Potential of Quesungual agroforestry system as a land use management strategy to generate multiple ecosystem services from sub-humid tropical hillsides

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Abstract

According to the Millennium Ecosystem Assessment, ecosystem services (ES) are the benefits people obtain from ecosystems, including provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth. The Quesungual Slash and Mulch Agroforestry System (QSMAS) has been suggested as a land use management strategy to generate multiple ES on hillsides of sub-humid tropics. Research studies conducted in Honduras from 2005 to 2007 showed that the production practices applied in QSMAS generates ES through beneficial effects on the soil plant-atmosphere continuum. Specifically, QSMAS contributes to food security through sustainable maize and common bean production under sub-humid conditions on steep slopes, by improving crop water productivity and soil quality, compared to the traditional slash and burn (SB) system. Additionally QSMAS is eco-efficient through the use of renewable natural resources, and also provides ES by reducing deforestation, soil erosion and global warming potential compared to the traditional SB system.

Key Words

Smallholder agriculture, sustainability, resilience, payment for environmental services.

Introduction

Within the terrestrial ecosystems, the soil is the main provider of environmental services (ES). The soil is a living system essential to sustain biological productivity, air and water quality, and plant, animal and human health (MEA 2005). Unfortunately, soil degradation is a severe problem for food production in rural areas, particularly in developing countries. Therefore, it is necessary to contemplate strategies for land management representing the best possible communion between generation of multiple services while preserving the natural capital (Lavelle 2008). The Quesungual Slash and Mulch Agroforestry System (QSMAS) is a smallholder production system that makes use of a group of technologies for the sustainable management of vegetation, water, soil and nutrient resources in drought-prone areas of hillside agroecosystems of the sub-humid tropics. The system was developed in southwest Honduras, Central America, by improving native farming practices with the participation of local farmers and technicians of Food and Agriculture Organization (FAO) and other national and international institutions. The system is based on planting annual crops (maize, common bean, and sorghum) with naturally regenerated trees and shrubs. QSMAS is being practiced by smallholders in Honduras, where the system has been successfully adopted by over 6,000 resource-poor farmers on 7,000 ha. This resulted in a locally recognized suitable alternative to the traditional slash and burn (SB) system, with biophysical and socioeconomic benefits at multiple scales ranging from farm level (increased crop water productivity, food security) to landscape (increased amount and quality of available water). The set of technologies responsible for the success of QSMAS can be summarized in four basic principles of conservation agriculture that contribute synergistically to its superior performance: (1) no SB, but through the management of natural vegetation; (2) permanent soil cover, through the continual deposition of biomass from trees, shrubs, and weeds, and through crop residues; (3) minimal disturbance of soil, through the use of no tillage, direct seeding, and reduced soil disturbance during agronomic practices; and (4) efficient use of fertilizer, through the appropriate application of fertilizers. The main objective of this research work was to determine the key principles behind the biophysical resilience of QSMAS and its capacity to sustain crop production and alleviate water deficits on steeper slopes with greater risk for soil erosion.

Methods

The performance of QSMAS was studied in southwest Honduras, within the Lempa River upper watershed department (district) of Lempira, from 2005 to 2007. Mean annual (bimodal) precipitation is ~1400 mm falling from early May to late October, with a long dry season of up to 6 months. Field plots were established to compare 5 main treatments (replicated on three different farms): QSMAS of three different ages (<2, 5-7 and >10 years-old), the traditional SB system, and secondary forest (SF) as a reference land use system (LUS). Annual management of QSMAS plots included slashing and mulching through pruning of trees and through crop residues while SB plots were managed through slashing and burning of native vegetation, before the onset of the rainy season. Maize and common bean were established in the early (late May) and later (late August) part of the rainy season, respectively, and managed following the timing, spatial arrangement and management practices that are commonly used in the region for the production systems under comparison. The four production system treatments (QSMAS of different ages and SB) were split in order to apply a fertilizer treatment (addition vs. no addition). In the fertilized treatments, the maize received 101 kg/ha of N and 55 kg/ha of P, while the common bean received 46 kg/ha of N and 51 kg/ha of P. Studies included monitoring and analysis of soil water dynamics, crop water productivity (CWP), greenhouse gas (GHG) fluxes, carbon sequestration and global warming potential (GWP).

