Tropical Ecology **57**(4): 751-764, 2016 ISSN 0564-3295

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Comparative analysis on the socio-ecological and economic potentials of traditional agroforestry systems in the Sikkim Himalaya

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Abstract: Five different traditional agroforestry systems viz. farm-based, forest-based, *Alnus*-cardamom, forest-cardamom, and *Albizia*-mixed-tree-mandarin were studied in the Sikkim Himalaya in order to evaluate and compare stand nutrient dynamics, N_2-fixation, and cost-effectiveness in relation to social and ecological resilience to the increasing externalities such as climate change. Overall soil nutrient availability was highest in *Alnus*-cardamom systems, followed by *Albizia*-mandarin systems. N_2-fixation in *Alnus*-cardamom systems was highest (95 kg ha^{-1}), followed by forest-based systems (59 kg ha^{-1}), and lowest in forest-cardamom agroforestry systems (9.5 kg ha^{-1}). Annual economic return was highest from *Alnus*-cardamom (US$ 1895), followed by forest-cardamom (US$ 1275), and *Albizia*-mandarin systems (US$ 1166). Output-input ratio was highest in *Alnus*-cardamom (12.05), and lowest in forest-based agroforestry (4.21). Climate change has primarily manifested itself as unpredictable or shorter duration of rainfall events. Exposed or abandoned agricultural land lacking tree cover decreases the retention time of soil water content, thereby drying of local springs/streams at lower altitudes. Crop productivity of large cardamom between traditionally suitable altitudes has declined by 10 - 20 % in the past 3 - 4 years. Farmers have perceived a shift in phenological calendar, most notably in the flowering period of plants. The future socio-ecological and economic resilience of this research lies in the collective design and implementation of an integrated agroforestry scheme, considered by farmers, scientists, agricultural extensions agents, and policymakers alike.

Key words: Adaptive management, climate change, Cost: benefit analysis, resilience, traditional farming systems.

Handling Editor: Mulualem Tigabu

Introduction

Traditionally land use practices have developed on both cultivated and uncultivated upland agricultural systems in the Sikkim Himalaya. Among these practices, some of the most common include intercropping multipurpose trees with understory subsistence/local food or cash crops. On private landholdings, livestock rearing involving sustainable utilization of fodder resources in

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adjacent private forest-land has been developed as a traditional practice of indigenous communities in Sikkim (Sharma & Rai 2012). Such practices have recently come under the umbrella of agroforestry, a term now used to define intensive land use systems where in multipurpose trees are combined with understory crops and/or animals within a long-term management plan (Ibrahim & Sinclair 2005; Nair 1993; Tamale *et al.* 1995). Successful agroforestry systems seek to recreate the complex relationships found in naturally occurring forest ecosystems by substituting economically viable plant and animal species to provide similar ecosystem services as the wild plants and animals would.

Little less than 12 % of the total area (7096 km^2) is cultivable in Sikkim- a small amount when one takes into account that almost 90 % of the population continues to depend on agrarian practices (Sharma & Acharya 2013). Agroforestry systems are socially accepted by mountain communities as among the most effective practices for conserving soil, water, and improving fertility, while at the same time providing a valuable source for food, timber, fodder and many other non-timber forest products (NTFP). Traditional agroforestry systems in mountain landscapes enhance genetic diversity among and between the many open pollinated landraces and their wild progenitors through adjacent or discrete connectivity between biological units (Sharma & Chettri 2005; Sharma & Liang 2006).

