Assessing the biophysical impact and financial viability of soil management technologies under variable climate in Cabo Verde drylands: the PESERA-DESMICE approach

Short title: Assessing SLM impact under variable climate: PESERA-DESMICE approach

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ABSTRACT

Field trials have demonstrated the potential of soil conservation technologies but have also shown significant spatial-temporal yield variability. This study considers the PESERA-DESMICE modelling approach to capture a greater range of climatic conditions to assess the potential effect of an improved agricultural management practice emerged from field trials as a promising strategy for enhancing food security and reducing soil and land degradation. The model considers the biophysical and socio-economic benefits of the improved soil conservation technique (T3) - residue mulch combined with pigeon-pea hedges and an organic amendment, against a local baseline practice (T0). The historic rainfall statistics and 50-year rainfall realizations provide a unique time-series of rainfall and an envelope of the potential crop yield. Envelopes of potential biomass production help express the agricultural risk associated with climate variability and the potential of the conservation measures to absorb the risk, highlighting the uncertainty of a given crop yield being achieved in any particular year. T3 elevates yield under both sub-humid and semi-arid climates with greater security for sub-humid areas even though risk of crop failure still exists. The technology offered good potential to increase yields by 20% in 42% of the dryland area in Santiago Island

and reduce erosion by 8.6-Mg ha^{-1}, but in terms of cost effectiveness, it might be prohibitively expensive for farmers lacking inputs. The findings can enable the assessment of policy options at larger scale or influence adoption of improved conservation measures under the climatic variability of the Cabo Verde drylands and resilience to future climate change.

KEY WORDS: PESERA-DESMICE, climate variability, sustainable land management, time series analysis, probability of yield.

INTRODUCTION

Land degradation persists as one of the most pressing environmental concerns with important consequences for sustainability at various levels through complex links with food production, poverty and climate change (Stringer et al., 2014, Fleskens et al., 2014). Soil erosion by water is recognized as an important worldwide driver of land degradation with consequences for the maintenance of soil fertility, sustainable dryland crop yields (Lal, 1995; Geissen et al., 2007; Kirkby et al., 2008; Muzinguzi et al., 2015), water availability (Araya et al., 2011), affecting food production, fuelwood, income and housing (Tesfaye et al., 2015). By removing the most fertile topsoil, erosion reduces soil productivity, potentially leading to a progressive loss of farmland where soils are shallow or conducting to desertification in more vulnerable areas (Xu et al., 2014; Baptista et al., 2015b; Xie et al., 2015;).

In semiarid and arid areas, rainfall variability, the occurrence of extreme drought and inappropriate historical land management practices have been recognized as contributing to serious environmental impact (Hessel et al., 2009; Baptista & Tavares, 2011; Ferreira et al., 2012; Baptista et al. 2015a). For example, in Cabo Verde, a Sahelian country severely affected by land degradation and desertification (Ferreira et al., 2013; Tavares et al., 2015), rainfall in 2014 was 65 % lower than the year prior. Consequently, Cabo Verde produced just 1000 Mg of corn in 2014 (FAO, 2015), the lowest output ever in the history of the country which has caused a considerable shortage of livestock feed.

This significant impact of the 2014 drought occurred despite enormous investment in soil conservation, which has become visible throughout the Cabo Verde landscape (Tavares et al., 2014; Baptista et al., 2015a). However, the biophysical and socioeconomic impacts of the conservation measures have been poorly assessed and, in particular, their performance under variable climatic conditions has not been documented. In recent years, a concerted approach based on Schwilch et al. (2012) has started to address this gap by documenting stakeholder consultations and carrying out field trials for selected sustainable land management (SLM) technologies.

SLM technologies are practical measures to prevent and/or decrease and/or reverse the effects of land degradation on land resources (e.g. soil and water) extending over defined spatial, temporal, and socio-cultural boundaries, and maintain and improve land productivity, water saving and use efficiency (Fleskens et al., 2014; Baptista et al., 2015b). Successful SLM technologies may support the rehabilitation of degraded land or conservation, helping to harness benefits over larger areas (Stringer et al., 2014). Yet, scaling-up adoption of SLM technologies beyond initial spatial, temporal and socio-cultural boundaries is challenging, often with low adoption of technologies due to design failures and lack of an approach that fully recognizes land managers' interests and socioeconomic dynamics (Tenge et al., 2005; 2007). Comprehensive identification and evaluation of SLM technologies are crucial to assess the applicability of promising technologies, their cost and the likely impact they will bring. Close stakeholder involvement in selecting the technologies to evaluate is vital (Schwilch et al., 2009; Tavares et al., 2014; Hessel et al., 2014; Baptista et al., 2015a). Model evaluation of the selected technologies additionally informs stakeholders regarding the spatial extent and regional impact of the technologies being considered; thus enhancing their understanding of the technology. Fleskens et al. (2014) highlight that this principle underpins the integrated PESERA-DESMICE (Pan-European Soil Erosion Assessment - Desertification Mitigation Cost Effectiveness) approach developed as part of the DESIRE project.

The PESERA-DESMICE modeling approach offers a methodology to assess the biophysical and socio-economic benefits of SLM technologies against a local baseline condition (Fleskens et al., 2014; Stringer et al., 2014). PESERA is a process-based erosion prediction model, which explicitly considers climate variability and can be adapted to consider SLM strategies. DESMICE is an economic model that operates through spatial cost-benefit analysis (CBA), considering the suitability of the conservation measures in terms of environmental conditions and market access. The modeling approach departs from the assumption that for SLM technologies to get adopted they need to be financially attractive to land managers in terms of cost reduction and /or benefit enhancement (Fleskens et al., 2014).

Although biophysical factors and land-use influence soil erosion, the results from plot studies typically indicate the benefits of adopted SLM measures. The aim of this paper is to appraise the applicability of the PESERA-DESMICE modelling approach to extend biophysical and economic benefits of a previously selected promising SLM technology (Baptista et al., 2015b; 2015c) across typical field conditions in the Ribeira Seca catchment, where the SLM had been tested, and over the whole Santiago Island under variable climatic conditions. The rainfall time series for modelling are generated from the distribution of historical data and provide the opportunity to explore a full range of climate variability beyond the period of the trials.

MATERIAL AND METHODS

Study site

The PESERA-DESMICE model application has been based on outcomes from a two-year field experiment carried out with stakeholder participation in three sites (São Jorge, site I; Serrado, site II; and Órgãos Pequenos, site III) in the Ribeira Seca watershed (RSW), which is the largest watershed on Santiago, the main agricultural island of Cabo Verde (Baptista et al., 2015a). The RSW has a drainage surface of approximately 72 km^2, is located on the east-central side of the Santiago Island (991 km^2), between latitude 15°07'40''W and longitude 23°32'05''W (Figure 1) and extends across four representative agro-ecological zones of the Cabo Verde classification: semiarid (49%), arid (20%), subhumid (20%) and humid (11%) (Diniz & Matos, 1986).

The climate of the RSW, as well as that of the Santiago Island, is characterised by a unimodal rainfall regime, with a short (3-4 month) humid season (July-October) and a long (8-9 month) dry season (November-June). Mean annual rainfall is extremely heterogeneous and has an irregular spatiotemporal distribution, varying from <200 mm in the downstream section of the watershed to 650 mm upstream. The 30-year (1980-2010) mean annual rainfall was 437, 300, and 310 mm at experimental sites I, II, and III, respectively, with most of the rain falling in August and September (INMG, 2010). The topography is rugged and predominant land use is rain-fed (e.g. dryland) agriculture, particularly of the staple crops (maize and beans) and groundnut, occupying >83% of the area (Figure 2). The remaining area is used for: irrigated crops (sugarcane, fruits, vegetables, cassava and sweet potato) 5%, forest 4%, rock outcrops 1% and 7% are built environment (Figure 2). Livestock keeping is an important activity in the watershed and in the country in general as most family farmers own animals that often graze freely. In 2013, Cabo Verde had 22000 cattle, 1117000 chickens, 190000 goats, 85000 pigs, and 12000 sheep (FAO, 2013).