Water infiltration and runoff were measured through rainfall simulation for 30 minutes using two intensities (80 and 115 mm/h). Soil water content was determined through soil sampling at three depths (0-10, 10-20 and 20-40 cm). Susceptibility of the soil to erosion was assessed in erosion plots (5 m length x 1.5 m width) over 3 years. Soil losses were determined through the comparison of the indices of soil erodibility K-USLE and Ki-WEPP corresponding to the Universal Soil Loss Equation (Wischmeier and Smith 1978) and to the Water Erosion Prediction Project (Nearing *et al*. 1989), respectively. Nutrient losses through erosion were quantified by determining total contents of N, P, K, Ca and Mg from samples of eroded soils. Water quality was assessed through the determination of NO_3^-, NH_4^+, total P, and PO_4^{-3} in samples collected at 45 DAP. Both eroded soil and water samples were collected in erosion plots in 2007. CWP, expressed as kg of grain produced per m^3 of water used as evapotranspiration, was calculated using the crop yield and soil water data obtained in 2007 and by estimating the evapotranspiration (ET) according to the method of Penman and Monteith (FAO 1998).

Annual GHG fluxes between soil and atmosphere were monitored using the closed chamber technique as described by Rondón (2000). At the beginning of the study, 4 PVC rings (height 8 cm, ø= 25 cm) were located in the experimental plots. In every chamber and at each sampling date (16 dates), 4 air samples were taken at 0, 10, 20 and 30 minutes, after installing the chamber (height 10 cm, over the PVC ring). Air samples were extracted from the closed chamber using a syringe with an adapted valve and then introduced into glass containers (pre-vacuumed vials by freeze drying). N_2O and CH_4 concentrations were determined in the laboratory, using a Shimadzu GC-14A gas chromatograph, equipped with FID (flame ionization detector) and ECD (electron capture detector) for methane (CH_4) and nitrous oxide (N_2O) detection, respectively. For CO_2 concentration, we used a Qubit Systems S151 gas analyzer, with infrared technology. GWP of the different LUS was calculated by using CH_4 and N_2O fluxes between soil and atmosphere, and C stocks from soil and tree biomass. For the traditional SB system direct emissions of CO_2, CH_4 and N_2O, from the biomass burning were also included. GHG fluxes of each LUS were multiplied by the global warming potential value, corresponding to the GHG (CO_2=1, CH_4=72 and N_2O=289) in a 20 year time horizon (IPCC 2001).

An emergy (from "embodied energy", a measure of the total energy used to make a product or service) evaluation was conducted as in Diemont *et al* (2006) to quantify resource use and system sustainability, using data from plots and relationships (energy input per unit of energy output) reported in other studies. The Environmental Loading Ratio (ELR, a measure of ecosystem stress due to a production activity) was given by the ratio from purchased and nonrenewable local inputs, to the emergy from renewable resources.

