Modelling the impact and viability of sustainable land management technologies: what are the bottlenecks?

L. Fleskens[1]
[1]Sustainability Research Institute, School of Earth & Environment, University of Leeds, Leeds LS2 9JT, UK, l.fleskens@leeds.ac.uk

ABSTRACT

Models are increasingly used for land use planning and impact assessment of sustainable land management (SLM) interventions. This requires biophysical models to be coupled to models that represent the socio-economic complexities of the area of interest. The PESERA-DESMICE integrated model combines a process-based erosion prediction model (PESERA) extended with process descriptions to evaluate the effects of measures to mitigate land degradation, and a spatially-explicit economic evaluation model to evaluate the financial viability of these measures (DESMICE). The model evaluates the applicability limitations and inventories the spatial variation in the investment and maintenance costs involved for a pre-selected portfolio of technologies. The physical effects of the implementation of the SLM technologies relative to the without situation are subsequently assessed and valuated in monetary terms. The paper builds on experiences with the PESERA-DESMICE model to assess costs and effects of SLM technologies for global desertification hotspots in the EU FP6 DESIRE project. Three bottlenecks are explored using case study applications of the PESERA-DESMICE model: 1. a lack of data on the spatial variability of investment costs; 2. the non-explicit temporal dimension of biophysical effects; and 3. failure to account for scale effects and individual decision-making contexts. Results show that each of these bottlenecks can have important consequences, i.e. considerably over- or underestimate the viability and effectiveness of SLM technologies. Still, getting insight in these factors and incorporating approximations into models, and testing robustness of the model using scenarios are deemed to be an important step forward to inform decision-making on SLM. While it can be assumed that land users will only potentially implement technologies if they are financially viable, there are many more factors which come into play. Work underway to integrate risk perception and cooperation between land users is highlighted.

INTRODUCTION

Various examples of sustainable land management (SLM) technologies are referred to as having brought about a transformation of degraded land into productive areas, and as having created renewed livelihood opportunities for local land users (e.g. WOCAT, 2007; Garrity et al., 2010). The scale on which SLM has been successfully implemented is usually highly localized, and the question arises whether such undertakings are replicable in other areas. Although the issue of defining ‘success’ of a SLM technology is multi-faceted, including environmental, economic and socio-cultural dimensions specific for the local context (Schwilch et al., 2012), financial profitability can be considered a minimum criterion for any measure to have a chance of being adopted elsewhere. Many studies assess economic impacts of SLM at the scale of individual measures, projects, and continental and global scales (Pimentel et al., 1995; de Graaff, 1996; Posthumus and de Graaff, 2005; Kuhlman et al., 2010), but so far the spatial variability of the profitability of SLM measures has received little attention.

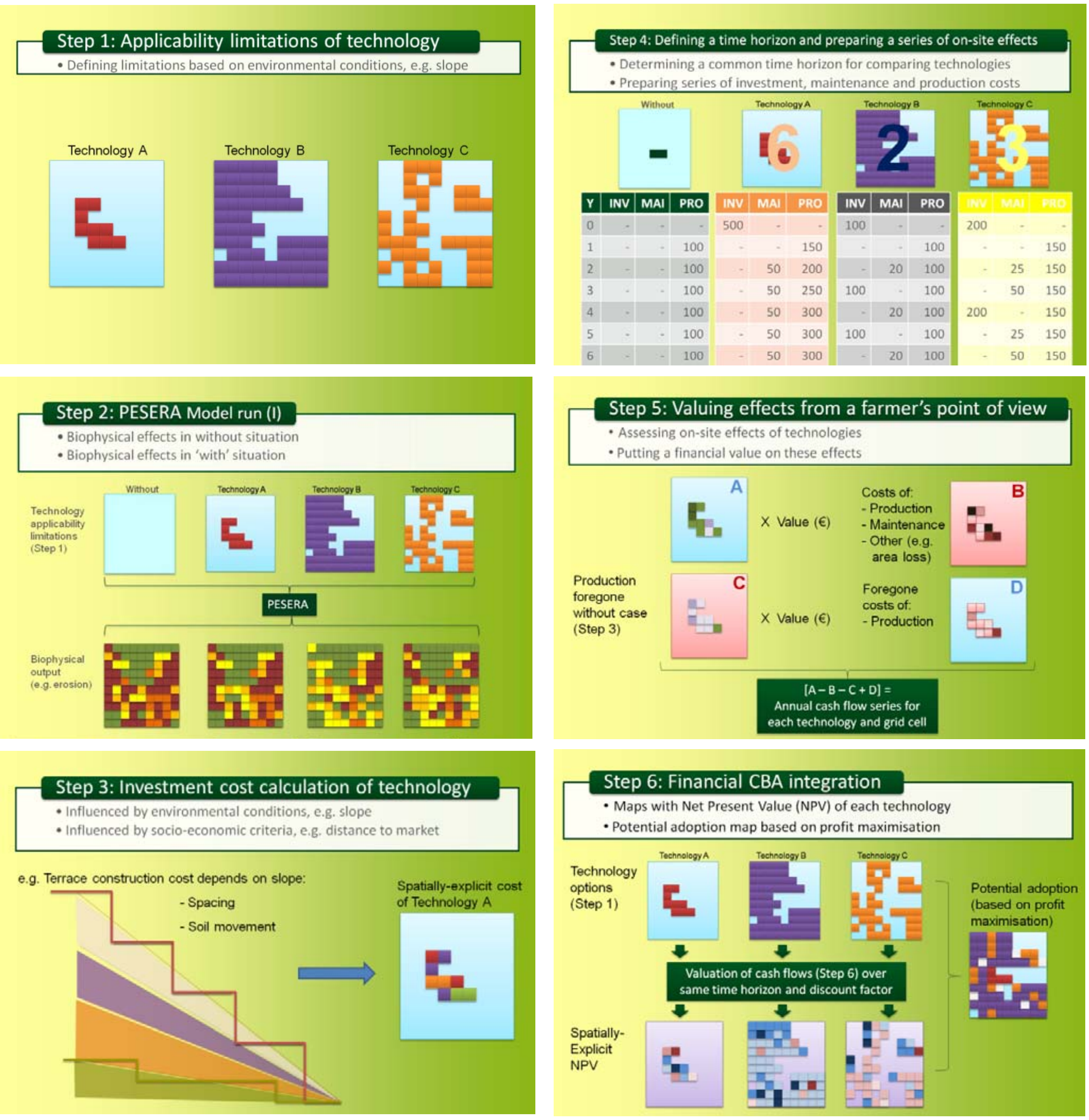
Moreover, current practice in learning from successful cases tends to focus on impressions, in the best cases backed up by data from the host region, with remarkably little testing of technologies for the conditions in the area for which it is deemed to hold promise. This trial-and-error approach to search for SLM can work, but comes with a number of inherent risks. Extension and agricultural development organizations risk losing their credibility if new introductions fail. Land users (and donor organizations in the case of development projects) might lose investments made, or worse – lose faith in a newly developed notion that SLM can be a tool to develop or diversify their livelihoods. Although experimentation comes naturally as part of any innovation process, it consumes considerable resources (if only time), and the conditions under which any testing can feasibly be performed are often limited. Thus, results of any testing carried out will still be inconclusive as to the potential for upscaling of the SLM technology of interest.