Over a two-year period, (2011 - 2012) study plots representing a baseline scenario (T0) and three SLM scenarios (T1-T3) were monitored at the three sites and T3 revealed a promising SLM technology for the steep slopes. Full details of the field study are presented in Baptista et al. (2015b). The baseline scenario (T0) represented a traditional maize/bean intercropping system with no input or conservation measure. The SLM scenario (T3) trialed represented a combination of mulch (4 Mg ha^{-1} of crop residue) and organic fertilizers (e.g. 4 Mg ha^{-1} of compost at site I, 4 Mg ha^{-1} of animal manure at site II, and 1 Mg ha^{-1} *Leucaena leucocephala* prunings at site III). In addition, in T3 pigeon-pea hedges were planted cross-slope at 3-meter intervals.

PESERA model background

The Pan European Erosion Risk Assessment (PESERA) model provides an objective, physically based and spatially explicit methodology to consider land degradation (Kirkby et al., 2008). Spatial applications at the continental scale at 1 km resolution and at 100m resolution at regional scale allow detailed observed data to be placed in the broader spatial context. As rainfall variability and the occurrence of drought are key issues in food security and land degradation in Cabo Verde consideration is also given to time series analysis at representative points to consider the probability of achieving a defined yield under baseline conditions (T0) and the SLM scenario (T3). Simulated time series generated from historical climate statistics are run repeatedly for each treatment to produce a probability distribution of yield, runoff and erosion. This approach aims to capture a representative picture of the rainfall variability observed on the island. Field observations and measurements enable a conceptual understanding of the SLM technology, which informs model adaptations. Through the comparison between the response of the treatments T0 and T3 to the variable rainfall, PESERA-DESMICE offers a methodology to compare the benefits of an adapted conservation scenario against a baseline scenario assessment. PESERA provides this comparison through a series of monthly estimates of biomass (productivity), runoff and erosion for T0 and T3.

The core of the PESERA model (for both spatial and point applications) is the water balance which partitions precipitation into interception losses, evapotranspiration (from the vegetation canopy and bare ground), overland flow, runoff and infiltration (Figure 3, Irvine & Kosmos, 2003). The rainfall is partitioned such that soil water remains available for plant growth after overland flow is conveyed (Kirkby et al 2008; Esteves et al., 2012). Transpiration is controlled by potential evapotranspiration and the availability of soil water. Soil organic matter contributes to the runoff threshold and infiltration capacity of the soil. Soil organic matter is built through *in situ* leaf fall and the addition of mulch. The organic matter decomposes as a function of temperature.

The PESERA model is first run to equilibrium to estimate initial or average conditions before the time-series model is executed. The equilibrium conditions are achieved by running the model with monthly climate statistics derived from the frequency distribution of observed daily rainfall totals. Daily rainfall data is used, as it is more readily available than finer temporal rainfall data even though it is appreciated that the finer storm detail is that which generates most overland flow and erosion.

DESMICE model background

The Desertification Mitigation Cost-Effectiveness (DESMICE) model (Fleskens et al., 2009; 2014) essentially performs a spatially-explicit financial cost-benefit (in terms of long term investments) or gross margin (in terms of annually repeated measures) analysis of SLM technologies. DESMICE evaluates the applicability limitations and inventories the spatial variation in the investment and maintenance costs involved for a pre-selected portfolio of technologies. The effects of the implementation of the SLM technologies (here the T3 scenario) relative to the without situation (T0 scenario) are subsequently assessed and valuated in monetary terms. DESMICE consists of a number of steps. First, an analysis is made where a SLM option can in principle be applied based on biophysical factors such as soil depth, slope, landform and land use. The output of this step is a map showing applicability in a dichotomous fashion. A subsequent step assesses investment costs based on environmental factors (e.g. slope) and socio-economic factors (e.g. distance to market) in a spatially explicit way. 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. Next, in case of assessing multiple SLM options, a common time horizon is set, which in the case of T3 was set at 1 year. Costs and benefits are subsequently assessed including production output (yield x value) realized with the technology, costs of implementing the technology and land use associated with it, and production output and costs of the land use in the without case (T0). Production output is derived from the PESERA model output of biomass yield. Again, benefits and costs may vary in both space and time. The annual cash flows thus established are used either in a financial cost-benefit analysis or, as in this study, gross margin analysis. For each grid cell, one of the following three possible outcomes will apply for assessment of an SLM option: if the gross margin is positive, the technology is deemed viable; if the gross margin is negative, the investment is not financially attractive; or the technology is not applicable in the area. Finally, per unit and aggregate cost-effectiveness indicators can be calculated, e.g. the cost per unit of soil conserved (as simulated by PESERA) by implementing an SLM option (Fleskens et al., 2014).

Model Application

Rainfall data

Climate variability and agricultural practice have been identified as drivers of land degradation in Cabo Verde (Tavares et al., 2014, Baptista et al., 2015a). T0 and T3 consider possible management options while rainfall records provide the basis for generating simulated time-series. These time series have been derived from rainfall data obtained from two locations, one (São Jorge) representing sub-humid and the other (Ponto Ferro) semi-arid conditions. The simulated time series are generated directly from the observed variability in the rainfall data (mean monthly rainfall, mean rain per rain day and coefficient of variation in rain per rain day), as the future rainfall predictions for Cabo Verde do not indicate a significant trend (McSweeney et al., 2010). The records extend beyond the two-year period of the field trials and, as such, they can be used to put the experimental rainfall in a wider context by considering frequency of the events experienced during the trials.

Rainfall frequency is estimated from the rainfall records at São Jorge as this station is more representative of the study site. The record covers the period 1983 – 2008 (Figure S1).

The return period of a given rainfall is estimated by fitting a Gumbel Extreme Value distribution to the observed annual rainfall totals and monthly values. Annual rainfall totals and monthly values are plotted for the duration of the record against a reduced variate 'y' ($here\ y = (-\ln\left(\frac{r}{n-1}\right)$) which describes the probability on a linear scale. The Gumbel Extreme Value distribution estimates the probability of a given event based on the observed mean and variance. This allows the observed event of the two-year field trial to be put in context with the extended rainfall record.

Adapted Model

Field observations inform the conceptual model for the SLM scenario (T3). A key element considered in the T3 scenario is the improved soil condition through the application of mulch, compost, animal and green manure in soil pits. Manure and mulch are added directly to the soil humus and above ground biomass residue respectively. In the adapted model, this impacts directly on the soil water storage capacity. Soil pits have previously been considered in the modelling of in-situ water harvesting technologies (Lebel et al., 2015). Although the benefits of pits have been highlighted, the application of organic matter is a much more significant component of the hydrological equilibrium. Several studies (Zougmoré et al., 2003; Sawadogo et al., 2008; Lebel et al., 2015) highlight that soil pits alone have little benefit, however, when combined with compost the soil water available to plant growth increases. A number of additional benefits of pits are not readily modelled such as increasing sediment-trapping efficiency, reducing the removal of seed and soil organic matter. Further, soil water available to plants is elevated as the infiltration is reduced, allowing greater soil water retention time.

