Environmental Management (2014) 54:1005–1021
DOI 10.1007/s00267-013-0202-x

An Exploration of Scenarios to Support Sustainable Land Management Using Integrated Environmental Socio-economic Models

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Received: 22 January 2013 / Accepted: 3 November 2013 /

Abstract Scenario analysis constitutes a valuable deployment method for scientific models to inform environmental decision-making, particularly for evaluating land degradation mitigation options, which are rarely based on formal analysis. In this paper we demonstrate such an assessment using the PESERA–DESMICE modeling framework with various scenarios for 13 global land degradation hotspots. Starting with an initial assessment representing land degradation and productivity under current conditions, options to combat instances of land degradation are explored by determining: (1) Which technologies are most biophysically appropriate and most financially viable in which locations; we term these the “technology scenarios”; (2) how policy instruments such as subsidies influence upfront investment requirements and financial viability and how they lead to reduced levels of land degradation; we term these the “policy scenarios”; and (3) how technology adoption affects development issues such as food production and livelihoods; we term these the “global scenarios”. Technology scenarios help choose the best technology for a given area in biophysical and financial terms, thereby outlining where policy support may be needed to promote adoption; policy scenarios assess whether a policy alternative leads to a greater extent of technology adoption; while global scenarios demonstrate how implementing technologies may serve wider sustainable development goals. Scenarios are applied to assess spatial variation within study sites as well as to compare across different sites. Our results show significant scope to combat land degradation and raise agricultural productivity at moderate cost. We conclude that scenario assessment can provide informative input to multi-level land management decision-making processes.

Keywords Integrated modeling · Scenario analysis · Spatial cost benefit analysis · Land degradation mitigation · Decision-making

Introduction

Globally, land degradation remains one of the most pressing environmental issues, with important implications for sustainability across various levels through intricate linkages with food production, poverty, and climate change (Meadows and Hoffman 2003; FAO 2011; Stringer et al. 2012). Efforts to address land degradation through enabling widespread adoption of effective remediation technologies are becoming more and more critical as land productivity needs to be fostered (Burney et al. 2010; FAO 2011) and resilience of agricultural systems enhanced (Koohafkan et al. 2012; Tittonell and Giller 2013). In this research, land degradation remediation or sustainable land management (SLM) technologies can be defined as practical measures to: (1) prevent and/or lessen and/or reverse the effects of land degradation on land resources (including soil and

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water) extending over defined spatial-, temporal-, and socio-cultural boundaries; and (2) maintain and improve land productivity, water saving and use efficiency. Such practical measures could (but do not necessarily) imply a change of land use, and land users' livelihoods.

Scaling-up the adoption of remediation technologies beyond initial spatial, temporal and socio-cultural boundaries is nevertheless challenging. Frequent low adoption rates of SLM measures in agricultural areas facing obvious land degradation have been reported (e.g., Tucker and Napier 2002; Bekele and Drake 2003; Tenge et al. 2005, 2007). Often, low uptake of SLM measures is due to failure of the design and the implementation of SLM approaches to fully recognize the land managers' interests and the socio-economic dimension. As an illustrative example, high initial investment costs may de-motivate farmers from applying particular SLM measures on their land (e.g., Tenge et al. 2005). In the same way, land managers may abandon existing conservation technologies due to substantial maintenance costs (Duarte et al. 2008; Bellin et al. 2009; Kizos et al. 2010). Environmental conditions may play an important role in the adoption processes of SLM measures, as demonstrated by the very high uptake of no-till systems in sloping olive groves in Southern Spain, where tillage is expensive (Franco and Calatrava 2012). With these challenges in mind, an integrated ex ante evaluation of potential technologies could serve as an important tool for examining the likely implications of implementing these technologies; hence, providing hints on those that are promising from a holistic perspective (Jansen et al. 1999; Blazy et al. 2010; Sirrine et al. 2010). We regard such evaluation processes as important in enabling land users to consider the implications of technologies based on scientific prediction alongside other factors influencing their preferences in selecting technologies. Such evaluations are also valuable in informing policy makers to help them decide which SLM technologies they should promote with policies.

Comprehensive identification and evaluation of remediation technologies are necessary steps in order to assess the spatial extent of the applicability of potential technologies, their cost, and the likely impacts they will bring. In the process of selecting which technologies to evaluate, close involvement of stakeholders, especially of land managers, is vital (Schwilch et al. 2012a; Hessel et al. 2013). In turn, the evaluation of the selected technologies further informs stakeholders regarding the regional impacts of the technologies under consideration; hence, enhancing their understanding about the technologies. This principle underpins the integrated PESERA–DESMICE framework (Fleskens et al. 2013) which was developed as part of an EU Framework 6 project: Desertification Mitigation & Remediation of Land (DESIRE; http://www.desire-project.eu/) and used for the analysis reported in this paper. PESERA is a process-based erosion prediction model and DESMICE is an economic evaluation model that is operationalized through spatial cost-benefit analysis (CBA) and can be added onto PESERA. The key assumption underpinning the modeling is that, to stand a chance of getting adopted, technologies need to be financially attractive to land managers in terms of cost reduction and/or benefit enhancement.

A multitude of studies on the evaluation of land degradation remediation technologies exist, including those based on CBA (e.g., Hengsdijk et al. 2005; Nyssen et al. 2006; Abu Hammad and Borresen 2006; Fleskens et al. 2007; Bizoza and de Graaff 2012; Balana et al. 2012). However, often such evaluations entail only one particular technology or cover only one specific study site. Here, we report on a scenario assessment across 13 study sites of the DESIRE project, spread over five continents. The novelty of the research reported in this paper is threefold. First, the analysis deals with multiple technologies. Second, the assessment is carried out for various sites with different characteristics, facilitating the cross-site comparison of similar land degradation remediation technologies. Third, to the best of our knowledge, this paper is the first attempt to frame the evaluation of remediation technologies through an exploration of multiple scenarios, allowing integration of technology assessment in environmental decision-making at multiple levels. Despite increasing recognition by policy makers and resource managers of the usefulness of scenario analysis for environmental management, the exploitation of the potential of such an approach is still lacking in the context of assessing measures to tackle land degradation.

As shown in this paper, the coupling of scenario analysis into the PESERA–DESMICE modeling framework provides an effective approach for up-scaling the costs and benefits of adopting a wide range of remediation technologies under various circumstances from field experiment results to regional scale. This approach also allows the assessment of the wider potential impacts of implementing different technologies (e.g., for food production) and can be used to help inform the design of effective policy intervention to promote adoption of the technologies. The research reported here makes an important academic contribution and simultaneously offers insights of high policy relevance. The following section introduces the study sites and describes in detail the different scenarios under which the evaluation of a number of technologies to combat land degradation was carried out. Subsequently, a synthesis of findings is presented and discussed; for a full overview of results from the scenario assessment, the reader is referred to Fleskens et al. (2012).

Methods

Study Sites

For this paper, the scenario analysis using PESERA–DESMICE modeling was implemented for 13 DESIRE study sites (Fig. 1). These sites have been selected as they are among the hotspots of land degradation across five continents: Africa, Europe, Asia, North-, and South America, whereby it should be noted that the focus of the DESIRE project has been on the Mediterranean and Mediterranean-type environments. The selection of the study sites was also intended to ensure a good representation of land use diversity and variation in the types of land degradation issues (Table 1). In some areas, land use is dominated by arable farming activities, while in other sites grassland for grazing animals is more prominent. In certain areas, forested lands receive important attention. Accordingly, the nature of the land degradation problem within each of the study sites and priorities for the deployment of mitigation strategies are largely shaped by the important land use types in the given areas. For example, where crop production is of high importance, land degradation typically tends to be linked to problems like water erosion (on-site) and sedimentation (off-site). On the contrary, forest fires have been a major issue in places like Portugal.

Given, the variation in the landscape and land degradation characteristics across the selected study sites, technical adjustments were necessary when running the PESERA–DESMICE simulations for particular sites. For example, the DESMICE model was applied in a non-spatially explicit manner to assess biogas as a land degradation mitigation option in the Boteti area in Botswana (Perkins et al. 2013). Biogas substitutes firewood as a source of energy, and is produced from animal droppings and waste materials that are hitherto mostly lost and not used productively. Despite the aforementioned adjustments, it was still possible to subject the outcomes from the different study areas into a cross-site analysis.

Some DESIRE study sites have not been included in the analysis carried out for this paper. In the Rendina basin (Italy), shallow landslides are the main problem for which PESERA was extended (PESERA-L; Borselli et al. 2011). However, the temporal and spatial dimensions at which shallow landslides occur are not readily translatable into land use management options for which to conduct a CBA, and therefore the DESMICE model could not be applied. The Nestos site (Greece) and two Russian study sites (Novij and Djanybek) feature salinization and water logging problems for which PESERA is not applicable. In principle, it would be possible to couple the DESMICE model with alternative models that are more suitable for these problems than PESERA, but this was not done in the current study.