Integrated environmental modeling constitutes a useful tool to manage risks and explore the potential of SLM technologies under a much wider range of conditions and/or for a much larger area than could be achieved through experimentation. The PESERA-DESMICE integrated model, conceptually described in Fleskens et al. (2009), presents a methodological approach for modeling the impact and viability of SLM technologies. This paper builds on experiences with PESERA-DESMICE in the EU FP6 DESIRE project, in which it was applied to desertification hotspots around the world. Specifically, the paper will point to a number of bottlenecks in the approach, discuss these, and highlight main areas for future model development. The model structure itself will due to space limitations not be presented here (a separate paper on this is being prepared; see Fleskens et al., forthcoming).

METHODS

PESERA-DESMICE Model Overview

This section outlines the PESERA-DESMICE modelling approach. The PESERA model (Kirkby et al., 2008) has in the



Step 1: Applicability limitations of technology

- Defining limitations based on environmental conditions, e.g. slope

Step 2: PESERA Model run (I)

- Biophysical effects in without situation
- Biophysical effects in 'with' situation

Step 3: Investment cost calculation of technology

- Influenced by environmental conditions, e.g. slope
- Influenced by socio-economic criteria, e.g. distance to market

e.g. Terrace construction cost depends on slope:
- Spacing
- Soil movement

Spatially-explicit cost of Technology A

Step 4: Defining a time horizon and preparing a series of on-site effects

- Determining a common time horizon for comparing technologies
- Preparing series of investment, maintenance and production costs

Y	INV	MAI	PRO	INV	MAI	PRO	INV	MAI	PRO	INV	MAI	PRO
0	-	-	-	500	-	-	100	-	-	200	-	-
1	-	-	100	-	-	150	-	-	100	-	-	150
2	-	-	100	-	50	200	-	20	100	-	25	150
3	-	-	100	-	50	250	100	-	100	-	50	150
4	-	-	100	-	50	300	-	20	100	200	-	150
5	-	-	100	-	50	300	100	-	100	-	25	150
6	-	-	100	-	50	300	-	20	100	-	50	150

Step 5: Valuing effects from a farmer's point of view

- Assessing on-site effects of technologies
- Putting a financial value on these effects

[A – B – C + D] = Annual cash flow series for each technology and grid cell

Step 6: Financial CBA integration

- Maps with Net Present Value (NPV) of each technology
- Potential adoption map based on profit maximisation

Valuation of cash flows (Step 6) over same time horizon and discount factor

Figure 1: The 6 steps of the PESERA-DESMICE modelling approach (DESMICE framework in which PESERA run is included).

context of the DESIRE project been adapted to evaluate the biophysical consequences of alternative land degradation remediation strategies (Kirkby et al., 2010). According to the WOCAT terminology, remediation strategies consist of technologies and approaches. A technology can consist of a single or multiple of four types of measures: structural, vegetative, agronomic and management measures, respectively (WOCAT, 2007). The PESERA-DESMICE framework embeds PESERA in a sequence of six logical steps in which the impact and feasibility of SLM technologies are assessed (see also Figure 1):

Step 1: Technology applicability limitations. First it is necessary to define where each technology can in principle be applied. Limitations as meant here are physical constraints, rather than factors reducing expectations that the technology will be cost-efficient. This is an important step in that it rules out the area where technologies cannot be applied e.g. terraces on steep slopes with shallow soils. Factors considered include: soil depth, slope, landform, land use, climate and distance to streams. For each technology, each of the above criteria will result in an output map showing the applicability in a dichotomous fashion. Only when all applicability limitations of a technology are satisfied can the technology be applied in a certain area.