Time series application

As way of validation, the PESERA baseline model and the adapted model were run against a single 50-year simulated rainfall time-series for the three study sites. Cumulative runoff and erosion are plotted for T0 and T3 (Figure S2a-b). Over the 50-year simulation, the reduction in average annual runoff and erosion is of the same magnitude as the observed site data (Baptista et al., 2015b). Extrapolating the experimental data beyond the plot scale requires further data at increasing scales to account for the complexity of scaling between plot area and PESERA hillslope application. However, the magnitude and direction of the observed change remains of greater value and interest when considering spatial applications.

Spatial Application

Applicability of the SLM scenario (T3) confined to areas under rainfed cropping. GLOBCOV data for Santiago Island (Bontemps et al., 2011) defined these areas. Slope also imposed further limitation on applicability. SRTM90 digital elevation data provided slope maps of the island, and land with slope >45% was considered too steep to apply the SLM technology.

Experimental data included estimates of the costs of inputs and produce (Table 1). From variations between experimental sites, it was estimated that 20% of cost levels was due to differences in accessibility, expressed as the distance between field and road. The island's main road network was taken from the gROADSv1 dataset (CIESIN/ITOS, 2013) and used to map variable transport costs based on Euclidian distance to the nearest road. For example, transport costs in Site I amounted to 4000 ECV; the site is at 500m distance to road, so transport costs of the 4 Mg crop residues amount to 0.2*4000/500 = 1.6 ECV per meter, or 0.4 ECV per Mg per meter. Based on experimental yield data (Baptista et al., 2015b), biomass partitioning was assumed as follows: 33% of biomass is produce (50% maize, 50% beans, at average price 130 ECV/kg) and 67% crop residues valued at 6 ECV/kg.

Soil type and depth are poorly defined at the available spatial resolution for Santiago Island. Available data classifies the majority of the island into one category and depth, where both are seemingly independent of landscape characteristics. However, it is noted from the study plots that biomass growth before and after mitigation may be more sensitive to land management practice and inputs rather than typical soil parameters. This observation therefore justifies the potential value of the spatial assessment based on available data. For the upscaling, climate data is distributed according to annual rainfall totals. However, rainfall variability is considered relative to the two points considered (São Jorge and Ponto Ferro). Mean erosion rates and crop potential are estimated under the rainfall time series derived from the observed climate data from these two stations.

Input data for DESMICE, average and standard deviation of biomass yield, was derived from a regression analysis of the probability maps of exceedance of nominal biomass yield. Parabolic trend lines were fitted through probabilities of having 0 (always 100%

probability), 0.8 and 1.2 Mg ha^{-1} biomass (PESERA). P_{50} values of biomass were taken to inform spatial financial viability assessment. Fluctuating biomass rasters were created using random normal raster creation with probability distribution details specific for T0 and T3. Random rasters were created independently for T0 and T3 to mimic variability due to a range of conditions, but the direction of variability was kept equal (e.g. positive and negative deviances coincide for both treatments).

RESULTS

Rainfall magnitude and frequency

Monthly and annual rainfall totals were plotted on a probability scale (Figure 4). The observed annual rainfall range of 2011-2012 (vertical black line) shows a return frequency range of 1 in 2 years to 1 in 5 years. The observed maximum monthly rainfall range (2011-2012) shows a return period from 1 in 2 years and 1 in 30 years relative to the long-term records. Records do not suggest significantly unusual dry periods but do indicate a significant monthly rainfall bias. Simulated 50-year time series generate rainfall variability that allows the impact of rainfall to be extended. Multiple simulations allow this to be extended further typically covering annual rainfall in the range between 200 – 1000mm.

Sensitivity to climate variability with / without treatment

Historical rainfall records, field observations and recent reports (FAO, 2015) highlight the potential rainfall variability of the climate in Cabo Verde. Thus, we consider the impact of rainfall variability on both the baseline and improved soil management conditions and the financial viability of the measures. The PESERA model has been modified to represent both the untreated plots (T0) and the treated plots (T3). The benefits of T3 are achieved through management inputs and cultivation practice. Improvements are observed for both climate zones (sub-humid and semi-arid) when treated (T3). However, despite significant improvement in the semiarid case, in the drier years yield does not exceed a nominal value of 0.8-Mg ha^{-1} as in the sub-humid case (Figure 5).

Time series analysis of yield and probability of yield

The time series approach allows repeated realisations of the climate to be generated from the frequency distribution of observed data, thus enabling sampling of the performance of the standard and improved practice across a much wider spectrum of climatic conditions. The envelope of potential biomass growth is derived from the modelling of repeated realisations. The maximum and minimum biomass predictions are plotted for a notional 50-year simulation for both climate zones (Figure 6a and 6b). Simulations of the SLM interventions indicate that biomass yield in the sub-humid regions tend to be secured (e.g. future yield level under climate variability exceeds nominal value over time). However, extreme years remain critical.

The probability of a given yield being achieved or exceeded is determined by treatment and climate variability at a given location (point). At a point, the probability distribution is derived with respect to treatment and climate (Figure 7). The probability for a given yield is derived from the cumulative frequency of 300 years simulated yields for treated and untreated sites in sub-humid and semi-arid climates. The generated probability is taken as the basis to distribute the probability of achieving a nominal value across the landscape based on annual rainfall totals assuming a similar distribution of observed inter-annual monthly variability applies across the island.

Spatial assessment at island scale

The probability of potential biomass growth envelopes can be considered across the island by setting a nominal limit and considering the probability of exceedence at each point based on the available climate distribution. The estimated probability for biomass growth greater than nominal values of 0.8 Mg ha^{-1} and 1.2 Mg ha^{-1} are presented in Figure 8. The change in the associated erosion risk is a direct result of the SLM intervention (Figure 9). Significant reductions of soil erosion are possible, from an average of over 15 Mg ha^{-1} to below 7 Mg ha^{-1}. Average biomass production was simulated derived from the probabilities of exceedence (Figure 10a-b), and allowed to vary between 2 standard deviations from the average value (Figure 10c-d). The effect of T3 is large relative to introduced variability in low potential arid zones, but in the most productive subhumid part of the island, the variability effect is larger than the difference in average yields between T3 and T0, hence some negative effect (T3 – T0 < 0) can be observed (Figure 10e-f).

Applicability limitations limit the suitability of the SLM scenario to about 42% of Santiago Island (Figure 11a). In addition, the distance to main roads is taken into account for transport costs of organic inputs to the fields for a number of situations (Figure 11b). This works out differently depending on the situation: if all inputs are locally available the SLM technology is an attractive investment in most parts of the island except in the high potential zones where negative results are possible because little difference in biomass production and higher costs involved in T3 compared to T0 (Figure 12a). However, although T3 is profitable in low potential zones it is unlikely that inputs are locally available. Therefore situations b and c explore the viability of the SLM technology if manure and crop residues are not locally available (Figure 12b) or only manure needs to be transported (Figure 12c). In situation b costs amount to ECV 48000 for inputs plus variable transport costs (0-14000 ECV for most remote locations), whereas in situation b an allowance is made of 24000 ECV for manure only and variable transport costs. Clearly, purchasing of inputs is generally too expensive, except in few locations.

The average maximum simulated reduction of soil erosion and food production increase in the Santiago Island were 8.6 Mg ha^{-1} and 0. 1 Mg ha^{-1}, respectively, corresponding to a low cost-effectiveness of 10060 ECV Mg^{-1} and 566 ECV per kg (Table 2).