Results

Evaluation of water dynamics at the middle of the rainy and dry seasons of 2007 showed a lower infiltration and higher runoff in SB system. During the rainy season, SB had the lowest infiltration (29.8 mm) and highest runoff (12 mm); in contrast, QSMAS >10 years had the highest infiltration (38.5 mm) and lowest runoff (4.8 mm). During the dry season differences between treatments in infiltration and runoff were small. Infiltration for 30 minutes ranged from around 44 mm in both QSMAS treatments to 41.9 mm in SB. Runoff ranged from 0.91 mm in QSMAS to 2.4 mm in SB. In 2007, precipitation and ET were 1005 and 491 mm in the early part of rainy season, and 419 and 272 mm in the later part, respectively. In the early part of the rainy season available soil water (0-40 cm soil depth) varied between 0.09 and 0.104 m^3/m^3, with QSMAS <2 and QSMAS 5-7 and was 10% and 16% higher, respectively, than in SF. In the later part of the rainy season the amount of available soil water varied between 0.11 and 0.127 m^3/m^3 in SB and QSMAS <2, respectively. The mean value of available soil water content (0-40 cm) in QSMAS systems (average of the three different ages) was significantly greater than that of the SB system, suggesting increased availability of water for crop growth. These improvements in QSMAS were related to changes in soil porosity due to increases in mesoporosity (30%) and macroporosity (19%), and decreased the soil bulk density. This increased the plant available soil water storage capacity and availability of water for crops in the dry season, and increased the capture of rainfall at the beginning of the rainy season. The highest soil loss occurred in 2005, and was markedly higher in SB followed by QSMAS and SF. The same trend was observed in 2006 and 2007, although differences were greater in 2005 due to higher rainfall intensity and to the recent conversion of SB plots from SF that resulted in bare soil and therefore higher susceptibility to erosion. Total soil losses over the 3 years from SB were 5.6 times greater than from the three QSMAS treatments, and 22 times greater than from SF. As a result, the SB system had the highest nutrient losses (kg/ha) of N (9.9), P (1.3), K (6.9), Ca (22.8) and Mg (24.2), while SF had the lowest losses of N (1.7), P (0.2), K (1.2), Ca (2.6) and Mg (2.7). Water quality was poorest in the SB system, with highest concentration (mg/L) of total P and PO_4^{-3} (2.30 and 0.29, respectively), and was much better in QSMAS >10 (0.18 and 0.25, respectively). SB also had the highest concentration of (mg/L) of NO_3^- and NH_4^+ (7.97 and 0.70, respectively), while QSMAS 5-7 had the lowest concentration of NO_3^- (6.13) and QSMAS >10 of NH_4^+ (0.24). SF had values of 0.65 for P, 0.43 for PO_4^{-3}, 4.73 for NO_3^-, and 0.92 for NH_4^+.

There was no interaction between LUS and fertilizer treatment on CWP. CWP (kg grain/m^3) for maize was greatest in fertilized systems of QSMAS <2 (0.48) and least with QSMAS >10 (0.18). In plots with no fertilizer application, the highest CWP was observed with QSMAS <2 (0.26) and the lowest with SB (0.10). In both fertilized and non-fertilized systems, CWP for common bean was greatest in QSMAS <2 (0.32 and 0.27 kg grain/m^3, respectively) and least with SB (0.10 and 0.07 kg grain/m^3, respectively). Fertilization increased CWP of maize (by 92%) and common bean (by 23%). These results may reflect adequate available soil water during the maize crop (from sowing to physiological maturity) in the early part of the rainy season, as precipitation was higher than ET. In the case of common bean grown in the later (drier) part of the rainy season, available water content in the soil decreased from flowering to physiological maturity, with lower precipitation than ET and therefore with a negative water balance. Under these conditions, QSMAS showed greater available water content in soil that resulted in greater grain yield and CWP.