Step 2: PESERA model run. The physical effects of implementing the technology can now be evaluated using the

PESERA model. This is done separately for each technology, taking into account its potential applicability area (step 1). To evaluate a technology, two model assessments need to be made:

i. The ***PESERA baseline*** is an assessment of a series of biophysical descriptors at an equilibrium state driven by mean climate, land use, soil and topography. These descriptors are an estimate of monthly estimates of biomass (productivity), runoff and erosion. The PESERA baseline assessment is achieved with best understanding and interpretation of current land management practice and technologies, and constitutes ***the without case*** in technology assessment.
ii. The ***adapted PESERA assessment*** is a representation of the same biophysical descriptors, but now evaluated as the simulated effects of a specific desertification remediation option. Adapted assessments are achieved with best understanding of the functioning of technologies. It hence forms **the 'with' case** of technology application.

Step 3: Investment cost calculation. The WOCAT technology questionnaires in most cases present a cost estimate of the technology. However, this estimate is made for its most common application area or is an informed estimate of average costs across several local application areas. In reality, construction costs will differ based on environmental factors (e.g. slope) and socio-economic factors (e.g. distance to market). The same holds for maintenance costs. In this phase, investment and maintenance costs will be made spatially explicit by considering both types of factors. The environmental variation is implemented by varying the quantity of specific inputs by using technology-specific rules linking the standard quantities per input category contained in the WOCAT database to the environmental conditions in each grid cell. The distance to market functionality was included in DESMICE as an option but not implemented for DESIRE study sites. It allows defining for each cost item the location of source areas (markets) and transportation costs assuming the cheapest transport path, either through a (road) infrastructure network or over a cost surface. Multiplying spatially-explicit inputs with their respective spatially-explicit costs gives the total investment or annual maintenance cost.

Step 4: Defining a time horizon and preparing a series of on-site effects. The technologies that are being assessed may have different economic lifetimes. Therefore, shorter-lived technologies are assessed over several cycles of re-investment (over the length of time that the longest lived technology is likely to last for). Years of (re-)investment are filled first; maintenance costs are subsequently added for years in between investment. Production costs need also to be considered because application of technologies may lead to a change of land use or use of input (e.g. more labour because of larger harvest).

Step 5: Valuing effects from a farmer's point of view. To value effects of a remediation strategy, the following will be assessed on a yearly basis for the lifetime of the technology (or multiple lifetimes):

A. Evolution of production output (yield x value) over time;
B. Evolution of costs of implementing the technology and land use associated with it;
C. Evolution of production output (yield x value) as it would develop were the mitigation strategy not applied;
D. Evolution of the costs of the land use in this 'without' case.

For each year, the net result can then be calculated as [A-B-C+D] (note that benefits and costs may vary both in space and time).

Step 6: Financial CBA integration. The annual cash-flows of step 5 are subsequently used in a Financial Cost-Benefit Analysis (FCBA). An important issue in FCBA is discounting, i.e. introducing an interest rate that depreciates costs or benefits occurring in the future relative to those felt now. Summing discounted cash-flows gives the Net Present Value (NPV) for each technology. For each grid cell, one of the following three possible outcomes will apply:

- The technology with highest NPV will be selected (when positive) (the adoption grid shows a possible configuration of technology A, B and C)
- No technology will be selected if all NPVs are negative (i.e. white pixels in potential adoption grid)
- No technology will be selected if no technology is applicable in the area (blue cells in adoption grid)

Scenario development. Once the steps 1-6 have been followed, PESERA-DESMICE can be used to run different scenarios. In the DESIRE project scenarios included policy scenarios to assess the effectiveness of financial incentive (and alternative) mechanisms to stimulate adoption of technologies if they are not economically attractive and two so-called 'global' scenarios with the objective to maximize food production and minimize land degradation respectively. The food production scenario selects the technology with the highest agricultural productivity (biomass) for each cell where a higher productivity than in the baseline scenario is achieved. The minimizing land degradation scenario selects the technology with the highest mitigating effect on land degradation or none if the baseline situation demonstrates the lowest rate of land degradation.

Exploring bottlenecks

In applications of the PESERA-DESMICE modeling framework in the DESIRE project (Fleskens et al., 2012) the three following complications were frequently encountered:

1. Spatial variability of investment costs is poorly known;
2. Timing of biophysical effects is not explicit;
3. Scale of implementation and individual circumstances are not taken into account.

The effects of these bottlenecks were explored by applying the respective methods described in the subsections below.