DISCUSSION

Sensitivity to climate variability

Historical rainfall records, field observations and recent reports (FAO, 2015) highlight the potential rainfall variability of the climate in Cabo Verde. The time series simulations generate rainfall variability that allows extending the impact of rainfall and putting the observed event of the two-year field trial in context with the extended rainfall record. The observed annual rainfall range for the experimental years (2011-2012) show a return frequency range of 1 in 2 years to 1 in 5 years. Although there were marked differences in rainfall between the experimental seasons (2011 and 2012), based on the historical record both seasons fall close to the average annual rainfall. However, the intra-seasonal pattern is significantly different, with one-month dominant in 2012. High monthly rainfall in September 2012 approached a 1: 30 year return period, skewing rainfall significantly and greatly reducing the length of growing season. Thus, results do not suggest significantly unusual dry periods but do indicate a significant monthly rainfall bias, as previously reported (Smolikowski et al., 2001; Sanchez-Moreno et al., 2014; Baptista et al., 2015c).

The model can be constrained to the plot scale results with and without treatment and as such, over the 50-year simulation, the reduction in average annual runoff and erosion is of the same magnitude as the observed site data (Baptista et al., 2015b). This helps validate the modified PESERA model as a suitable model but requires further consideration at the field and slope scale to consider more confidently the biophysical impact of the improved SLM technique. However, as stated earlier the magnitude and direction of the observed change remains of greater value and interest when considering this spatial application.

Time series analysis and probability of yield

Improvements were observed for both climate zones (sub-humid and semi-arid) when treated with the proposed SLM (T3). However, despite significant improvement in the semi-arid case, in the drier years yield does not exceed a nominal value of 0.8-Mg ha^{-1} as in the sub-humid case. Though T3 elevates biomass yield under both sub-humid and semi-arid climates, risk of crop failure still exists. Results also suggest greater security or return on investment in sub-humid rather than semi-arid conditions.

The historic rainfall statistics and the multiple 50-year rainfall realisations capture a fuller range of climatic conditions, providing a unique time-series of rainfall, simulated crop yield and an envelope of the potential crop yield. Envelopes of potential biomass production help express the agricultural risk associated with climate variability and the potential of the conservation measures to absorb the risk, thus, highlighting the uncertainty of a given crop yield being achieved in any particular year. This information can directly inform or influence the adoption of conservation measures under the climatic variability of the Cabo Verde drylands.

Applicability of the improved scenario

While analysis at plot level is informative, upscaling the analysis to the island level was able to demonstrate that the viability of the improved technology is questionable from a farmer's perspective. By fluctuating the yield level to represent natural variability, it could be established that T3 could lead to yield increase in 81% of circumstances. However, given additional labour costs, if crop residues and manure are available locally, investment in the technology is attractive in 65% of cases. However, land users have to buy and transport manure to the farm, a favourable return on investment occurs in only 10% of cases, and if also crop residues have to be sourced off-farm, this drops to a mere 3%. The investments involved are too high to justify investment for the benefit of reduced risk of poor crop yield alone. Further data are required to be able to quantify the contribution of pigeon pea to system productivity.

It seems appropriate to consider additional benefits from the improved technology, which could be applied on 41679 ha, or 42% of Santiago Island. It should be noted though that the land cover map used to inform the area of rainfed cropping (Bontemps et al., 2011) includes mosaic land cover classes, which are leading to a higher area under agriculture than observed from governmental data that shows a 50% less potential area (PEDA, 2005). Notwithstanding this discrepancy, the average reduction of soil erosion that can be achieved was simulated to be 8.6-Mg ha^{-1} (Table 2). Apart from the direct on-site damage, with the dominant local soil bulk density this translates in a loss of 0.6-0.7 mm of soil annually, which implies nutrient losses of e.g. 86 kg N and a gradual reduction of maximum available soil water. Several authors (Ali et al., 2007; Zhang et al., 2011; Xia et al., 2013; Baptista et al., 2015c) also reported similar rates of erosion-related nutrient loss. Considering the medium to long-term impact of land degradation, the cost-effectiveness of the investment for the purpose of soil conservation could, in some cases be of sufficient interest. The increased food production is, when considered in isolation, not cost-effective with a per unit cost of over three times the crop price. However, in total 4800 Mg food could be produced extra annually, which is almost 50% more than was produced in the whole archipelago in 2014 (FAO, 2015) and could be a strategic asset from a food sovereignty perspective. There is finally a need to consider effect on the regional water balance and any improvements to off-site conditions, such as raising local water table and reducing stream erosion and sedimentation of downstream reservoirs.

While the improved technology show great biophysical potential as an adaptation strategy to climate change, there exist specific barriers to its adoption (e.g. availability of crop residue and organic amendment, which will need to be addressed to guarantee its successful application at a wider scale (Lebel et al., 2015). Moreover, for farmers to adopt technologies, these must be attractive in economic terms, e.g. have potential from a farmer’s perspective, lead to cost reductions, benefit enhancements, or both (Teshome et al., 2013; Fleskens et al., 2014). Strategies to assist farmers in simultaneously conserving water and nutrients have shown promise in similar environments (Wakeyo & Gardebroek, 2013; Zougmoré et al., 2014). In the case of Cabo Verde, improvement of animal husbandry practices seems to hold good potential as simulations highlighted insufficient financial returns for farmers with poor availability of organic amendments. The quantification of off-farm benefits to society would enable the government to decide on institutionalizing a Payment for Ecosystem Services scheme to incentivise farmers to adopt SLM technologies.

CONCLUSIONS

Using the PESERA-DESMICE modelling approach, we analysed the potential benefits for upscaling an innovative land management technique – residue mulch combined with pigeon-pea hedges and an organic amendment – that emerged from field trials at Santiago Island, Cabo Verde. Biophysically, the technique offered good potential to increase yields by 20% in 42% of the Santiago Island area and reduce erosion by 8.6 Mg ha^{-1}, but might be prohibitively expensive in terms of cost effectiveness for farmers lacking crop residues, manure, or both. The technique elevates yield under both sub-humid and semi-arid climates with greater security for sub-humid areas even though risk of crop failure still exists due to rainfall variability. Simultaneous improvement of land management and animal husbandry would be required to fulfil the promise of the technology. In addition, a governmental payment for ecosystem services scheme could incentivise farmers to adopt the technology. Further research should also look at the downstream effects through a series of nested catchment studies to consolidate impact of the technology. Despite limited data availability and considering that the purpose of our analysis was not to extensively test, calibrate and validate the model, we conclude that PESERA-DESMICE could be calibrated to local conditions using data from two years of field experiments, complementing missing data with data from global datasets. Based on our results the PESERA-DESMICE modelling approach enables the assessment of policy options at larger scale, under variable climatic conditions, to improve soil management and, thus, resilience to future climate change.

ACKNOWLEDGEMENT

This paper forms part integral of the research funded under the Netherlands Universities Foundation for International Cooperation (NUFFIC) through the NFP-PhD-10/132) for which we are grateful. We appreciate the support of the Instituto Nacional de Investigação e Desenvolvimento Agrário of Cabo Verde (INIDA) that provided logistics and laboratory facilities during the field work and the DESIRE project - Desertification Mitigation and Remediation of land (under EU FP6 - contract # 037046 GOCE) that provided the framework for the study and partial funds for the field work.

We also appreciate the collaboration of farmers of Ribeira Seca during the workshops and field experiments.

Supporting Information

Supporting information in the form of figures are available online for this paper.

Figure S1. Long-term rainfall record for S. Jorge station, Cabo Verde.

Figure S2. Plot scale cumulative runoff and erosion rates.