Defining Scenarios

The analysis undertaken for this paper builds upon the PESERA–DESMICE integrated modeling framework described in Fleskens et al. (2013). In principle, the PESERA–DESMICE model offers an effective way to scale up the potential impacts of the adoption of land degradation remediation measures from experimental field plots across

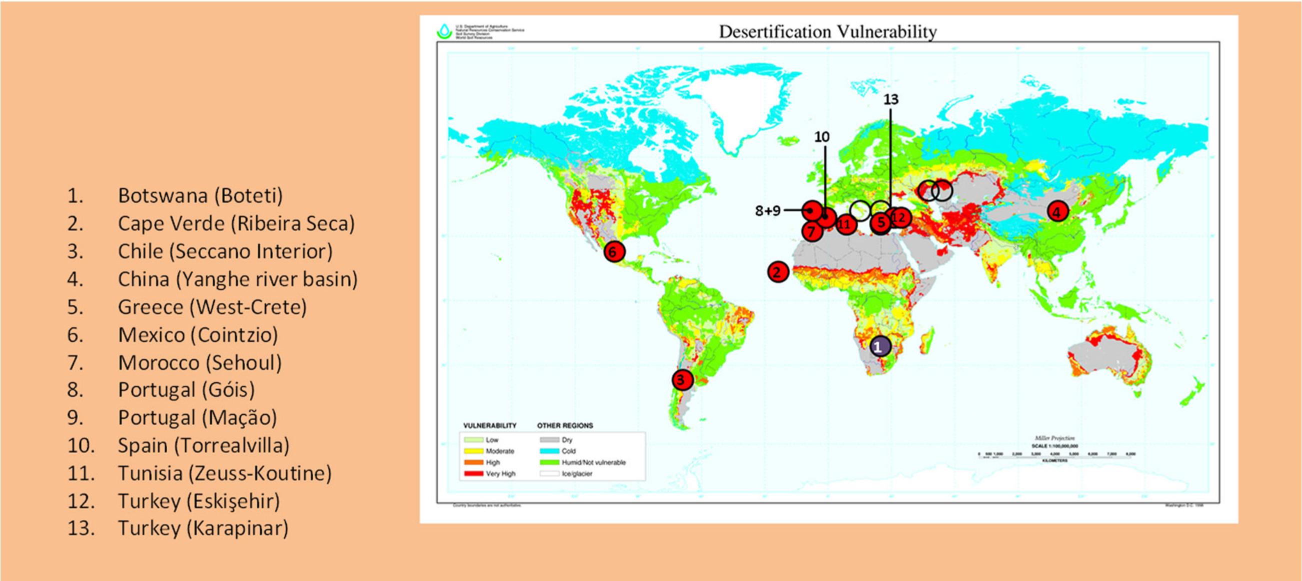

Fig. 1 Locations of DESIRE study sites for which PESERA–DESMICE was run

Table 1 Key characteristics of study sites

Site	Land use	Main degradation processes
Botswana—Boteti (3,000 km^2)	Arable agriculture, grazing livestock, grasslands	Drought, human-induced wind erosion
Cape Verde—Ribeira Seca (71.50 km^2)	83 % subsistence rainfed agriculture (corn and beans), 5 % irrigated; 4 % forest	On-site: water erosion, off-site: sedimentation
Chile—Secano Interior (9,097 km^2/1,699 km^2 simulation zone)	Cereals, forest plantations, grass and shrubland	Water erosion
China—Yanhe River Basin (7,678 km^2)	Cropland, dam-land, paddy field, forest plantations, shrub, cash trees, orchards and grassland	Water erosion and sedimentation of reservoirs and riverbed
Greece—West-Crete (720 km^2)	Scrublands, rainfed (olives) and irrigated agriculture, forests, and natural pastures	Water erosion, soil and water salinization, water stress
Mexico—Cointzio (640 km^2)	Scrublands, forests, rainfed and irrigated agriculture, and grasslands	Water erosion
Morocco—Sehoul (397 km^2)	Arable land, forest, shrubland	Water erosion
Portugal—Góis (263 km^2)	Pine and eucalyptus forests, arable land, unproductive land and settlements	Forest fires, land abandonment through depopulation
Portugal—Mação (400 km^2)	Pine and eucalyptus forests, arable land, unproductive land and settlements	Drought, compounded by catastrophic forest fires
Spain—Rambla de Torrealvilla (266 km^2)	Rainfed agriculture (cereals, almonds, olive), irrigated agriculture (horticulture, fruit trees, grapes), livestock.	Water erosion, soil salinization
Tunisia—Zeuss-Koutine (897 km^2)	Rangeland, tree crops, annual crops (cropping linked to water harvesting)	Water & wind erosion, rangeland degradation and drought.
Turkey—Eskişehir (90 km^2)	Arable land (cereals, sugar beet, sunflower), pastures, forest	Water and wind erosion, droughts, urbanization
Turkey—Karapinar (156 km^2)	Arable land (cereals, maize, sugar beet, potato, fodder crops), pastures	Wind erosion, salinization, overgrazing

landscapes of interest and was here applied at a resolution of 100 m, with all results reported on a per hectare basis. A multi-scenario assessment was made to fully explore the usefulness of the PESERA–DESMICE model. For this purpose, different types of scenarios were developed to simulate the physical and socio-economic effects of proposed remediation technologies under a wide array of circumstances presented by each of the specified scenarios. The scenarios are described in the next sections.

Baseline Assessment of Land Degradation (i.e., the PESERA Baseline Run)

This assesses the magnitude of land degradation problems (in terms of soil erosion or fire severity index—Kirkby et al. 2008; Esteves et al. 2012) and the biomass production potential across the different study sites under current conditions. Biomass production potential can show nuances in productivity caused by environmental gradients as well as the sometimes large variation between different land uses—e.g., arable land versus forests. The units of biomass production are kg/ha or ton/ha and include whole-plant biomass, not just yields. A harvest index is therefore required to calculate the latter. In most cases, a single output map is generated for initial conditions. However, in some cases, a lack of clarity over current study site conditions, for example, in relation to the level of compaction, commanded the production of more than one set of baseline output maps.

Technology Scenario

This assesses the biophysical effects and financial viability of mitigation options for those areas to which they are applicable. Determining these "applicable areas," i.e., the share of the study area where the technology can, in biophysical terms, be implemented, constitutes a first step in technology scenario simulations (Fleskens et al. 2013) and is followed by a spatial assessment of financial viability. Technology scenario assessments form the core of the scenario simulations, as subsequent policy, adoption, and global scenarios are based on them. Input data was primarily obtained from an assessment of each technology using the WOCAT (World Overview of Conservation Approaches and Technologies) methodology (Schwilch et al. 2012b), field experiments (Jetten and Shrestha 2012), and information sheets with further data requests that were completed by study site researchers. For the simulation, costs of inputs (including technologies) and prices of agricultural outputs are given in local currency and Euros to facilitate comparison between sites. Soil erosion maps compare annual soil erosion across situations "with" and

Box 1 Assumptions for financial viability calculations

Financial analysis of the technology under consideration is an essential element of each technology scenario, and is revisited in any policy scenario (where applicable). Exact cost and benefits are difficult to define. Care has been taken to err on the conservative side so that the assessment does not paint too rosy a picture of the technology. When using the presented figures, the following list of important assumptions made need to be borne in mind:

- A profitability or NPV greater than 0 is deemed to be the minimum required for financial viability of a technology. It is acknowledged that many factors come into play for a land user to decide to implement a technology, but if a technology does not at least maintain the current financial status quo, the technology is deemed not attractive.
- In the technology scenario, all costs are assumed to be incurred by the land user (or other decision-making entity). Any subsidies or other forms of incentives are excluded from the analysis. The results thus reflect the financial attractiveness of a technology for spontaneous adoption. Subsidies are included in the policy scenarios.
- In the policy scenario, it was assumed that policies equally impact all land users and that policies are continued indefinitely.
- Study site researchers struggled to estimate spatial variation in investment costs of technologies. Environmental variations (e.g., with slope steepness) are taken into account for structural measures such as terraces, but distance to source areas and markets was not taken into account in the analyses.
- While the temporal dimension of changes in productivity is crucial for land users, PESERA assessments of technologies produce equilibrium outputs. The time lag to arrive at these equilibrium conditions is not explicit. In the case of some management measures, especially those implemented on severely degraded lands, it may take a very long time to arrive at equilibrium conditions. Linear trends are assumed in these cases, with equilibrium conditions assumed to be reached after 20 years.
- Similarly, current conditions are assumed to be at equilibrium. No ongoing productivity decline due to progressing degradation is considered in the “without” case.
- Where perennial crops are planted as part of a technology, progression of productivity is set according to local and species-specific trends.
- Some structural technologies harvest water or accumulate land from a larger area. In these cases, a conversion factor such as a catchment to cropped area ratio (CCR) has been assumed. Conditions in the catchment area are assumed to remain constant after implementing the technology.
- In the specific case of Portuguese study sites, where technologies are intended to mitigate risk of wildfire occurences, analyses have been performed based on actual fire outbreaks between 2000 and 2009 for which spatial data were available. In these cases, a single financial viability estimate is given as the application of the technologies is not assessed from an individual land user perspective but for a municipality as a whole.
- All financial analyses are sensitive to price fluctuations. Although no sensitivity analyses are performed, one of the most difficult assumptions is the price of labor (opportunity) costs. All analyses have duly priced all labor input at the going daily wage rate in the study areas. Land users are known to accept lower return to labor in several circumstances (slack season, conservation works around the home in spare time, etc.) so financial viability maps can be regarded as conservative estimates.

