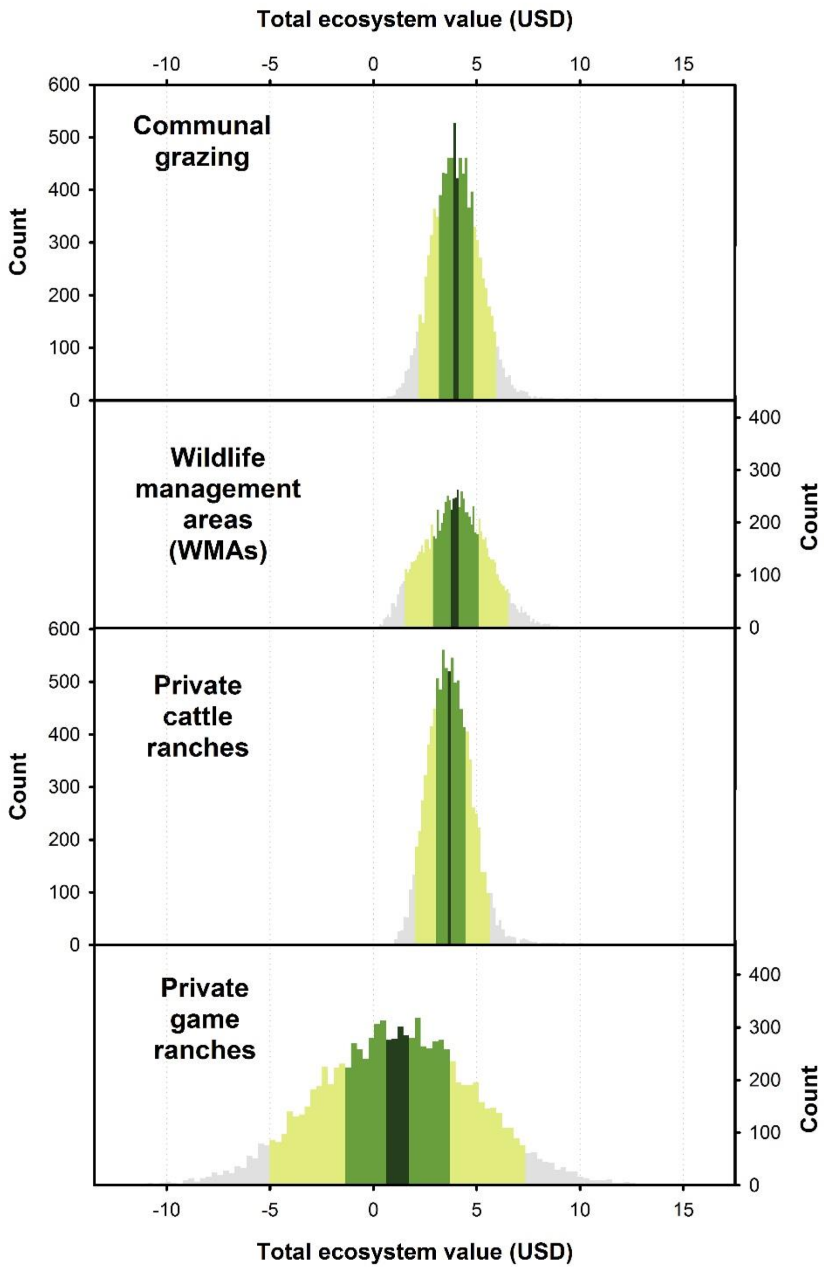

Figure 2. Overall ecosystem service value (USD / km^2) under four land uses in Botswana's Kalahari rangelands assessed through Monte Carlo simulations. The different shades of green show confidence intervals around the median, defined by the 5% and 95% quantiles (lightest green), 25% and 75% quantiles and 45% and 55% quantiles (darkest).