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Table 1: Cost of inputs and produce of the conventional (T0) and improved (T3) soil management scenarios.

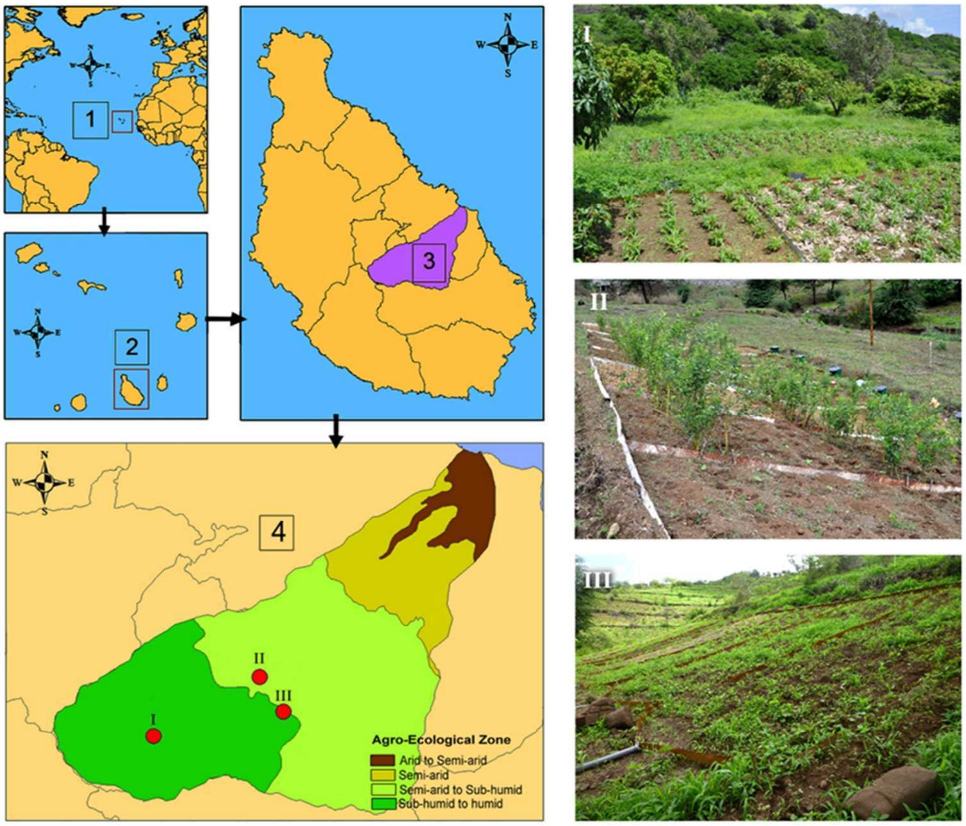
Item	Scenario T0 # of units	Scenario T0 unit price (ECV)**	Scenario T0 total cost (ECV)	Scenario T3 # of units	Scenario T3 unit price (ECV)	Scenario T3 total cost (ECV)
Labour (man days/ha)	85	800	68000	100	800	80000
Seeds						
maize (kg.ha^{-1})	12	100	1200	12	100	1200
beans (kg.ha^{-1})	12	160	1920	12	160	1920
pigeon pea (kg.ha^{-1})	0		0	5	200	1000
Organic amendments Site I						
Crop residue (kg.ha^{-1})*	0		0	4000	6	24000
compost (kg.ha^{-1})	0		0	4000	8	32000
Organic amendments Site II						
Crop residue (kg.ha^{-1})*	0		0	4000	6	24000
Animal manure (kg.ha^{-1})*	0		0	4000	6	24000
Organic amendments Site III						
Crop residue (kg.ha^{-1})*	0		0	4000	6	24000
green manure (kg.ha^{-1})	0		0	1000		0
Transportation (ECV ha^{-1})						
Products to local market	1	1000	1000	1	1000	1000
Materials to the field*	0	0	0	1	4000	4000

* Costs depending on local availability of inputs and need for transportation. ** (Cabo-Verdean Escudos).
Source: own experimental data, local price information.

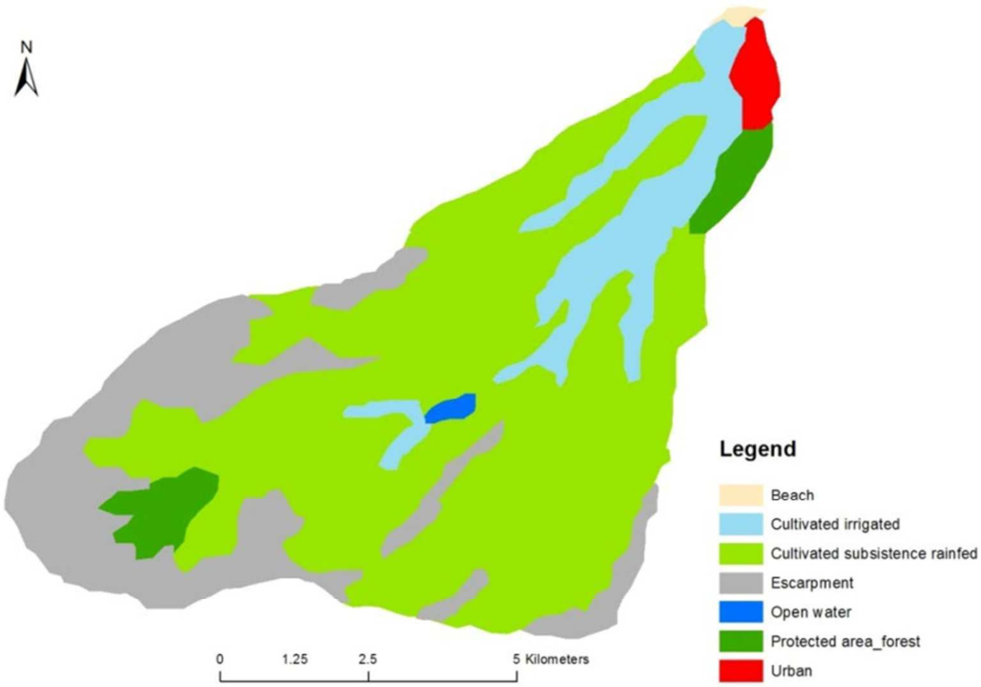
Table 2: Cost-effectiveness indicators for selected ecosystem services for the T3 scenario.

	Unit value	Total value	Cost-effectiveness
T3 applicable area		41679 ha	
Reduction of soil erosion	-8.6 Mg ha^{-1}	-358 * 10^{3} Mg	10060 ECV Mg^{-1}
Increased food production	115 kg ha^{-1}	4800 Mg	566 ECV kg^{-1}