“without” the implementation of technologies. For the Portuguese study areas, where wildfires are the main degradation problem, erosion maps are replaced with fire severity index maps and analysis focuses on total biomass rather than yields as a reduction in biomass accumulation is considered the main mitigation outcome here. Financial viability assessments come in two forms: (i) for agronomic measures that need to be repeated annually as part of the production cycle, the outcome of a partial budget analysis of the difference of costs, and benefits in the “with” and “without” situation is presented; (ii) for technologies requiring investment (monetary or in kind) and where benefits accrue only after a certain period, CBA is applied and includes valuation of labor and the use of a discount factor (set at 10 %). In investment analyses, the lifespan of technologies was taken into account and planning horizons of up to 20 years were considered. The output in this case presents the Net Present Value (NPV) of the investment. Box 1 summarizes the most common assumptions made in calculating profitability or NPV of remediation options.

Policy Scenario

This assesses the effectiveness of financial incentive (and alternative) mechanisms to stimulate adoption of technologies if they are not financially viable. Local policies have in some cases been considered based on an analysis of policies and drivers (Mantel et al. 2011) or other information from study sites. Policy scenarios are presented for any incentive or strategy that could help to improve the viability and/or extend the adoption of a technology with the final goal of enhanced mitigation of land degradation. Most frequently, policy scenarios assess the cost-effectiveness of subsidies to reduce investment costs to implement a technology for land users (e.g., an incentive in the form of a 50 % reduction is often presented). The policy scenario starts with a description of the issue and the type of incentive/strategy to be evaluated. Subsequently, the profitability of the technology with and without the policy is compared. Due to data constraints and the peculiarity of the land degradation problems, for some study areas, estimates for profitability are given for the entire area and are not spatially explicit. Finally, cost-effectiveness indicators are presented to assess the cost of the policy measure (from a public or governance perspective) in relation to the environmental benefit obtained. Cost-effectiveness can be expressed in monetary units per ton of soil loss prevented, or per hectare of land saved from burning.

Adoption Scenario

This considers the simulated technologies (if more than one) simultaneously and assumes that the most profitable option has the highest potential for uptake by land users. In other words, adoption scenarios are presented where multiple technologies with partially overlapping applicable areas are being assessed. In order to make the NPV of different options comparable, the same time horizon is applied to the analysis: at minimum the lifespan of the technology with longest longevity and at maximum 20 years. The purpose of the adoption scenario is to provide an overall view of the spatial arrangement of the possible mitigation options, and the adoption patterns if it is assumed that in each cell (1 ha), the most profitable technology (i.e., the one with the highest NPV) is selected. This assessment is made for all technology scenarios ("without policies") and all policy scenarios combined ("with policies"). For many study sites, only a single technology scenario was run, or different technologies had mutually exclusive applicable areas. In such cases, there would be no added value in presenting an adoption scenario, which is hence not elaborated.

Global Scenario

This takes a reverse approach to the policy scenario. Instead of asking what the effectiveness of a policy is, it considers the technical capabilities of the remediation option(s) in creating impact across the study area, and then provides an investment requirement (localized, for land managers, and aggregate, for policy-makers). The objective of this analysis is not so much a local analysis, but to provide a global comparison of potential impact—hence the name "global scenario." Two types of global scenarios were defined which address major sustainable development challenges for agriculture: (i) food production maximization scenario and (ii) land degradation minimization scenario. The food production maximization scenario explores potential scope for increased food production by assessing how much more food could be produced in an area if land degradation remediation technologies were adopted to the extent that they enhance crop production. This scenario selects the technology with the highest agricultural productivity (biomass) for each cell where a higher productivity than under current conditions is achieved. The land degradation minimization scenario explores the extent to which soil erosion could be curbed if effective remediation technologies were fully implemented. This scenario selects the technology with the highest mitigating effect on land degradation or none if the initial situation demonstrates the lowest rate of degradation (but see Box 2). In both types of global scenario, the absolute and percentage improvements relative to current conditions are presented. Note that for food production, yield increases are reported rather than biomass increases (see also Box 2). For erosion reduction, negative rather than positive numbers are effective and color coding for soil erosion reduction classes have been inverted to illustrate this. Biophysical impact and financial indicators are subsequently provided. These are also used to calculate the main indicators: yield increase per hectare and per capita for food production maximization scenarios, and erosion reduction per hectare and cost per ton of soil prevented from eroding for land degradation minimization scenarios.

Box 2 Limitations of global scenarios

For land degradation minimization scenarios, assessment is limited to reductions in soil erosion rates. We are aware that there are many other types and symptoms of land degradation, and potential variables to express degradation processes. Different types of land degradation, such as wildfires, were not considered in this assessment. An example of a different symptom of land degradation is bush encroachment which impacts pasture quality (e.g., in Botswana) but in other ways (soil erosion reduction, carbon sequestration) is actually beneficial.

For food production maximization scenarios, increased cereal yields, even of different crops, are deemed to be directly comparable across study sites as they have similar calorific content. Yield increases of other crops, such as olives and apples, are also provided but not included in cross-site analysis due to their non-staple character. Still other production increases, such as rangeland productivity having an impact on livestock production, and agave production for alcohol distilling, have not been reported here.

Results

Magnitude of Land Degradation Across Study Sites

Assessments of the magnitude of soil erosion under current conditions were made for a range of study sites. The results of these assessments show spatial variations even within individual study sites (e.g. Figure 2). By comparing these assessments, it becomes apparent that there are large differences between sites (Fig. 3a). According to the results of the PESERA simulations for current conditions, the Seccano Interior (Chile) demonstrates the most severe soil erosion, while Yanhe river basin (China) and Eskisehir (Turkey) also rank high. West-Crete