The incorporation of N_2 fixing tree species *Alnus nepalensis* and *Albizia* spp. in traditional agroforestry systems is ecologically significant due to their shared capability in transforming atmospheric nitrogen and mineral phosphorous from the soil into nutrient rich litter while providing optimal shade conditions to understory crops. Several studies have demonstrated the important role of both *Alnus* and *Albizia* in the Himalayan watersheds (Neupane *et al.* 2002; Sharma & Sharma 1997; Sharma *et al.* 2001; Sharma *et al.* 2002b). It is increasingly evident that the mountain watersheds in Sikkim are subject to excessive soil erosion and nutrient leaching leading to land degradation (Rai & Sharma 1998). There is growing evidence that properly managed agroforestry systems could present a viable alternative to the increasing deforestation and unsustainable land-use practices in Sikkim which have, in recent years, caused degradation of scarce arable land (Carter & Gilmour 1989; Neupane *et al.* 2002; Rai & Sharma 1998; Sharma 2001; Sharma & Liang 2006). In light of climate variability and its impacts on agriculture, the ecosystem services provided by agroforestry are significant for their positive contributions towards the water, carbon, and nitrogen cycles, as well as for their cultural and socioeconomic potentials in precipitous mountainous regions. Comparative studies on agroforestry systems are, however, still lacking in the Sikkim Himalaya. There is yet to emerge an empirical study on adaptation strategies, socio-ecological and economic opportunities, and resource use regarding traditional agroforestry systems in Sikkim at the wake of changing climatic variation and impacts. This paper attempts to explore resource management, cost-effectiveness and climate change resilience of five different agroforestry systems in Sikkim *vis-à-vis* a comparative analysis on quantitative data obtained through years of research.

The specific research objectives were to investigate the (1) stand structure and functioning of existing traditional agroforestry systems and on-farm crop diversity, (2) soil chemical properties of the stands and role of N_2-fixing *Alnus* and *Albizia*, (3) energy output: input ratio and cost benefit analysis, and (4) dimensions of climate change adaptability and potential implications for future policymaking.

The diversity of agroforestry practices of the Sikkim Himalaya are examples of diversifying production systems and increasing the sustainability of smallholder farming systems in response to increasing climate change impacts (Sharma & Rai 2012). Therefore, it is critical to understand agroforestry structure and function, soil chemical properties and fertility maintenance and cost-effectiveness of the practices to understand the adaptive management of these systems for building ecological resilience and human well being.

Methods

Location and climate of study sites

Three experimental sites located at Mamley (South District) and Sumik (East District) and Kabi (North District) of Sikkim were selected for study, which are the watersheds of Rangit River and Teesta River, respectively. These sites extend within 27º 15' 05" to 24º 17' 36.6" N latitude and 88º 28' 6.9" to 88º 39' 27.1" E longitude, within the agro climatic zones between 800 - 2000 m. These study sites are more than 80 - km apart and contain representative samples of the five main systems of traditional agroforestry practices in Sikkim: Farm-based, forest-based, *Alnus*-cardamom-based, Forest-cardamom and *Albizia*-mixed tree-Mandarin orange-based. Traditional incorporation of N_2-fixing trees *Alnus nepalensis* and *Albizia* spp. is a practice especially found in cardamom-based and mandarin-based agroforestry in Sikkim.

The study sites at three locations were closely comparable; the structural and functional differences were attributed to the adaptive management of the agroforestry systems. Soils were, in general, acidic in reaction due to heavy seasonal rainfall and base leaching from surface soil to low horizons. Relatively young Typhic Hapludolls and Dystric Eutrochrepts were typically found in the very steep slopes (> 50 %), and Umbric Dystrochrepts and Cumulic Hapludolls were found in the steep slopes (30 - 50 %) under temperate forests and in cultivated systems (Das *et al.* 1996).

The study areas are all located in the Indian monsoon belt where the temperate climate contains three main seasons: winter (November-February), spring (March-May) and rainy season (June-October). Mean monthly maximum temperature ranged from 14.3 - 23.3 °C, mean monthly minimum temperature from 5.4 - 15.8 °C, and rainfall ranged between 2500 to 3500 mm in the study sites. Relative humidity varied between 80 - 95 % during the rainy season and decreased to about 45 % in spring. Soil was acidic (pH 3.8 - 5.6) and pH varied widely with depth. The variation in pH of surface soils was minimal between stands (17 %). The soil was sandy loam in composition, with 11 - 30 % clay, 15 - 40 % silt and 34 - 65 % sand. Soil porosity was measured between 57 - 70 % following Anderson and Ingram (1993).