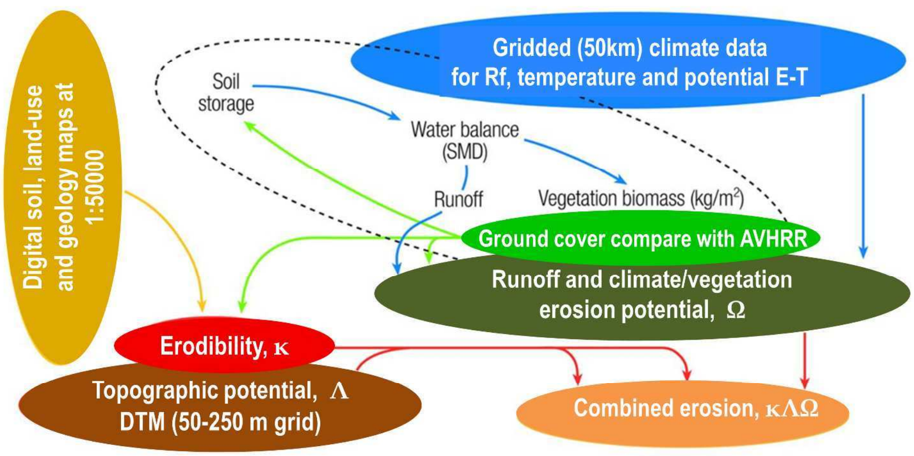
100 ECV = 1 US$



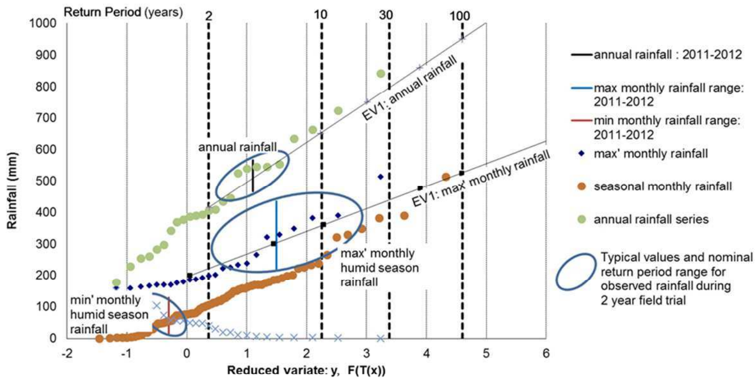
Location of the experimental sites within the Ribeira Seca Watershed, Santiago Island (the study site) and Cabo Verde and field aspects of experimental sites at I, II and III. Adapted from Baptista et al. (2015b).
106x89mm (300 x 300 DPI)



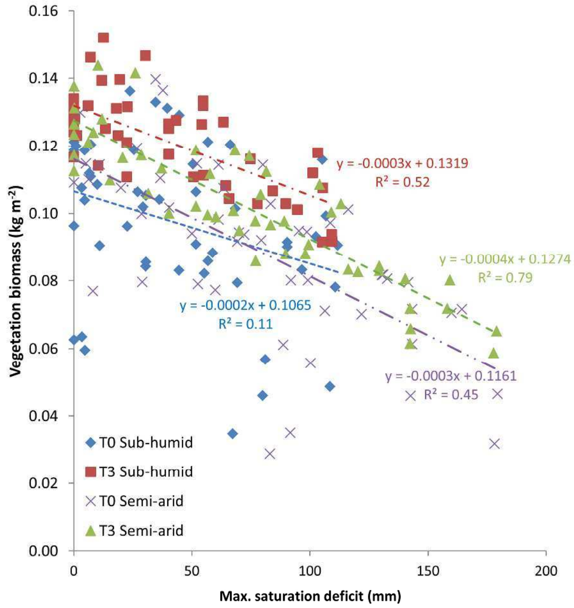
Map of land use types in the Ribeira Seca Watershed showing the dominance of rain-fed farming.
76x53mm (300 x 300 DPI)



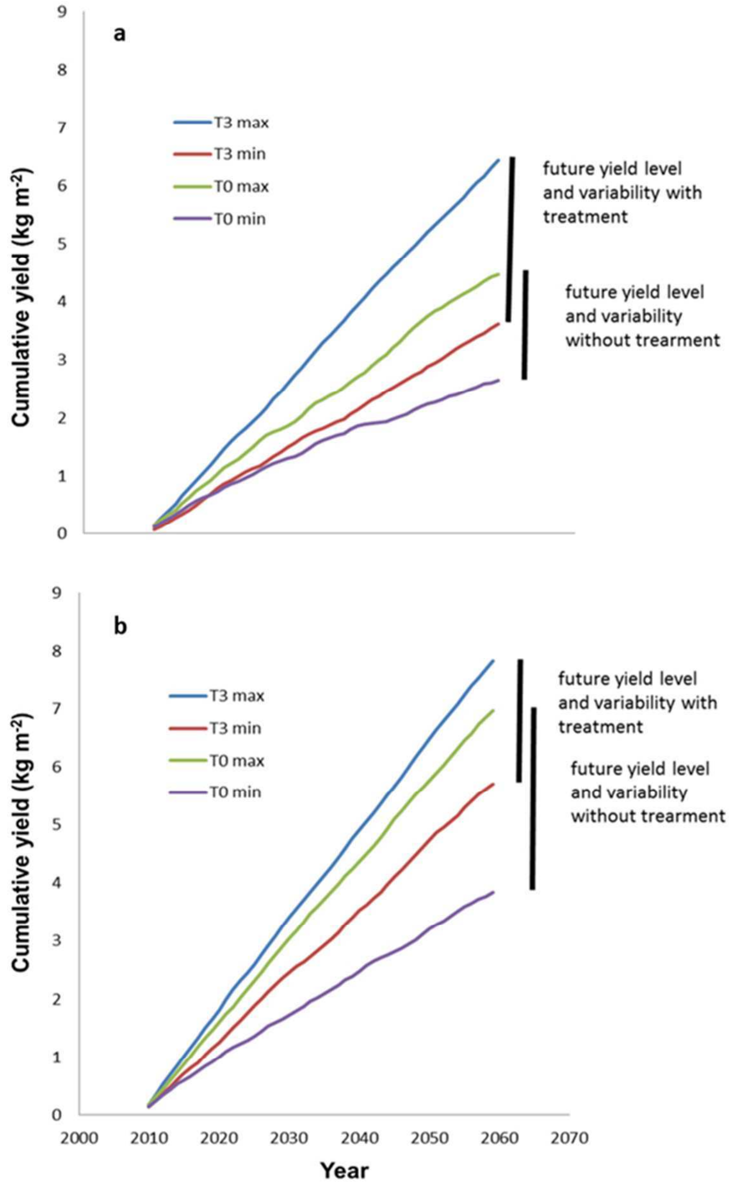
PESERA model: partitioning of rainfall (after Irvine & Kosmas, 2003)
254x190mm (300 x 300 DPI)



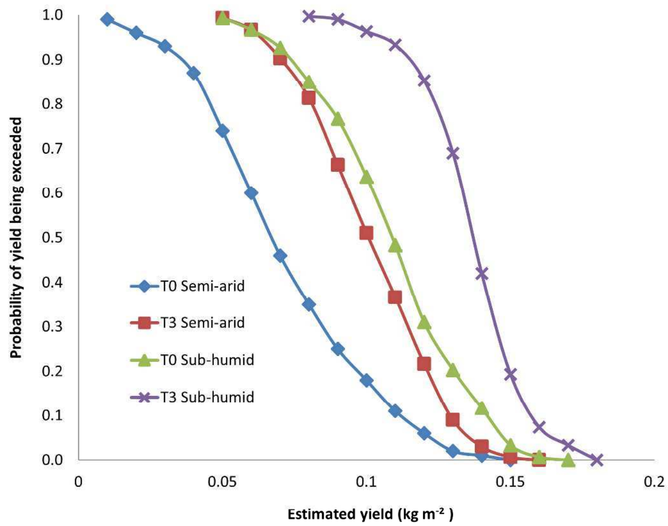
Gumbel Extreme Value Estimates; derived from the probability distribution of observed rainfall (plotted as a linear reduced variate value).
108x60mm (300 x 300 DPI)