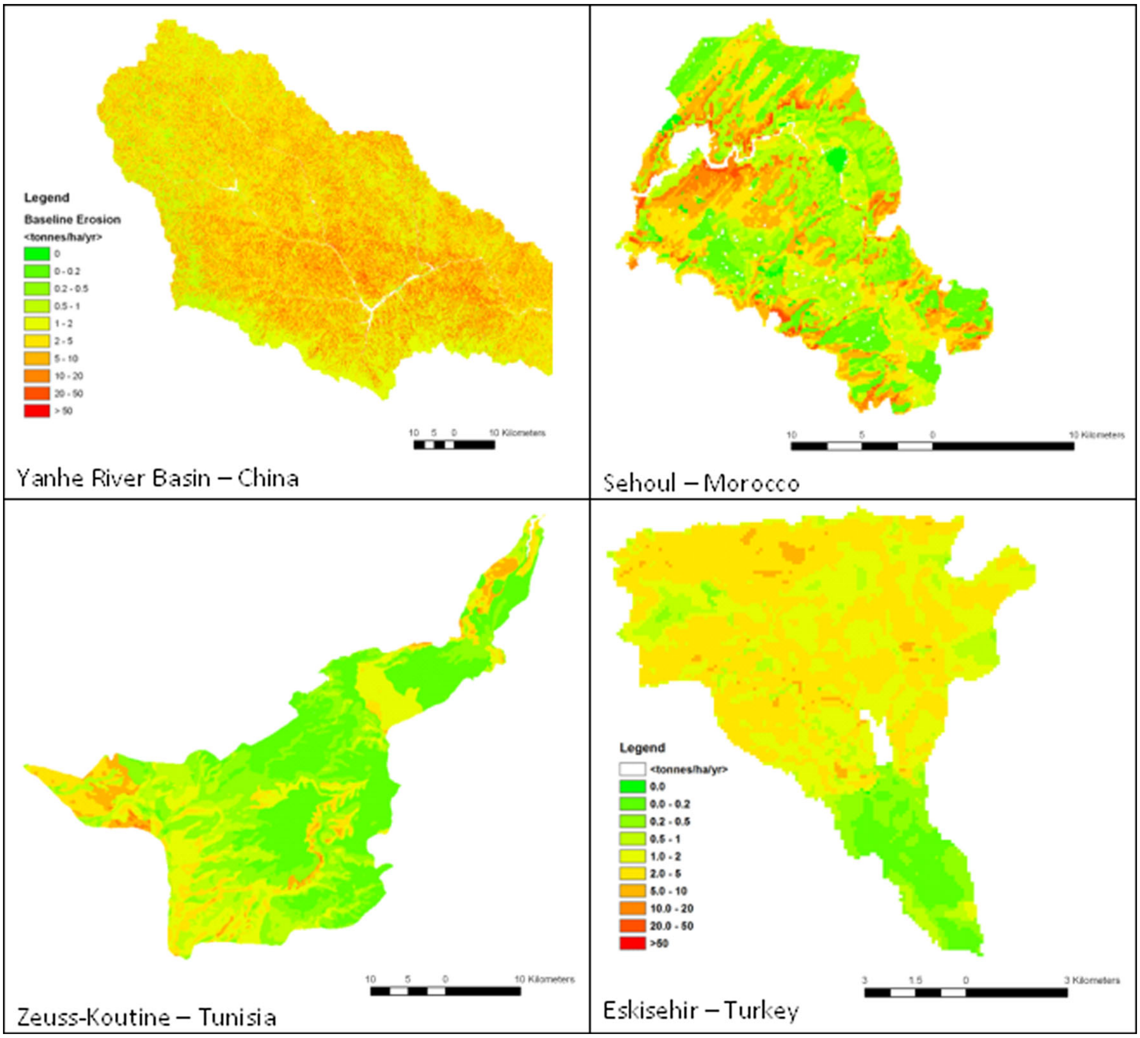

Fig. 2 Examples of PESERA baseline land degradation assessment maps

(Greece), Cointzio (Mexico) and Sehoul (Morocco) show a more mixed picture, with both pockets of unaffected and severely affected land. According to these results, the Torrealvilla (Spain) and Zeuss-Koutine (Tunisia) areas are only moderately affected by soil erosion. One very remarkable result is the low degradation problem in Karapinar (Turkey). In this site, wind erosion rather than water erosion is the main degradation problem, which further leads to the need to recognize that either lower soil loss rates are already alarming or wind erosion processes were not adequately modeled, e.g. because of a lack of good wind speed data.

It is interesting to compare model assessment of soil erosion with land degradation mapping using expert knowledge (Fig. 3b). The latter was done to assess the degradation context of all DESIRE project study sites using the WOCAT mapping method (Van Lynden et al. 2011). When comparing Fig. 3a and b, one can see that in:

- China—the proportion of the area affected by serious land degradation is roughly similar in both assessments; experts are more optimistic in classifying the remaining land as little affected than model results suggest;
- Mexico—there is little agreement between model results and expert opinion, with the latter assessing the situation as being much less degraded;
- Morocco—both model and experts sketch a mixed picture of land degradation, with a striking level of agreement;
- Spain—although both methods emphasize intermediate classes of land degradation, the model is on this account more optimistic than the experts;
- Tunisia—experts consider over 70 % as severely degraded, whereas the model assesses 70 % as being degraded very little;
- Turkey (Eskisehir)—there is again a striking agreement between model and expert opinion indicating that this is a severely degraded site;

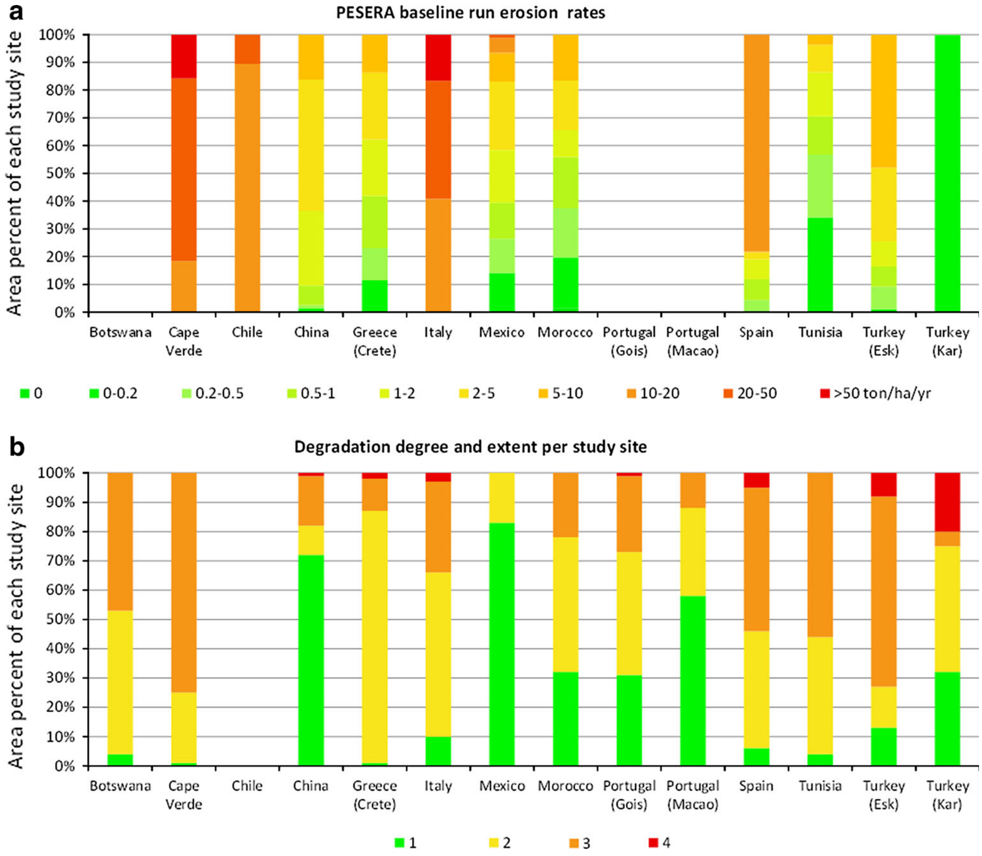

Fig. 3 **a** Overview of PESERA baseline run erosion rates; **b** Degradation degree and extent according to WOCAT mapping, with *1* light, *2* moderate, *3* strong, and *4* extreme degree of degradation (source Van Lynden et al. 2011). Total averages per study site; note that for the Botswana and Portuguese sites with other degradation types (bush encroachment, wildfires) erosion rates were not modeled, and for Chile, no WOCAT mapping data was available

- Turkey (Karapinar)—little agreement exists, with experts noting severe land degradation and the model missing any degradation problem (as is briefly discussed above).

Overall, the Tunisian site is the most arid, followed by the Spanish and Turkish sites, which overall seem to have more severe land degradation in expert opinion than model assessment. It could be that low levels of vegetation typical for those more arid conditions influence the experts, or that PESERA is too sensitive to slope angle in comparison to plant cover.

Technology Scenarios

The effectiveness and financial viability of a total of 22 remediation technologies were simulated in the combined study sites. As Table 2 shows, structural measures ($n = 8$) were the most common, followed by agronomic measures (7), management measures (5), and vegetative measures (2). In order to include technologies, availability of experimental data (Jetten and Shrestha 2012) was in many cases a requirement to understand the functioning and effectiveness of the technology and to calibrate PESERA to local site conditions.

When classifying the simulated technologies according to the type of measure, a gradient of increasing cost of investment can be observed going from Agronomic < Management < Structural ≈ Vegetative measures (Fig. 4a). Agronomic measures were very cheap and in one case actually presented cost savings (range −€30 to €79 per ha); they can be incorporated in the annual crop production cycle and are confined to application on arable land. Management measures are more versatile and included a variety of technologies ranging from biogas to prescribed fire for fire prevention and controlling access to fields or rangelands. Management measures typically command an investment analysis as benefits tend to accrue in the medium to long term. The same holds for structural measures. Variability in investment costs was high in the structural measures category due to the inclusion of some expensive structures (e.g., checkdams for land in the case of China). Vegetative measures were surprisingly the most expensive category. Although only consisting of a non-representative sample size of two technologies, one could generalize and say that due to their implementation in restoration activities, large investments were required and in order to enable seedlings to survive, additional management, and structural measures are also necessary.