Varying the spatial variability of investment costs

Taking as an example the application of bench terraces with loess soil walls in the Yanhe River basin in the Loess Plateau of China, spatial variability of investment costs was defined as follows:

$$INV_S = US\$1{,}823 \ * S/30 \qquad (1)$$

where INV_S is the investment cost per hectare for slope gradient S (in percent) and US\$1,823 is the investment cost reported for a standard slope of 30%.

Calculating the average investment cost per hectare across the area where the technology is applicable (3,732 km^2) with Equation 1 gives US\$1,591 ± 717. To assess the effect of different levels of variation of investment costs with slope gradient, the mean was subtracted from the INV_S data layer and the resulting raster multiplied with factors 0.75, 0.5, 0.25 and 0 before adding the mean investment cost again. This approach resulted in a number of rasters with the same average investment cost but different standard deviation and ranges (Table 1), which were subsequently used to assess the financial viability of the technology following the steps of the PESERA-DESMICE framework.

Varying the timing of biophysical effects

The technologies assessed in the DESIRE project included agronomic (e.g. minimum tillage) as well as structural, vegetative and management SLM measures. All measures, but especially the second group, impact on slow soil ecological processes and will gradually improve soil structure and fertility, and hence system productivity. The PESERA model simulates the equilibrium conditions in the with and without technology case. One of the sites where PESERA predicted a particularly large improvement in productivity was in the Sehoul area close to Rabat, Morocco – for gully control by plantation of atriplex (*Atriplex halimus*). The PESERA model output simulation is however not ‘temporally explicit’. In the standard calculation, in the DESMICE calculations it was assumed that production would increase linearly until reaching its maximum value after 20 years - i.e. time to maturity TTM = 20. By employing Equation 2, net present value was calculated for time productivity series with different TTM values (15, 18, 25, 27, 30 and 33 years):

$$NPV_{TTM=j} = \left(\sum_{t=1}^{t=20} \frac{max(t/j, 1)}{(1.1)^t} \right) * NPV_{TTM=20} \qquad (2)$$

Where NPV_{TTM} refers to the net present value of the cash flow series over 20 years for the case with implementation of gully control only; *j* and *t* are measured in years and NPV in currency. After calculating NPV_{TTM} values, investment costs and total discounted production in the without case (which remain the same under different TTM values) need to be subtracted. Finally, for evaluation of the effect of TTM, the percentage of cells in the applicability area of the technology is calculated.

Scale and individual circumstances

As PESERA-DESMICE is implemented on grid cells of fixed size approximating rather than representing actual fields, and more generally because individual circumstances of land users are not taken into account, economies of scale are usually not considered. Notwithstanding, such aspects can be considered by running scenarios under different assumptions, as has for instance been done for the cost of fencing which reduces exponentially if larger areas are fenced. We will here consider the Boteti area in Botswana where profitability of household level biogas production was assessed. Biogas releases time (and perhaps financial resources) that would otherwise be spent collecting firewood. Perkins et al. (in press) present various scenarios, mostly assuming village-wide adoption of biogas. However, two situations relating to individual circumstances provide an interesting comparison:

i. Early adopter; cow dung has at present no market value in the study site – it just needs to be collected from borehole sites where cattle are concentrated. The first few households to install biogas production facilities can do so from 1 of the 4 boreholes in the villages at zero opportunity cost.
ii. Resource-poor late adopter; if a household does not own or cannot rent carts or vehicles collection of dung must be done on foot, involving high labour (opportunity) costs.

For both situations the break-even price of firewood is calculated – see Perkins et al. (in press) for further details. Arguably, the individual perspective is beyond the scope of the PESERA-DESMICE model; nevertheless it is included to illustrate the need for context analysis and as an example of scale relations that emerge when pixels interact.

RESULTS

Impact of spatial variability of investment costs

The case study of bench terraces in the Yanhe river basin in China shows an important influence of variable investment costs (Figure 2). When no spatial variability is taken into account, terraces are financially attractive in 13% of the area where they can technically be implemented. This proportion rises to 50% if costs are taken proportionate to the reference slope (Equation 1). Figure 2 clearly demonstrates that the effect of spatial cost variability is not linear; not considering or underestimating the level of variability in costs may hence considerably underestimate potential profitability of bench terracing, whereas overestimating the level of variability of the required investment may rapidly lead to exaggerated viability estimates. Not only does the percentage of the area where the technology can be economically implemented change, but also the locations (Figure 4). In absence of slope-related spatial variability, slope does not exert any influence and viability is in this case primarily responding to climatic variation. As the slope dimension is phased in, more and more less sloping land in areas with suboptimal climatic conditions replaces rugged areas with highly suitable climate.