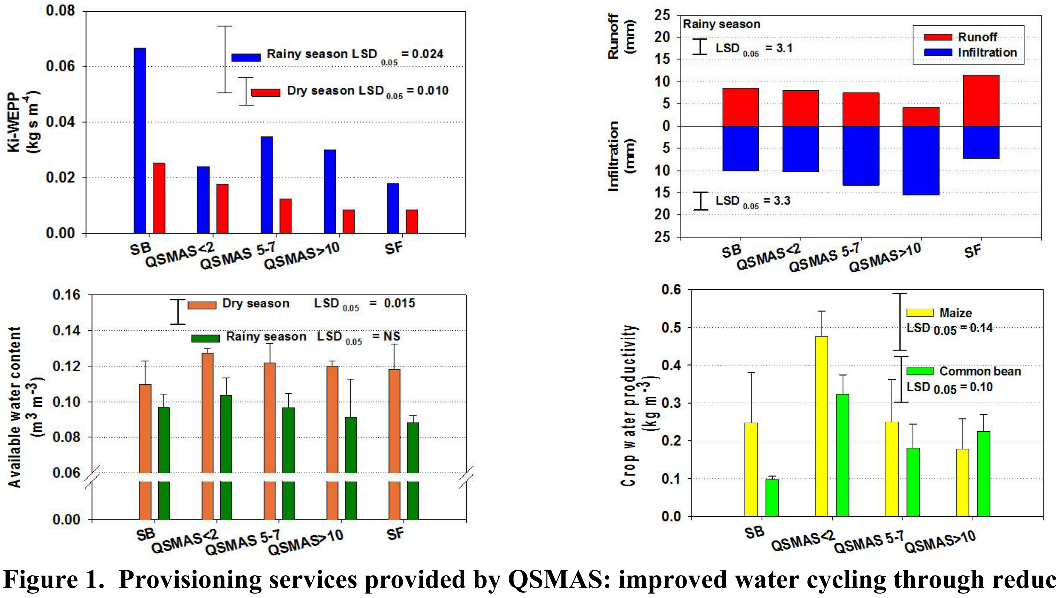

Figure 1. Provisioning services provided by QSMAS: improved water cycling through reduced susceptibility to erosion (top left), increased infiltration and decreased runoff (top right) and improved soil water storage capacity (bottom left), and improved food security through enhanced crop water productivity (bottom right).

C stocks were higher in SF and QSMAS, with higher accumulation in SF for aboveground C (C in trees and shrubs) and in QSMAS >10 for belowground (soil organic) C (Figure 2). The SB system could generate higher annual losses of above ground C due to burning, while young QSMAS plots (<2 and 5-7 years old) generate some losses of below ground C. QSMAS also had a much lower GWP (10.5 Mg Equiv. CO_2) than SB traditional system (40.9 Mg Equiv. CO_2). SF had a very low GWP (1.14 Mg Equiv. CO_2) (Figure 2). Based on the current adoption of QSMAS and consequent regeneration of SF in the Lempira department where QSMAS is practised and projecting its impact on GWP for a period of 20 years, it is estimated that the adoption of QSMAS will result in a decrease of 0.10 Tg Equiv. CO_2 compared to SB. Higher C stocks in soil and the aboveground tree biomass indicate a gradual accumulation of C in SF and QSMAS >10. According to the emergy evaluation SF and QSMAS had less environmental impact than SB (highly affected by levels of soil erosion) as noted in the ELR with values of 0.63, 0.14, and 0.02, respectively.

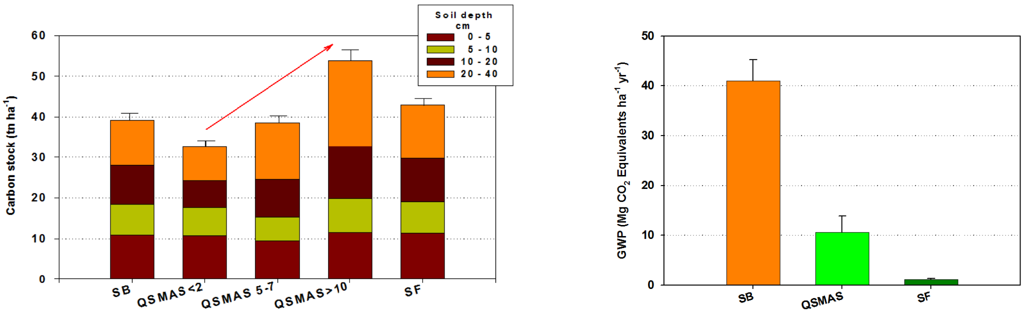

Figure 2. Regulating services provided by QSMAS: reduced global warming potential through improved C accumulation (left) and lower methane emission (right).

Conclusions

The results indicate that the production practices used for managing QSMAS have beneficial effects on the soil-plant-atmosphere continuum, soil quality, landscape and the environment. Compared to SB system QSMAS is eco-efficient through the use of renewable natural resources, and also provides ecosystem services including: (1) Provisioning services: food security through improved crop water productivity and yields at lower costs; and improved water cycling through reduced runoff, erosion, water turbidity and surface evaporation, and increased infiltration, soil water storage capacity and use of green water; (2) Regulating services: reduced global warming potential through lower methane emission and improved C accumulation; (3) Supporting services: mitigation of soil degradation through improved structure, biological activity, organic matter, nutrient cycling and fertilizer use efficiency, and restoration and conservation of biodiversity; and (4) Cultural services: improved quality of life through the regeneration of the landscape. Potential on the payment for environmental services provided by QSMAS could enhance its attractiveness to local and national authorities in countries with policies to protect ecosystems in the face of climate change.

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