Table 2 Overview of technologies in each study site for which PESERA–DESMICE simulations were run and their classification according to main WOCAT categories: agronomic, management, structural, and vegetative

Study site	Technology name (WOCAT code[a])	Type
Boteti, Botswana	Biogas (BOT05)	Management
Ribeira Seca, Cape Verde	Terraces with pigeon pea (CPV01)	Structural
Seccano Interior, Chile	No tillage with sub-soiling (CHL01)	Agronomic
Yanhe river basin, China	Bench terraces with loess soil wall (CHN51)	Structural
	Checkdam for land (CHN52)	Structural
	Year-after-year terraced land (CHN53)	Structural
Cointzio, Mexico	Minimum tillage in rain-fed and irrigated maize	Agronomic
	Land reclamation by agave forestry with native species (MEX02)	Vegetative
Sehoul, Morocco	Gully control by plantation of atriplex (MOR15)	Vegetative
	Mulching (fencing) and conventional tillage (MOR16A)	Management
	Mulching (fencing) and direct seeding (MOR16B)	Management
Góis, Portugal	Prescribed fire (POR02)	Management
Mação, Portugal	Primary strip network system for fuel management (POR01)	Structural
Torrealvilla, Spain	Reduced contour tillage in semi-arid environments (SPA01)	Agronomic
Zeuss-Koutine, Tunisia	Jessour (TUN09)	Structural
	Rangeland resting (TUN11)	Management
	Tabia (TUN12)	Structural
Eskişehir, Turkey	Contour plowing (ETH43)	Agronomic
	Woven fences with contour plowing (TUR05)	Structural
Karapinar, Turkey	Minimum tillage	Agronomic
	Stubble fallowing	Agronomic
	Plowed stubble fallowing	Agronomic

[a] WOCAT codes are used in the DESIRE-WOCAT book (Schwilch et al. 2012b)

Next, we verified that for the technologies modeled (under widely variable circumstances), most frequently about half of the hotspot can be treated due to applicability limitations. However, in some cases this was considerably less (checkdams for land—China: 9 %; gully control by planting fodder shrubs (*Atriplex halimus*)—Morocco: 10 %) or more (terraces with pigeon peas (*Cajanus cajan*)—Cape Verde: 76 %; rangeland resting—Tunisia: 69 %). When aggregating per type of measure, management measures seem to have the widest range of applicability, followed by structural and agronomic measures (Fig. 4b). It is suggested that vegetative measures typically demand more specific conditions and are consequently less widely applicable.

Within applicable areas, many technologies are not profitable in about 70 % of the area. Figure 4c shows the aggregated financial viability of the technologies considered. This figure needs to be interpreted with caution as many factors come into play. For agronomic measures, effectiveness is an important factor. Yields may not respond or even be negatively affected, rendering the technology unviable despite its low cost. For management measures, their versatile nature means that although they are widely applicable, they are not universally financially viable. Together with structural measures, another factor with large influence is the time horizon after which the technology is evaluated. Some measures, for example, are not profitable after 10 years, but very profitable after 20 years. For structural measures, another factor that contributes to mixed financial performance is their sometimes very high investment cost. For the two vegetative measures, which are shown to be attractive in 100 % of their applicable area, one should not forget that this is on a limited area—i.e., they may be highly specialized measures. More importantly however, the "without" case is unproductive in these instances, and as plants need to grow to maturity, an appropriate time to evaluate the measure may be more easily determined than with other cases.

Policy Scenarios

A total of 11 policy scenarios were run for eight different sites, of which this section provides a brief overview. The policy schemes explored in our analysis included potential support from government to potential adopters of technologies through subsidy allocation and land zoning regulations. The analyses compared adoption for a "with subsidy" policy to a "without subsidy" one, and adoption

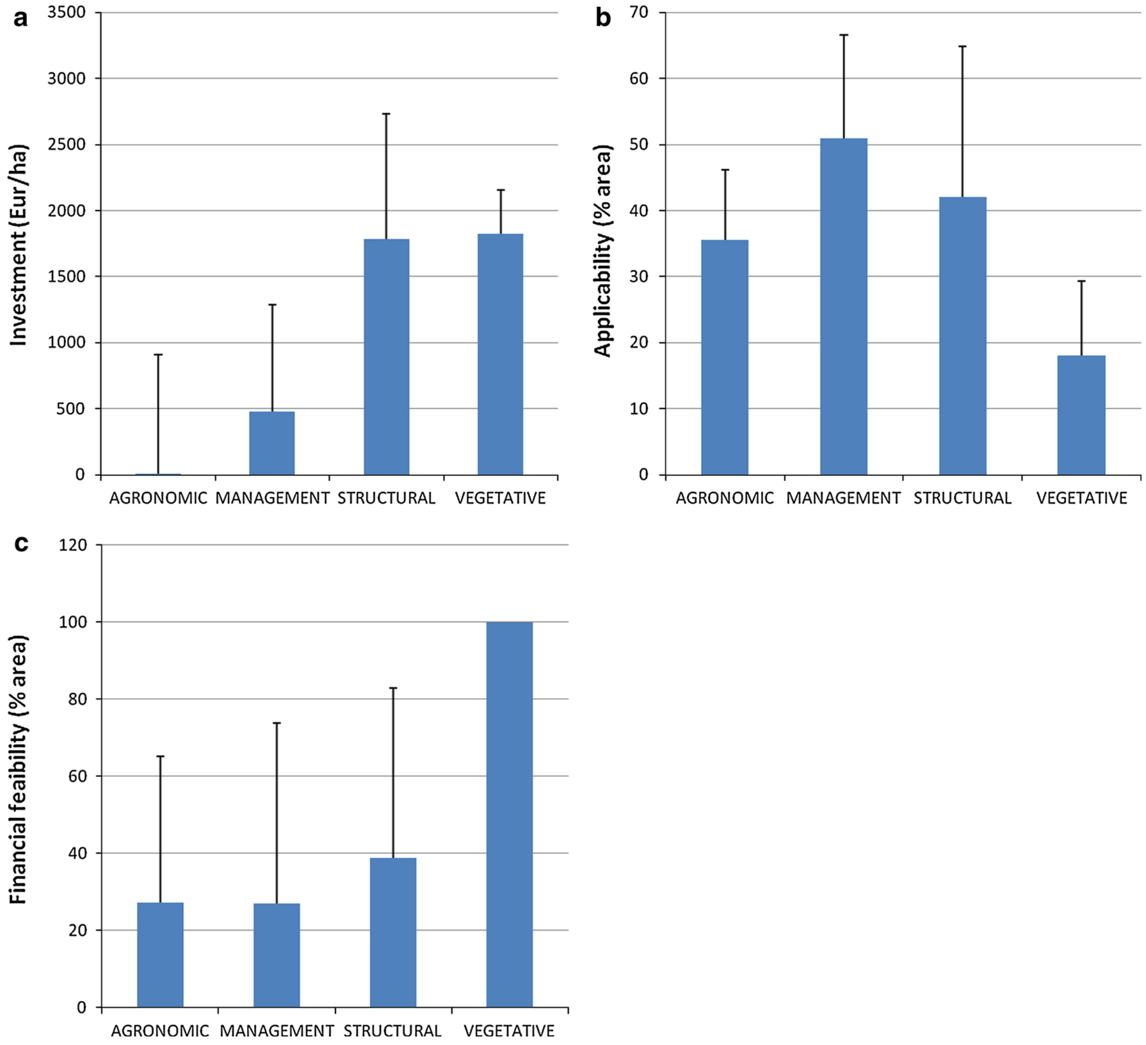

Fig. 4 Investment costs (**a**), applicability limitations (**b**), and financial viability (**c**) of different types of measures

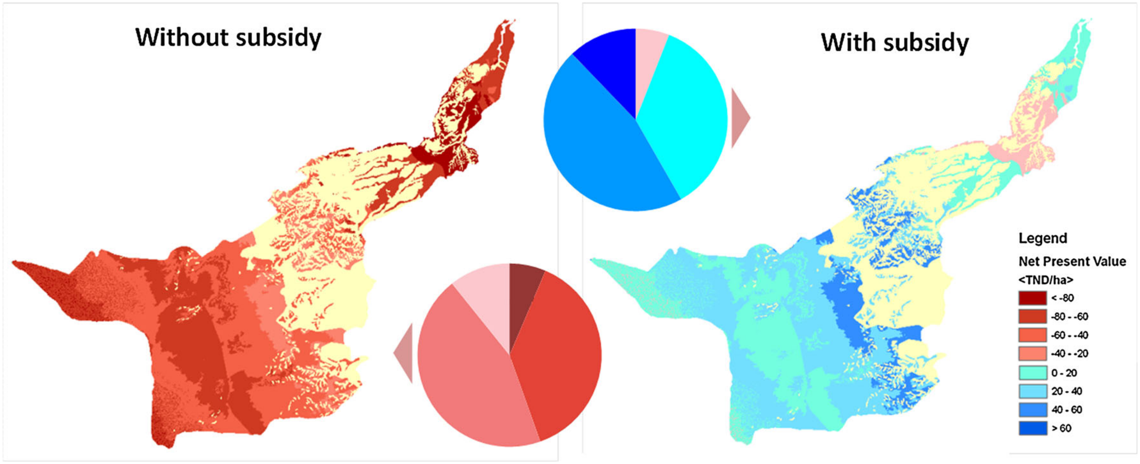

Fig. 5 Assessing the potential of policy for encouraging wider adoption of mitigation technologies (example from subsidy provision for Zeuss-Koustine in Tunisia)