Influence of timing of biophysical effects

Gully control with atriplex in Sehoul, Morocco is not very sensitive to small changes around the assumed 20 years it takes to reach maximum productivity (Figure 3). However, this is a rough assumption, so we should look further than the short range between 18 and 25 years where the viability of the technology is not affected. When approximating a TTM of 15 years, the viability of atriplex planting rapidly reaches 100% of the applicable area, up from 82% on the stable area from 18-25 year. Even more dramatic is the drop between a TTM of 25 and 30 years, when the technology seizes to be viable in more than 60% of the applicable area. What happens here is that the NPV in a large area where the technology was profitable at a TTM of 25 drops below 0 (Figure 5). Although the rate of change slows down when TTM exceeds 30 years, gully control with atriplex seizes to be profitable everywhere at a TTM of 33 years (Figures 3 and 5). From this example, it is clear that one would need to be confident of the interval 18-25 years it would take vegetation to reach maximum productivity, outside of which the system becomes very sensitive to the issue of timing.

Table 1: Levels of spatial cost variability and resulting range of investment costs for bench terraces in Yanhe river basin, China.

Investment cost (US$)	Relative level of spatial cost variability				
	0	0.25	0.50	0.75	1
Maximum	1,591	2,488	3,386	4,284	5,182
Minimum	1,591	1,196	801	406	12
Standard deviation	0	179	359	538	717

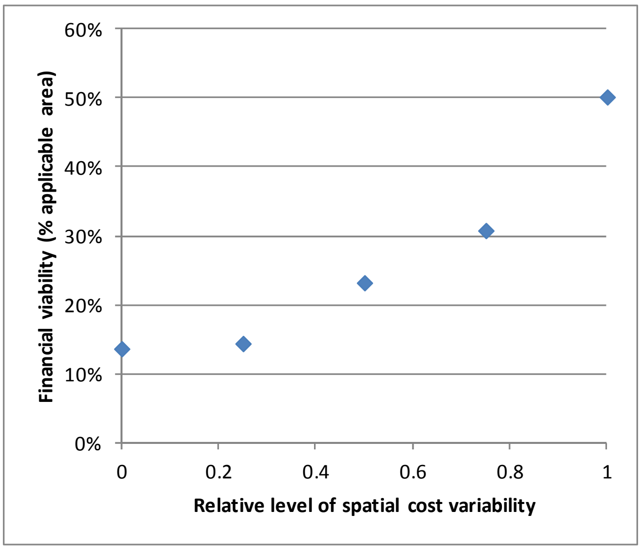


Figure 2: Financial viability of bench terraces in Yanhe river basin under different levels of spatial investment cost variability.

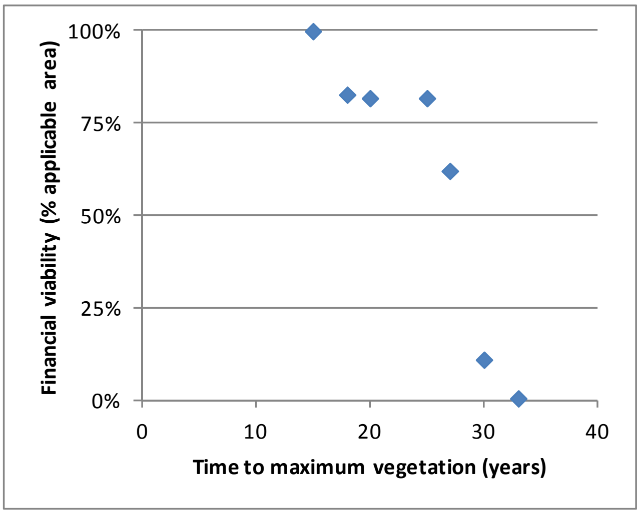


Figure 3: Financial viability of gully control with atriplex in Sehoul as a function of time to reach maximum productivity.

Scenarios for scale, context and perspectives

When cattle dung collection involves no opportunity costs of labour, e.g. a pioneering adopter of biogas who would exclusively collect dung from a nearby collection area (from his or her own kraal for instance), the tipping point for opportunity cost of firewood collection would be US$0.87 per day. On the other hand, when dung collection from up to 11 km distance needs to be performed on foot – the cost would be US$12 taking into account labour opportunity costs; the tipping point would only be reached at firewood collection costs of US$12.87 per day. These figures illustrate important (order of magnitude) differences of viability between land users with different moments of adoption and resource availability, and also stress the importance of scale and context, as was also found in other model applications: the area (number of pixels) of land conserved by checkdams installed for this purpose, the price of fencing, catchment to cropped area ratio of ex-site water harvesting, and the initial conditions of the area for which the assessment is made: rehabilitation and maintenance rather than new construction of SLM technologies is often required. The profitability of SLM depends on such factors.

DISCUSSION

In studies of adoption of SLM technologies, plot location is often found to be of importance (e.g. Staal et al, 2002; Noltze et al., 2012). The spatial variation in investment costs of SLM technologies and distance to markets are likely to play a key role, although explicit studies of variations in costs are scarce (e.g. Shively, 1999; Tenge et al., 2005). As Heidkamp (2008), it in a more general context, puts it: “the environment has been largely ignored beyond its treatment as a more or less passive location condition or resource factor input”. Although the illustration of cost differentiation with slope for bench terraces in China provides an example of the susceptibility of outcomes to this factor, the finding that taking variability in investment cost into account leads to a larger viability is specific. In other cases, for example where data is gathered from a relatively cheap experiment in optimal conditions, considering spatial variability factors might lead to reduced levels of predicted viability. Much data on spatial variability of different types of SLM technologies probably exists in design manuals, project documents, and other grey literature. A review of those materials will help to define some generic relations that can be used to improve model assessments of SLM. The modelling approach adopted here assumes that spatial cost variability can be expressed as a function of one or two variables, or else that such variability is an input. Concrete cost information is however difficult to obtain. An additional complication is that labour tends to form a significant proportion of investment costs, but that valuation of labour can only be approximated using labour opportunity costs (e.g. Posthumus and de Graaff, 2005).