Agroforestry Systems

The traditional agroforestry practices under study are broadly categorized into five systems: farm-based, forest-based, *Alnus*-cardamom based, forest-cardamom based, and *Albizia*-mixed tree-mandarin based systems (Table 1). In farm-based agro-forestry, farmers manage multipurpose tree species for fodder, fuel and timber, along with other direct and indirect uses within and around the surrounding open cultivable land. In many instances, trees are planted on terraced risers to increase soil stabilization and intercropped with a variety of other plants used in the household economy. This system consists of *Sukhabari* (rainfed-field) with maize-potato, maize-ginger and vegetables, and *Pani-khet* (rice-based) with rice followed by winter crops and vegetables. Here, management of fodder trees surrounding vegetable and cereal production is integral to maintaining the livestock.

Forest-based agroforestry is in fact a managed support forest-land adjacent to the open cropped areas, where farmers grow multipurpose trees on certain parcels consisting of bamboo and multipurpose timber species. Under forest-based private agroforestry, farmers do not cultivate food crops; instead they allow non-timber-forest produce to grow understory. In a unit of household land-holdings, apart from other land uses, the forest-based agroforestry functions as aquifer recharge catchments. Forest-based agroforestry are practiced to grow multipurpose species for timber and fuel wood. Farmers grow bamboo groves, woods for making ploughs and other farming implements, and primarily for protecting the open agriculture terraces.

Cardamom-based agroforestry is categorized into two sub systems: *Alnus*-cardamom and forest-cardamom systems. Large cardamom (*Amomum subulatum*) is a high value cash-crop which, when properly cured, stores well for extended periods. Large cardamom generally produces low volume per plant, but the trade off is that it requires relatively low labour inputs. Himalayan alder (*Alnus nepalensis*) is a naturally occurring tree associate with cardamom, valued for its ability to provide appropriate shade, fix atmospheric N_2, and generate nutrient rich litter which helps facilitate a more efficient cycling of nutrients (Sharma *et al.* 2008, 2010). It is a pioneer species on freshly exposed landslide soils, denuded habitats, rocky and landslide-affected slopes, steep stream banks and natural areas. Farmers then gradually plant cardamom saplings and maintain the tree density on a yearly basis and thus they establish the *Alnus*-cardamom association (Sharma 2001; Hunsdorfer 2013).

The indigenous farmers have sound understanding that alder trees support soil fertility and thus they plant or allow *Alnus* to grow naturally in different land use systems. Scientific understanding following adequate analysis of *Alnus*-cardamom agroforestry systems have proven this traditional practice as economically remunerative, ecologically adapted, with comparatively high carbon sequestration potential (Sharma *et al.* 2000, 2002a, 2002b). Sikkim produces about 40 % of the world's large cardamom, standing second after Nepal (Partap *et al.* 2014). This is a traditionally innovated, self reliant agroforestry system- one which exploits a naturally occurring plant guild in order to take advantage of its variety of ecosystem services while simultaneously meeting a unique market niche (Sharma *et al.* 2009).

Albizia-mix tree-mandarin is yet another promising agroforestry system at lower elevations, in which mandarin orange trees are the principal cash crop intercropped with maize, ginger, buckwheat, finger millet, pulses, oilseeds, taro and yam. *Albizia*, another N_2 fixing tree species is also commonly grown with other trees in this mandarin-based agroforestry system (Sharma 2012). The diversity of crops and associated tree species are maintained in the system for meeting household food, fodder, medicine, and other subsistence needs. Farmers consider *Alnus* an excellent shade tree for understorey large cardamom crop, and a valuable timber at maturity (30 - 40 year-old trees), while they consider *Albizia* a plant that primarily enriches soil fertility (Sharma 2001). As a management practice farmers cut down matured *Alnus* and *Albizia* trees considering that they no longer support soil fertility (Partap *et al.* 2014).