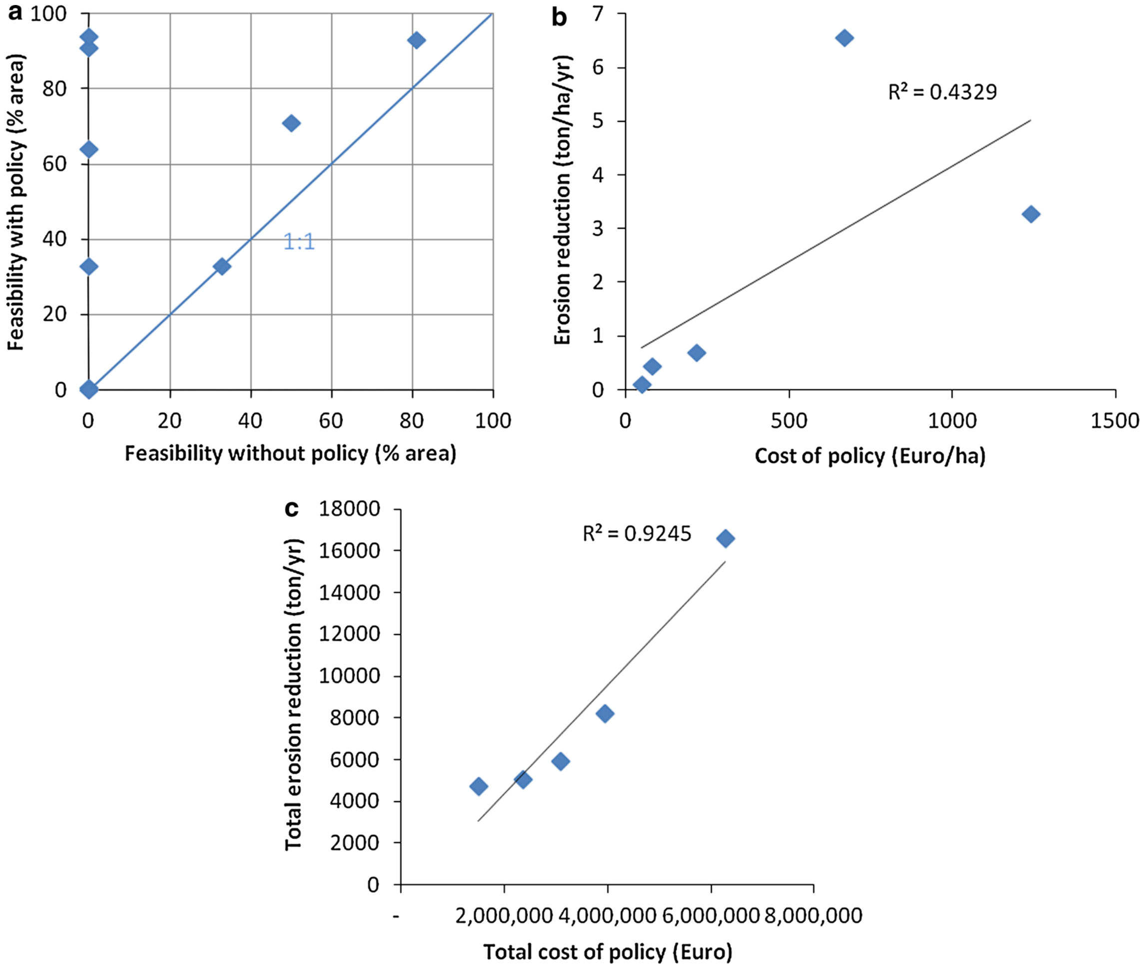

Fig. 6 **a** Effectiveness of policy scenarios on financial viability of technologies; **b** per unit cost-efficiency of policy measures assessed; and **c** total cost-efficiency of policy measures assessed

for a "with land zoning" policy to a "without land zoning" one. The first question we can ask is whether policy options (subsidies or land zoning) facilitated the up-scaling of land degradation remediation options. In most cases, mitigation technologies are not readily attractive financially to farmers due to, for example, the high investment cost for installing the technology. In other cases, the adoption of certain technologies would mean that farmers will have to halt production for a certain period of time, which in turn can have significant cost implication for the farmers. To illustrate, the introduction of rangeland resting in Zeuss-Koustine (Tunisia) may be difficult as it requires access to alternative feed, which is expensive if sourced from the market. One possible solution could be for the government to devise a subsidy to compensate land users for alternative feed requirements. The subsidy amounts to TND 30 (€15) per ha in the first year, and TND 70 (€35) spread over the next 3 years. To put this in perspective, annual returns from rangeland are TND 40–70 (€20–€35) in the "without" case, while the model projects 4- to 7-fold increases after resting the land for 4 years. The policy applies to designated areas and requires land users to rest rangeland for a minimum of 4 years. The analysis shows that the policy will significantly improve the financial attractiveness of rangeland resting (Fig. 5), and thus facilitate wider adoption of this mitigation option by lowering switching costs.

Figure 6a shows a large spread in financial viability of technologies under situations with and without policy interventions. The 1:1 line is the no-effect line and usually one expects only the area above the line to be populated; the larger the distance to this line, the more effective a policy is. The chart shows that in a few instances, policies do not result in increased technology viability. On two occasions, there are slight improvements to an already quite high viability, e.g., from 81 to 93 %. In the remaining cases, an unprofitable technology is raised to being viable in between 33 and 94 % of the applicable area.

Comparing the per area unit costs of technologies with their effectiveness in reducing soil erosion, from a sample