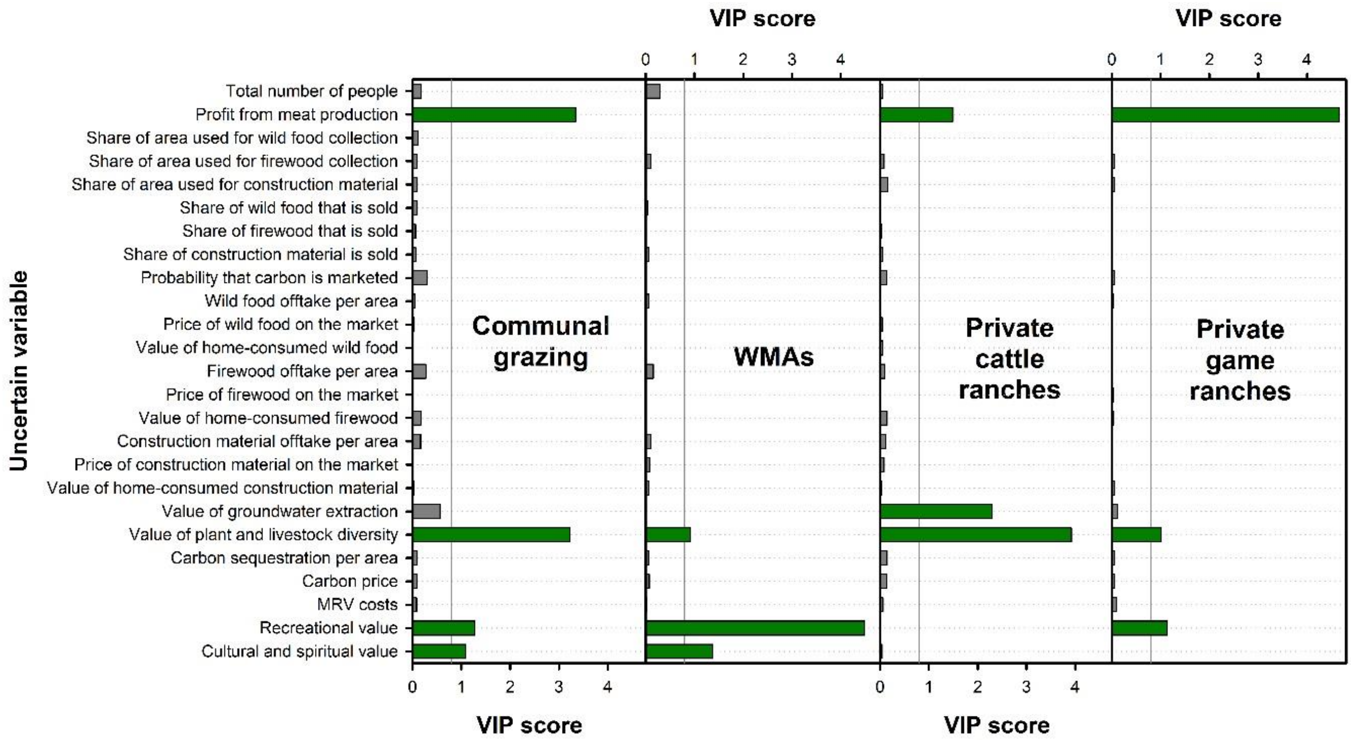

Figure 3. Importance of uncertainty about the value of individual ecosystem services for explaining variation in estimates of the total ecosystem services value provided by four land use types in Botswana's Kalahari rangelands. Variable importance was assessed by the Variable-Importance-in-the-Projection metric of Partial Least Squares regression, applied to the output of Monte Carlo simulations.

TABLES

Table 1. Ecosystem services assessed through Monte Carlo analysis in Botswana Kalahari

Ecosystem service	Ecosystem service category
	PROVISIONING SERVICES
Food (commercial)	Net profit of meat production
	Stocking level
Food (wild)	Gathering of veld products
	Subsistence hunting
Fuel	Firewood collection
Construction material	Collection of thatching grass and poles for fencing
Groundwater	Value of water extracted (USD / km^2 / yr)
Plant and livestock diversity	Species and genetic diversity between forage species
	Genetic diversity between livestock breeds
	REGULATING SERVICES
Climate regulation	Value of carbon sequestration (USD / km^2 / yr)
	CULTURAL SERVICES
Recreation	Revenues from Community Based Natural Resource Management trophy hunting and photographic safari (USD / km^2 / yr)
	Ecotourism potential
	Wild animals diversity
Cultural/ Spiritual benefits	Presence of landscape features or species with cultural/spiritual benefits