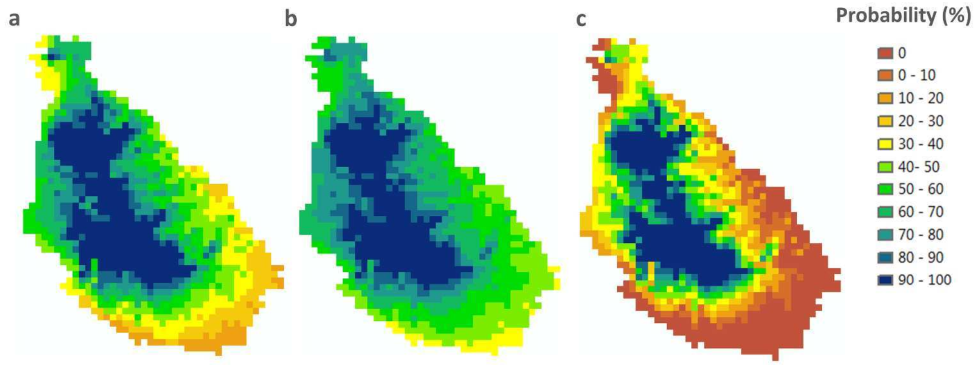
Simulated biomass from treatments T0 and T3 under sub-humid and semi-arid conditions. Treatment T3 elevates yield under both sub-humid and semi-arid climates, although risk of crop failure still exists.
254x190mm (300 x 300 DPI)



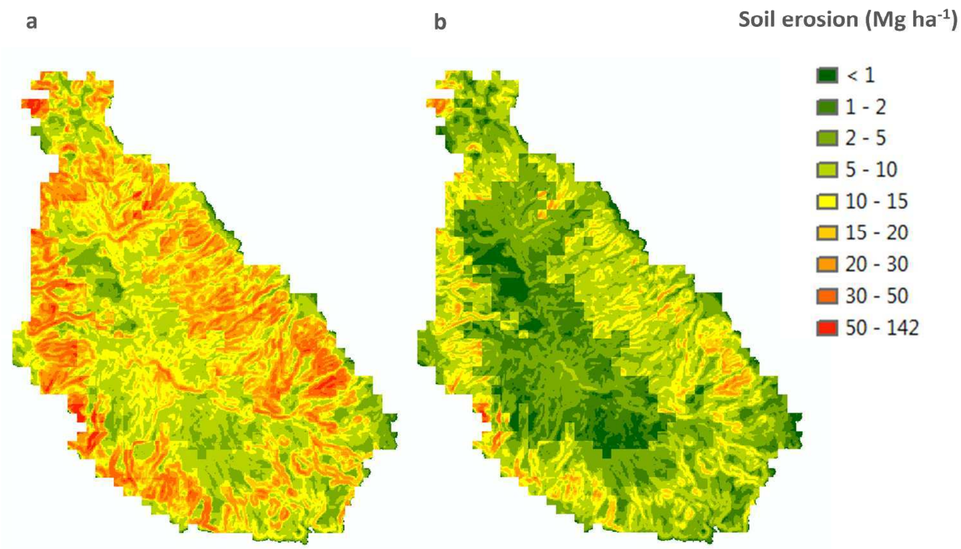
Envelopes of potential biomass production for sub-humid (a) and semi-arid (b) conditions indicating that biomass yield in the sub-humid regions tends to be secured. Rainfall data for São Jorge (annual rainfall 450 mm) and Ponto Ferro (annual rainfall 300 mm) respectively.
55x88mm (300 x 300 DPI)



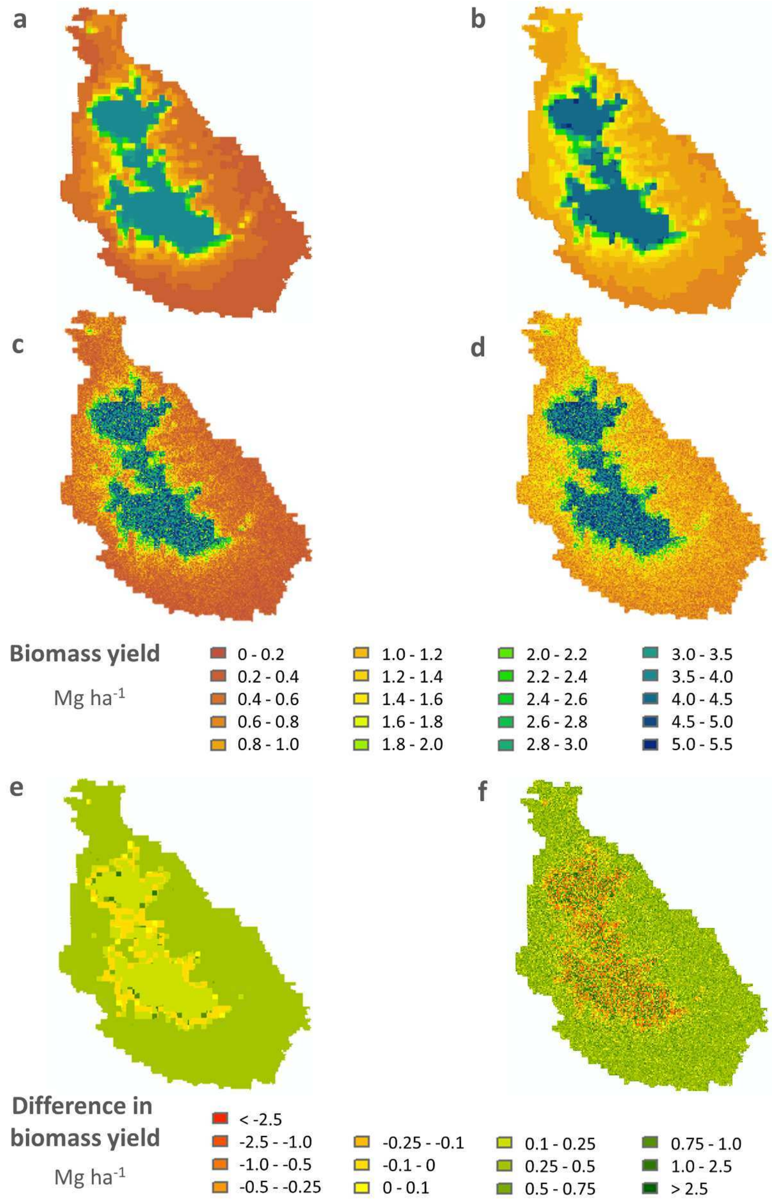
Probability of achieving yield level as a function of climatic conditions and agricultural management at two given locations.
254x190mm (300 x 300 DPI)



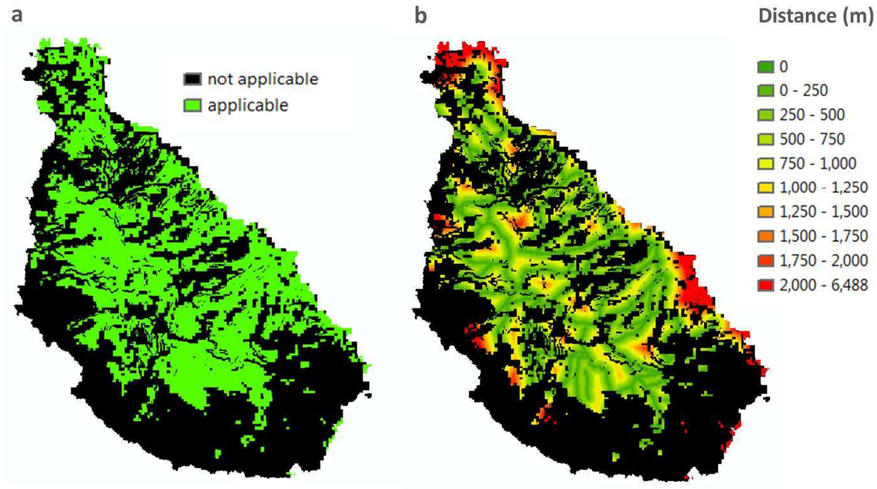
Probability of biomass production exceeding a nominal value: (a) Baseline (T0) p>0.8 Mg ha-1; (b) Improved (T3) p>0.8 Mg ha-1; (c) Improved (T3) p>1.2 Mg ha-1.
254x190mm (300 x 300 DPI)