The timing of biophysical effects has potentially significant influence on viability of technologies. The point version of PESERA allows simulation in time series mode after equilibrium conditions have been established. The grid version of the model, which was used here, lacks this facility. Still, model validation, specifically of timing of effects, is difficult due to interactions and the paucity of long-term field trials which are intensively monitored. Due to these difficulties, as well as uncertainty of any future productivity and prices, model results need to be viewed as indicative only and robustness to different conditions explored before making recommendations. Although the illustrative case study had a long term restoration goal, the cumulative effects of annually repeated SLM technologies may also be significant (see e.g. Hobbs et al., 2008). The importance of the temporal dimension in evaluating technologies is clear from the inclusion of a discount factor in CBA. This can work two ways: in the case of technology application, it is important for land users to start reaping benefits as early as possible; but in the without case, ongoing degradation can further affect yield levels (Lal, 1995). Degradation and restoration pathways furthermore have very different characteristics; future work includes adapting the model framework here presented to interact with an ecological model of discontinuous transitions (Kéfi et al., 2007).

Issues of scale and comparative advantage are well-studied in economics. For impact assessment models of SLM, these can be considered in scenario studies (as the example of biogas in Botswana), or – where such variation stems from land user characteristics – integrated in agent-based models (Matthews et al., 2007). The environmental context is an important factor in the assessment of technologies with design factors beyond the field

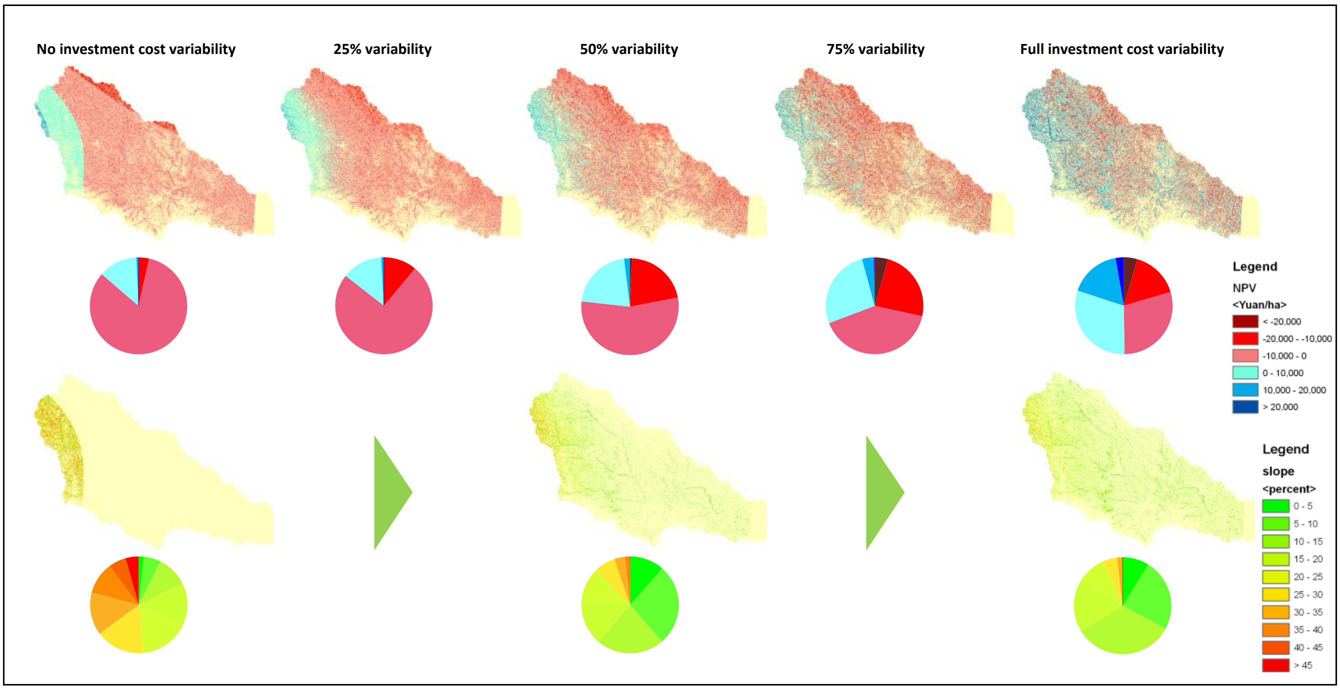


Figure 4: Maps of NPV and slopes of profitable bench terraces in Yanhe basin (China) for different levels of spatial cost variability.