Estimation of biomass and productivity

Estimations of tree density, basal area, and above-ground productivity were carried out on sample plots of 30 × 40 m in the five different agro-forestry stands of all the three sites, numbering 15 plots total (0.36 ha per each age group totalling to 1.8 ha). Tree diameter increment, litter production, decomposition and agronomic yield estimations were carried out in these sample plots. Each tree in the sample plots of all age groups was marked and diameter at breast height (DBH) measured twice, in January 2007 and in January 2009 (covering two annual cycles). Allometric relationships developed by Sharma and Sundriyal (1996) and Sharma and Ambasht (1991) were used to estimate tree biomass and net primary productivity.

Mean annual increments for the aboveground components of the individuals in the sample plot were obtained by DBH increment measurements. The measured net change in the component biomass over a one year period yielded the annual biomass accumulation, and the sum of the different components gave net production of tree strata, provided as net primary productivity (NPP). Floor-litter was randomly sampled in replicates (n = 5) in an area of 1 m^2 from each plot in both January 2008 and January 2009, the results were extrapolated to represent stand values. Agronomic yield, fuel-wood extraction, crop residue, and fodder collection were estimated by interviewing the farmers who maintain the respective agroforestry stands. Additional information on collection of wild edibles and non-timber forest products (NTFPs) were generated by formal and informal discussion with the communities and the respective households.

Soil chemical analysis

Fresh soil samples (3 replicates × 2 soil depths × 15 plots) were collected and immediately taken to the laboratory. Sample pH was analyzed using the glass electrode digital pH meter (Systronics). Percent soil moisture was determined by drying the soil samples in a convection oven at 80 °C until reaching constant weight. Additional soil samples were air dried, ground into powder, passed through a 2- mm sieve and used for seasonal nutrient analysis. Soil organic-C was analyzed following the Walkley-Black method. Total-N was estimated by modified Kjeldahl method (Anderson & Ingram 1993). Total-P was estimated using hydrogen peroxide oxidized acidified ammonium fluoride extract by chlorostannous reduced molybdophosphoric blue colour method (Jackson 1967), and available-P was calculated using sodium bicarbonate extract by colorimetric method (Anderson & Ingram 1993). Bulk density of soil (mass per unit volume in g cm^{-3}) in all experimental plots was determined from cores taken at 0 - 15 cm and 15 - 30 cm depths in randomized locations within the stands. Soil porosity was measured following Anderson and Ingram (1993).

Root nodule biomass and nitrogen fixation

Root nodule biomass was estimated by harvesting root nodules of three representative samples of each tree species and then pooling them together to find the average. Acetylene Reduction Assay (ARA) technique was used to estimate the nitrogenase activity (Stewart *et al.* 1967). The experiment was carried out at field conditions and analysis was done in the laboratory in Perkin Elmer Gas Chromatograph. The rates of N_2-fixation were calculated using a conversion ratio of 3:1 acetylene by nitrogen (Hardy *et al.* 1973). The value was then converted into per ha basis, according to the associated nodule biomass of *Alnus* and *Albizia* trees sampled.

Estimation of energy and input/output ratio

Inputs and outputs of energy and cash were

Table 1. Different agroforestry systems with their common characteristics.