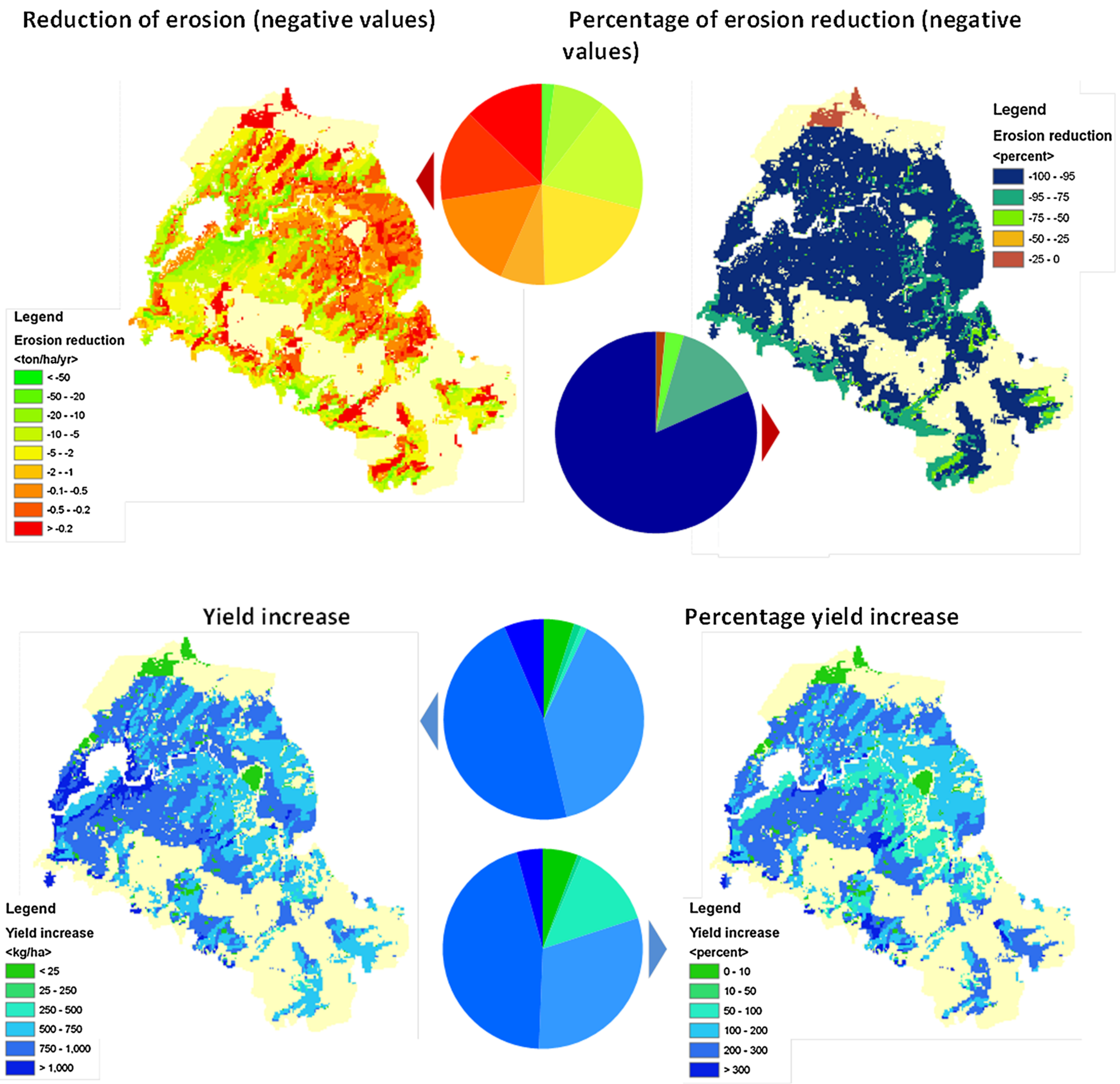

Fig. 7 The benefits of adopting mitigation technologies for alleviating land degradation and for increasing food production (example from the case of Sehoul in Morocco)

of policy scenarios for which cost data was available ($n = 5$), a general trend of increasing effectiveness with increasing cost can be observed (Fig. 6b). A much stronger correlation was found between total cost of a policy and its effectiveness in reducing soil erosion (Fig. 6c). The difference between the two charts is that in the first instance, the area aspect relates to the cost of (subsidies toward implementation of) technologies on a per hectare basis; whereas in the second case, the total cost of a policy can be high because of a large applicable area.

Adoption Scenarios

For study sites where more than one technology is applicable, an adoption scenario was run to assess the financial attractiveness of multiple technologies in conjunction. It is assumed that the most profitable option has the highest potential for uptake by land users. This adoption scenario assessment was only relevant for two study sites, where multiple technologies were applicable in overlapping areas: Yanhe River Basin in China and Sehoul in Morocco. For Yanhe River Basin, bench terraces (CHN51), checkdams for land (CHN52), and year-after-year terraced land (CHN53) were considered. All three options were compared for a 20-year time horizon, according to specifications in the technology scenarios. The long time horizon was chosen as none of the technologies is profitable after 10 years, even if investment costs are subsidized to the 50 % level. For checkdams, a ratio of treated to conserved area of 1:3 was assumed. In 9 % of the area, all 3 options are applicable; in 44 % two options are applicable; and in the remaining 47 % of the area none of the technologies is

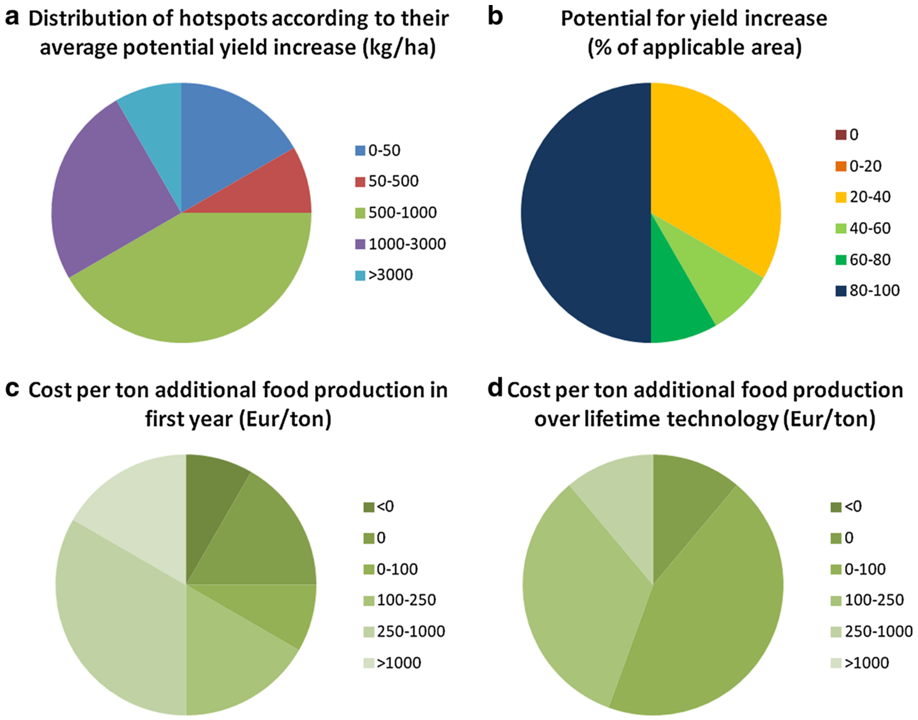

Fig. 8 **a–d** Results for cross-site comparison of food production maximization scenario

applicable. The technologies tested are together applicable in 53 % of the study area. Without policies, year-after-year terraced land is the most profitable, although checkdams do give higher returns in isolated cases. With subsidies, the relative profitability of bench terraces and checkdams improves, but these occupy land where year-after-year terraced land would be most beneficial. There is thus no change in the total area of land that would be attractive for technology implementation. For Sehoul, fencing and *Atriplex* plantation (MOR15), applicable on degraded land, and the two mulching variants (conventional tillage and direct seeding—MOR16A/B) for arable land were considered. A comparison between these three mitigation technologies was made for a 10-year time horizon. In 2 % of the area, all three mitigation options are applicable; in 40 % of the area two options are applicable; in 9 % only one option is suitable and there are no applicable technologies for the remaining 49 % of the area. Together, one or more technologies tested are applicable in about half of the study area (woodlands being excluded). In the absence of policies, only mulch with direct seeding offers scope for adoption in about a third of the area. Considering the policy scenarios separately for each technology, in 15 % of the Sehoul study area improved attractiveness of technology implementation could be obtained.

Global Scenarios

The analysis suggests that in most study sites the adoption of mitigation technologies can bring about positive impacts in terms of both curbing soil erosion problems and restoring agricultural productivity. These benefits vary, however, not only between different study areas, but also within individual sites (e.g. Fig. 7).

Figure 8 shows the results of cross-site analyses of opportunities for increased food production. Average potential yield increase ranges from less than 50 kg/ha to more than 3000 kg/ha (Fig. 8a). However, in three quarters of the study sites, productivity can increase by more than 500 kg/ha. In half of the cases, where increased food production is possible, improvements can cover the vast majority of the applicable area (Fig. 8b). In all sites, yield increases can be obtained in more than 20 % of the applicable area. The investment costs required to achieve this are substantial when looking at the first year (Fig. 8c, $n = 12$, average cost €567/ton when one case with "cost" below zero is excluded), but are reduced when aggregating over the economic life of technologies (Fig. 8d, $n = 9$, average cost €145/ton).

Similarly, opportunities to reduce land degradation exist universally across applicable areas: at minimum, soil can be conserved by the technologies assessed on 70 % of the applicable area. The rate at which soil loss can be reduced is either very high (80–100 %) or moderate (0–40 % reduction), in function of the effectiveness of different types of SLM technologies. In some cases, there are no additional costs involved to reduce soil loss; in others, substantial investments (>€1,000/ton) need to be made if analyses are done over a single year of erosion reduction. When spread out over the lifetime of technologies, erosion reduction becomes much more affordable, at rates often below €250/ton, and in a considerable number of cases, below €100/ton.

Discussion

The various scenarios allow a detailed ex ante assessment of SLM technologies, with a baseline assessment of land degradation pointing out the extent and spatial variation in degradation rates; technology scenarios exploring questions such as which technologies are applicable and where, and how effective and financially viable they are; policy scenarios helping to assess whether a subsidy programme or zoning regulation would help increase the uptake of the technologies; adoption scenarios allowing an assessment of best practices under various conditions; and global scenarios opting for a goal-oriented rather than adoption-oriented analysis of SLM technology potential. Moreover, apart from an "intra-site" analysis, we have shown that the scenario assessment can also be employed to perform "inter-site" comparisons. The latter has rarely been done in a structured fashion, but the methodology here presented can help target investment in certain technologies to particular degradation hotspots, where they are most cost-effective. There is also scope to assess the financial viability of technologies documented for one area (i.e., where it is trialed or implemented) when transferred to another area, by updating unit cost price information.