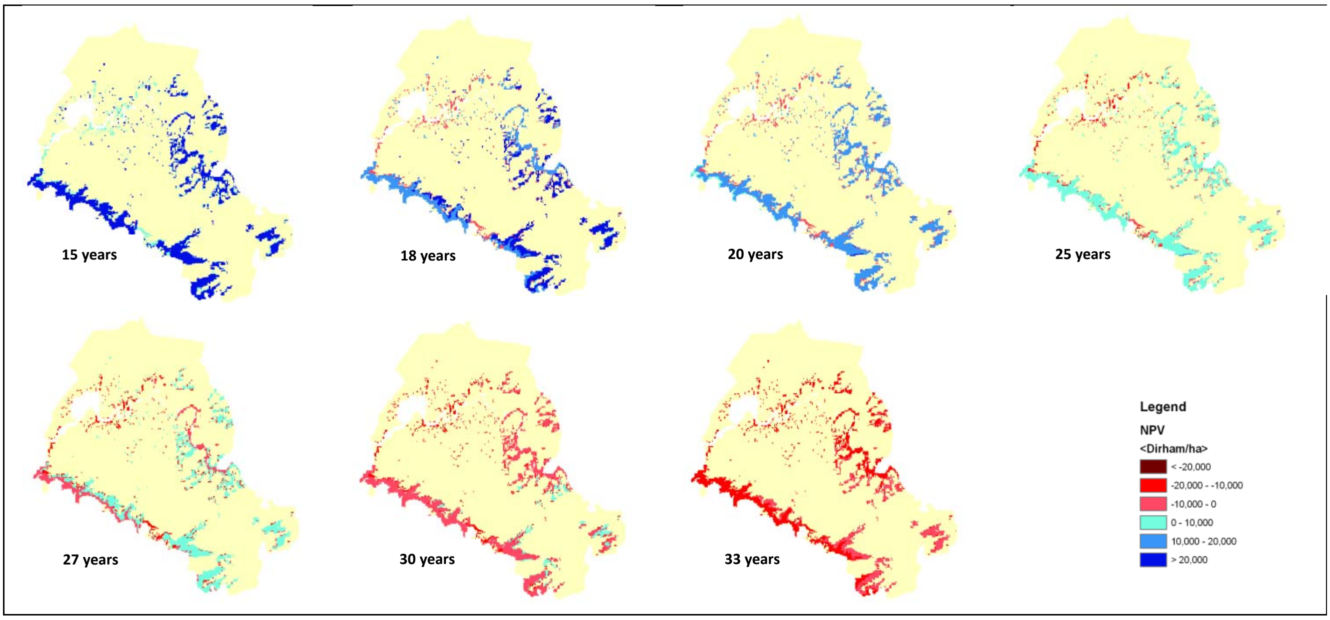


Figure 5: Maps of NPV of gully control with atriplex in Sehoul (Morocco) under different time lags to reach maximum productivity.

scale, such as ex situ water harvesting technologies. Follow up work for PESERA-DESMICE will consider cascading water harvesting technologies to take into account optimum catchment to cropped area ratios and the influence of upstream-downstream linkages in a spatially-explicit way. The Botswana example shows low costs for early adopters of biogas. While that may true, innovators usually incur higher costs as they adapt technologies to their context (Rogers, 2003). For resource-poor late adopters of biogas, costs are prohibitively high, and it is likely that they would either continue to rely on firewood, or have to wait for entrepreneurs to create a local dung market and organise supply of dung to biogas installations, or to develop a biogas market. This alludes to a need to consider agents when assessing SLM, even though coupling land and household data is challenging (Happe et al., 2011). It also points to another important issue: if we are interested in the upscaling of SLM and the conservation outcomes that it brings about, the diffusion of uptake can have significant impact and the process cannot be ignored. Adoption decisions are complex and consider much more than profitability of SLM. An important aspect is the resilience of SLM under variable conditions. Scenario analysis using models is likely to be important to assist in making complex decisions. Future work in this field includes building attitudes to conservation, cooperation and risk into PESERA-DESMICE.

CONCLUSION

The PESERA-DESMICE integrated model is presented as a framework to assess the impact and viability of SLM technologies. This and other models with similar purpose face a number of bottlenecks. The first is a data problem of the spatial variability of investment costs. In a case study, we show that this may make the difference between a technology being profitable in 13% or 50% of the study area and is hence a problem that needs to be addressed. The second bottleneck is that biophysical models should be able to simulate gradual processes in a temporally explicit way for economic evaluations to hold ground. It is pertinent to do so explicitly in a dynamic context of environmental change rather than by comparing equilibrium states, as: i) the current (degrading) conditions may deteriorate; and ii) not only the increased productivity, but also the increased resilience of sustainably managed land to pressures and stresses should be assessed. Finally, financial profitability assessment constitutes a narrow approach; for more realistic upscaling prospects, other factors need to be incorporated to reflect decision-making processes in a more balanced way.

ACKNOWLEDGEMENT

The PESERA-DESMICE modelling framework was developed in the project ‘Desertification Mitigation & Remediation of Land – a Global Approach for Local Solutions’ (DESIRE) with funding from the EU FP6 (grant number 037046).