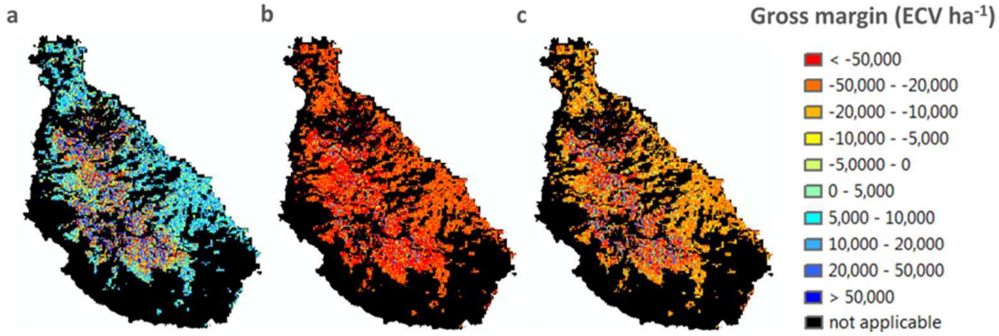
Erosion rate status for baseline T0 (a) and improved T3 (b) conditions.
254x190mm (300 x 300 DPI)



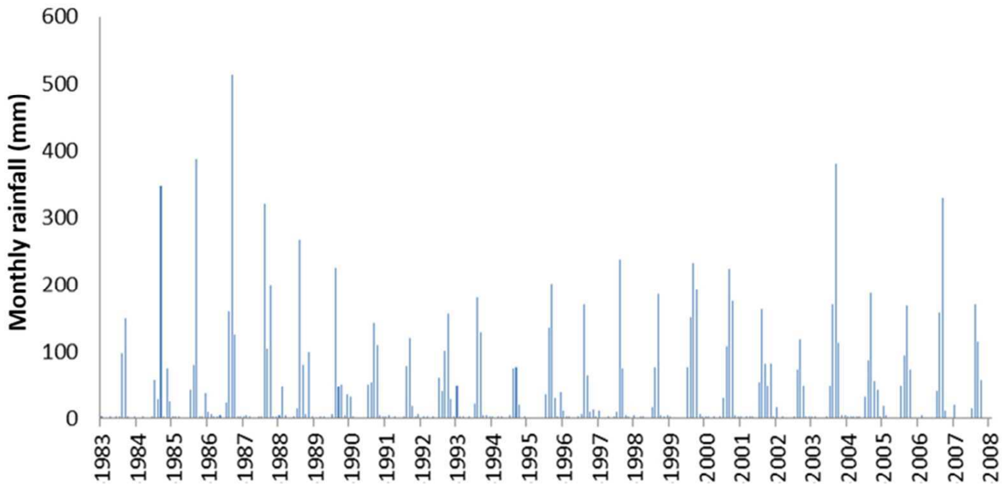
Average biomass production under T0 and T3 derived from the probabilities of exceedance using generic rules (a-b), or introducing random effect of up to 2 standard deviations from the average value (c-d). The difference between biomass production under average T3 (b) compared to T0 (a) conditions is given in (e), and between fluctuating and average T3 conditions in (f).
190x254mm (300 x 300 DPI)



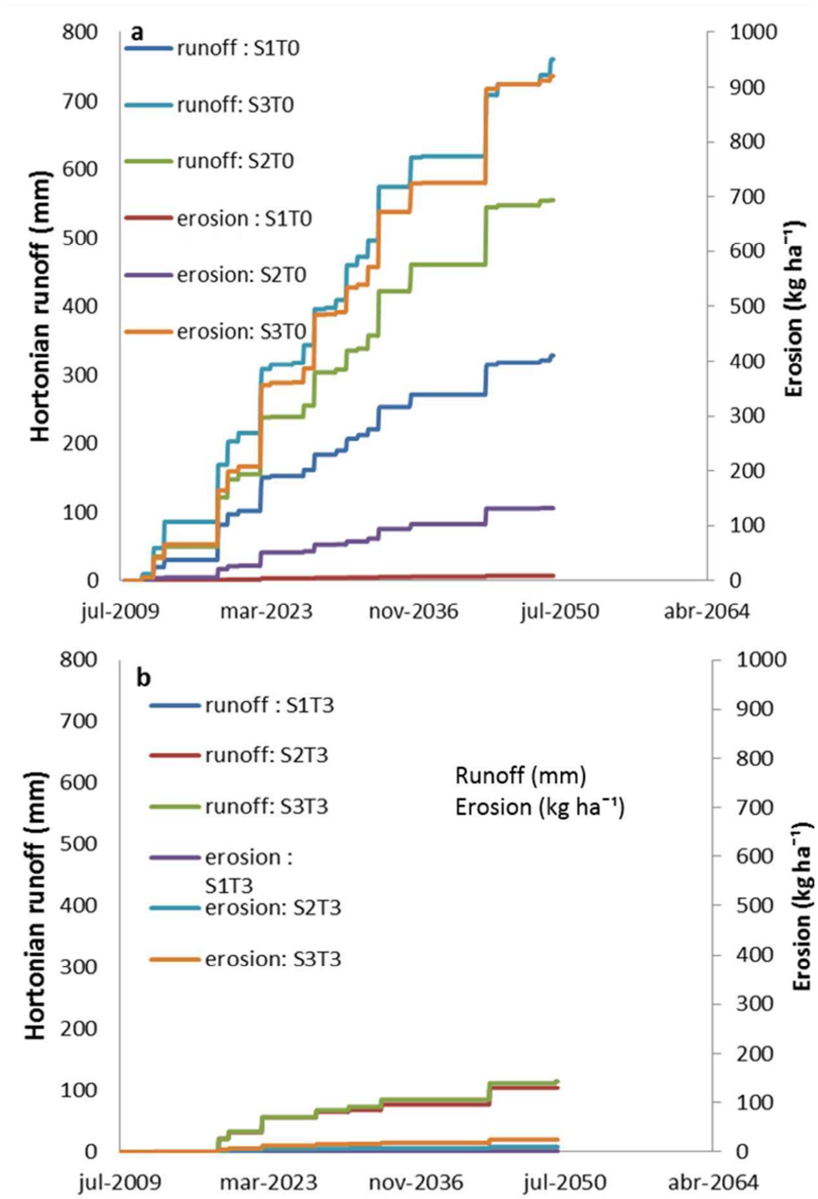
Suitability of improved technology at island scale (a) in relation to the distance to main road (b).
254x190mm (300 x 300 DPI)



Gross margin analysis of T3 in relation to T0 under three different scenarios: (a) organic inputs are locally available; (b) organic inputs are not locally available; (c) transport of manure only. All results shown in Cabo-Verdean Escudos (ECV, 100 ECV = 1 US$).
90x30mm (300 x 300 DPI)



Long-term rainfall record for S. Jorge station indicating both rainfall total and growing season characteristics.
81x39mm (300 x 300 DPI)



Plot scale cumulative runoff and erosion rates for baseline condition -T0 (a) and SLM option -T3 (b).
61x90mm (300 x 300 DPI)