The spatially explicit nature of the PESERA–DESMICE model scenarios that allow assessment of the variability of the profitability of SLM technologies across landscapes is a new feature for SLM research. With a longer tradition in nature conservation studies, such research is currently only emerging for SLM (e.g., Lescot et al. 2013). The scenarios we have presented focus on a single financial viability criterion (NPV > 0), which is not the only factor that will influence uptake of SLM measures, albeit arguably a crucial one. The spatial profitability variation of SLM measures has been shown to have important implications for the adoption potential of measures across landscapes and their consequent environmental effects (Fleskens 2012). Where other studies including Lescot et al. (2013) focus on the aggregate off-site effects in catchment areas, the present study focused on on-site effects. Although further work is underway to include assessment of off-site impacts and incorporate factors such as land tenure, market access, and attitudes toward collaboration and risk, scenario outcomes of more complex models are also less appropriate to unravel cause-effect relationships (cf. Marohn et al. 2013). In fact, not only could environmental effects be considered, but also social and economic impacts (König et al. 2012; Marohn et al. 2013), and even indirect economic effects (cf. Fleskens et al. 2013).

Our integrated scenario modeling approach was found useful by land managers, supplementing the outcomes from field experiments and generic recommendations that were insufficiently capable of guiding SLM planning in farmers' fields in heterogeneous study sites (Stringer et al. 2013). The approach can therefore help to inform land user decision making by providing an insight into possible futures that perhaps they would not otherwise be able to visualize. The scenario assessments show that (simple) technological options exist to minimize land degradation and increase food production. Many technologies are, however, only profitable in the long run (e.g., 20 years), which means that high investment costs constitute important financial barriers for adoption. Low cost agronomic and management measures that deliver important benefits in the short term are the preferred technologies but may not be feasible or viable everywhere. Recent research by Calatrava and Franco (2011) and Franco and Calatrava (2012) shows that mulching was applied by 43 % of farmers in southern Spain, whereas minimum tillage was adopted by 90 %; the fact that the latter SLM technology involves a saving relative to conventional practice explains its spontaneous widespread uptake. These types of measures can be compared with structural measures which often require policy interventions to ensure continued maintenance (de Graaff et al. 2010).

The scenarios are built around an assessment of the degree of land degradation and biophysical impact of land management interventions with the PESERA model. As such, PESERA plays an important role in the methodology. We have used three outputs from PESERA (erosion rates, fire severity index, and biomass production) to calculate on-site financial impacts. Further outputs could have been used to inform a broader assessment of the value of ecosystem services such as carbon sequestration and reduced downstream sedimentation, but this would require resorting to economic valuation methods (cf. Balmford et al. 2008) or multi-criteria assessment. Assessing multi-faceted biophysical effects might also require more sophisticated ecological field assessment methods (e.g., Rubio and Bochet 1998; Kosmas et al. 2000), combined with comprehensive geospatial assessment (Buenemann et al. 2011) to support model development and conservation planning. As the grid-based assessment on a 1 ha-basis essentially mimics the field scale, with no interaction between cells, a financial assessment was deemed particularly appropriate. The method is also well-suited to scrutinize variability effects across the landscape, while other methods focus on the aggregate landscape effects (Salvati et al. 2011).

The DESMICE component of the modeling presented in this paper primarily relies on financial data systematically collected for the various technologies using questionnaires documenting expert knowledge (Schwilch et al. 2012b). It further makes use of additional information requested from study site researchers. Variation of investment costs of technology has proved to be difficult to obtain. However, such variations can have important implications for the analysis (Fleskens 2012). A review of published papers and gray literature is recommended as follow-up work to fill this data gap. In addition, the temporal dimension of changes in productivity is crucial for land users. Biophysical models (e.g., PESERA) should be able to separate immediate and gradual aspects. Moreover, the ongoing land degradation in the "without" case is not yet considered (Fleskens et al. 2013). An analysis of the robustness of the modeling outputs to climatic variability, prices (notably of labor opportunity costs) and discount rates is also essential. However, despite the need to rely on secondary data, acknowledgment of model shortcomings, and a lack of calibration possibilities, scenario assessments with integrated models such as PESERA–DESMICE can help determine location-specific financially viable technologies to combat land degradation problems effectively. Such ex ante assessments are most valuable as input to decision-making processes (Stringer et al. 2013) and to inform whether expanding pilot experiments and/or transferring these experiments to other sites would be worth doing, which in the absence of these assessments, can be much more expensive and time-consuming.

Furthermore, our necessary assumption that financial viability only determines land user decision making requires some critical reflection. Land managers select their management practices based on a wide range of interacting considerations (Stringer et al. 2009). While evidence from our scenarios provides a valuable information input for land users, the complexity of the decision-making process surrounding adoption of SLM technologies needs to be acknowledged (Bekele and Drake 2003; Calatrava and Franco 2011; Franco and Calatrava 2012; Kassie et al. 2013). For example, if the use of a technology violates a particular important social or cultural norm, regardless of the financial implications of its use, the technology will not be more widely adopted. Risk and uncertainty are also important factors that the NPV criterion fails to capture. There may be a risk that a technology will not deliver (e.g., a drought could prevent the successful growth of vegetative measures), or if land managers do not trust the scenario outputs, due, for example, to the simplification of input data, this will also affect the technology adoption. While these complexities have not been explicitly addressed in the scenario analysis presented here, they nevertheless require acknowledgment (see Stringer et al. 2013).

Finally, scale considerations play an important role, both for the application of scenario assessments at a single study site and for inter-site comparisons with global scenarios. The study sites included in this research varied from <75 (Cape Verde) to >7,500 km^2 (China), but were small in relation to national territories. Still, they frequently extended beyond low-level administrative boundaries and typically included multiple layers of governance structures and policies. This juxtaposition may give rise to unclear, and sometimes conflicting, policies, and political processes which could affect the temporal and spatial governance framework of a defined area. For example, policies may provide incentives for certain types of SLM technologies and not for others, or for some subset of farmers to adopt them but not for others. It is also possible that investments in SLM technologies are discouraged by uncertain continuity of policies. To fully consider such complexities within a single analysis proves challenging. Nevertheless, this paper demonstrates that an integrated modeling framework such as the coupled PESERA–DESMICE can be useful to comprehend the otherwise less tractable complexities at different scales (e.g., within a single site and between multiple sites). There is considerable scope for further exploitation of the integrated PESERA–DESMICE approach as more and higher quality data on spatial variation of costs and on field trial performance of a wider range of SLM technologies become readily available and as land users' preferences and policies are represented in more detail.

Conclusions

This paper has presented a scenario approach to assess the feasibility, viability, and effectiveness of a portfolio of land degradation mitigation technologies using the PESERA–DESMICE integrated environmental socio-economic modeling framework. The approach can be applied to understand the spatial variation of investment requirements and performance of technologies within a given study site as well as to make inter-site comparisons of the potential and cost-effectiveness to combat land degradation. The exploration of the scenarios applied within and across 13 land degradation hotspots in five continents shows that land degradation mitigation technologies can reduce soil erosion in on average 18 % (vegetative measures) to more than 50 % (management measures) of study site areas. Apart from agronomic measures, which are often cheap, average investment costs of land degradation technologies vary from slightly below €500 per ha for management measures to about €1,750 per ha for structural and vegetative measures with important variability both within and between sites. Despite these investment costs, the appraised technologies were financially viable in 25 % (agronomic and management measures) to 100 % (vegetative measures) of the areas in which they are applicable. Policy incentives to increase viability of measures led in many cases to important gains in the area where technologies could bring a positive financial return to land users while reducing soil erosion. Yield increases of more than 500 kg per ha are possible in more than 40 % of the areas where technologies are applicable in over two-thirds of the cases; in the majority of cases at a cost of less than €250 per ton grain over the lifetime of the technologies. Soil erosion can be reduced by at least 20 % and often more than 80 % of current soil loss rates in more than 80 % of the applicable areas for over 80 % of the study sites; generally at a cost of less than €100 per ton of soil conserved over the lifetime of the technologies. We argue that despite the assumption made that adoption of SLM technologies would be possible if the financial return to the land user is positive, the assessment of technologies under a range of scenarios can give important information to decision-makers at all levels. Further improvements to the methodology are possible by developing a more systematic inventory of spatial variability of costs and benefits and by better understanding and representing preferences of decision-makers. There is, however, an important trade-off between more detailed assessment and the applicable scale of analysis; solving this trade-off is context-specific and requires collaboration between researchers and decision-makers.

Acknowledgments This study was funded by the EU Framework 6 Desertification Mitigation & Remediation of Land—a Global Approach for Local Solutions (DESIRE) Project (037046). We thank all study site teams for their contributions and support throughout the research process.

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