REFERENCES

Fleskens, L., Irvine, B., Kirkby, M.J., Nainggolan, D., Reed, M.S., Termansen, M. (2009) ‘A model that integrates the main bio-physical and socio-economic processes interacting within an agro-ecosystem’ DESIRE Report 63 D5.1.1.

Fleskens, L., Irvine, B., Kirkby, M., Nainggolan, D. (2012) ‘Model outputs for each hotspot site to identify the likely environmental, environmental and social effects of proposed remediation strategies’ DESIRE Report D5.3.1.

Fleskens, L., Kirkby, M., Irvine, B. (forthcoming) ‘The PESERA-DESMICE modelling framework for grid-based assessment of the physical impact and economic viability of land degradation mitigation technologies’ *Environmental Management* (DESIRE special issue).

de Graaff, J. (1996) ‘*The price of soil erosion – an economic evaluation of soil conservation and watershed development’* PhD Thesis Wageningen University, The Netherlands.

Garrity, D.P, Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M., Bayala, J. (2010) ‘Evergreen Agriculture: a robust approach to sustainable food security in Africa’ *Food Security* 2:197–214

Happe, K., Hutchings, N.J., Dalgaard, T., Kellerman, K. (2011) ‘Modelling the interactions between regional farming structure, nitrogen losses and environmental regulation’ *Agricultural Systems* 104: 281-291.

Heidkamp, C.P. (2008) ‘A theorethical framework for a ‘spatially conscious’ economic analysis of environmental issues’ *Geoforum* 39: 62-75.

Hobbs, P.R., Sayre, K., Gupta, R. (2008) ‘The role of conservation agriculture in sustainable agriculture’ *Philosophical Transactions of the Royal Society B* 363(1491): 543-555.

Kéfi, S., Rietkerk, M., van Baalen, M., Loreau, M. (2007) ‘Local facilitation, bistability and transitions in arid ecosystems’ *Theoretical Population Biology* 71: 367-379.

Kirkby, M.J., Irvine, B.J., Jones, R.J.A., Govers, G., the PESERA team (2008) ‘The PESERA coarse scale erosion model for Europe: I – Model rationale and implementation’ *European Journal of Soil Science* 59: 1293-1306.

Kirkby, M.J., Irvine, B., Poesen, J., Borselli, L., Reed, M. (2010) ‘Improved process descriptions integrated within the PESERA model in order to be able to evaluate the effects of potential prevention and remediation measures’ DESIRE Report 75 D5.2.1.

Kuhlman, T., Reinhard, S., Gaaff, A. (2010) ‘Estimating the costs and benefits of soil conservation in Europe’ *Land Use Policy* 27: 22-32.

Lal, R. (1995) ‘Erosion-Crop Productivity Relationships for Soils of Africa’ *Soil Science Society of America Journal* 59: 661–667.

Matthews, R.B., Gilbert, N., Roach, A., Polhill, J.G., Gotts, N.M. (2007) ‘Agent-based land use models: a review of applications’ *Landscape Ecology* 22: 1447-1459.

Noltze, M., Schwarze, S., Qaim, M. (2012) Understanding the adoption of system technologies in smallholder agriculture: The system of rice intensification (SRI) in Timor Leste. *Agricultural systems* 108: 64-73.

Perkins, J.S., Reed, M.S., Akanyang, L., Atlhopheng, J.R., Chanda, R., Magole, L., Mphinyane, W., Mulale, K., Sebego, R.J., Fleskens, L., Irvine, B.J., Kirkby, M.J. (in press) ‘Making land management more sustainable: experience implementing a new methodological framework in Botswana’ *Land Degradation and Development.*

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Sphritz, K., Fitton, L., Saffouri, R., Blair, R. (1995) ‘Environmental and Economic Costs of Soil Erosion and Conservation Benefits’ *Science* 267: 1117-1123.

Posthumus, H., de Graaff, J. (2005) ‘Cost-benefit analysis of bench terraces, a case study in Peru’ *Land Degradation and Development* 16: 1-11.

Rogers, E. M. (2003) ‘*Diffusion of Innovations (fifth edition)’* Free Press, New York.

Schwilch, G., Bachmann, F., de Graaff, J. (2012) ‘Decision support for selecting SLM technologies with stakeholders’ *Applied Geography* 34: 86-98.

Shively, G. E. (1999) ‘Risk and returns from soil conservation: evidence from low-income farms in the Philippines’ *Agricultural Economics* 17: 165–177.

Staal, S.J., Baltenweck, I., Waithaka, M.M., deWolff, T., Njoroge, L. (2002) ‘Location and uptake: integrated household and GIS analysis of technology adoption and land use, with application to smallholder dairy farms in Kenya’ *Agricultural Economics* 27: 295-315.

Tenge, A.J., de Graaff, J., Hella, J.P. (2005) ‘Financial efficiency of major soil and water conservation measures in West Usambara highlands, Tanzania’ *Applied Geography* 25: 348-366.

WOCAT (2007) ‘*Where the land is greener – case studies and analysis of soil and water conservation initiatives worldwide’* H.P. Liniger and W. Critchley (Eds.). CTA/FAO/UNEP/CDE, Berne, Switzerland.