Agri-horti-silvipastoral system	Agri-silvi-pastoral system	Horti-silviculture system		
Farm-based	Forest-based	*Alnus*-Cardamom	Forest-Cardamom	*Albizia*-mixed tree-mandarin
Multi-layered vegetation structure with fodder species, shrubs and under-storey crop based garden agroforestry	Multipurpose tree species for fodder, fuel and timber and bamboo groves, and animal feed bank and for other productive needs	Large cardamom-based agroforestry with *Alnus nepalensis* is as shade tree for understorey cardamom crop	Mix tree species as shade trees for the understorey cardamom crop grown	Multilayer arrangement of fruit orchards predominantly with mandarin orange trees as the main horticultural crop
Multiple intercropping in terraced productive zones, multipurpose trees and shrubs grown on the terrace edges, agrobiodiversity is high, diversity of paddy grown in terraces and pulses on bounds	Managed as support land for fuel, medicines, fodder, building materials, NTFPs and other minor forest products, pasture lands, catchments for water sources, etc.	Act as catchments for recharging springs, corridor for mammals, habitat for wildlife, provides fuelwood and ground fodder	Diversity of timber trees and fodder trees are also grown, is catchment for recharging springs, corridor for mammals, habitat for wildlife	Agrobiodiversity rich, fodder trees, multi-cropping of under-storey traditional crop varieties, buckwheat, beans, protein crops, yams, taros, etc.
Homesteads involving animal husbandry, traditional beekeeping, vegetable crops, medicinal plants, etc.	Grazing livestock, remunerative	Highly remunerative system in term of ecological adaptability and economic return	Ground fodder, NTFPs, medicinal plant, soil and water conservation, highly remunerative	Highly remunerative as cash crops such as orange /ginger and tuber /food crops, vegetables are grown
Nutrient exhaustive, high input system	Low input system	Low input system	Low input system	Nutrient exhaustive, high input system

estimated for all the agroforestry stands. The energy inputs were composed of farm labour (human and draught animals) and fuel wood used for drying and curing the cardamom capsules. Energy in the form of farm labour was calculated using 0.15×10^4 kJ ha^{-1} following Freedman (1982). Energy value of plant materials was estimated by using the oxygen bomb calorimeter (Lieth 1975). The energy contents from each of the components of agroforestry trees and understory crops was calculated by taking the product of mean energy value and biomass (Sharma *et al.* 2002c). Energy content of firewood was estimated from total dry mass and its energy value. Energy output in the form of agronomic yield, firewood and fodder extractions from the agroforestry systems was calculated as a product of dry biomass and energy values.

Climate change and socio-ecological impacts

A total of 88 households were selected at random and interviewed followed by field observation. Extensive field surveys and observations were conducted using a structured questionnaire in the study areas during December 2011 through December 2013. The households were surveyed to investigate the range of livelihood options associated to the large cardamom-based farming systems and their contribution to household economy. Further, we carried out field sampling to document the indicators of climate change impacts

Table 2. Stand characteristics in the different agroforestry stands. Values are pooled from site replicates.

Parameter	Agroforestry Systems				
	Farm-based	Forest-based	*Alnus*-Cardamom	Forest-Cardamom	*Albizia*-mixed tree-mandarin
Tree density (trees ha^{-1})	198 ± 25	843 ± 132	417 ± 17	723 ± 124	280 ± 54
Basal area (m^2 ha^{-1})	6.43 ± 1.21	21.36 ± 3.66	19.51 ± 3.43	12.51 ± 1.49	5.10 ± 1.23
Tree biomass (t ha^{-1})	12.84 ± 2.54	59.45 ± 3.25	64.61 ± 5.81	23.42 ± 4.53	15.21 ± 26
Net primary productivity (t ha^{-1})	4.65 ± 1.87	8.43 ± 2.39	12.61 ± 3.26	5.13 ± 0.99	3.51 ± 1.26
Agronomic yield of crops (t ha^{-1} $year^{-1}$)	1.14 ± 1.65	0.21 ± 0.04	#0.31 ± 0.10	#0.26 ± 0.12	1.25 ± 0.50*
Edible NTFPs collection (kg ha^{-1})	124 ± 24	207 ± 5.34	30.41 ± 6.91	105 ± 20	50 ± 12
Fodder collection (t ha^{-1})	2.36 ± 0.89	5.73 ± 2.54	0.21 ± 0.09	3.57 ± 2.18	2.81 ± 1.35
Stand litter production (t ha^{-1} $year^{-1}$)	9.35 ± 3.26$	7.34 ± 2.17	10.25 ± 0.46	6.93 ± 2.51	4.80 ± 1.81
Crop residue (t ha^{-1} $year^{-1}$)	8.42 ± 2.47	0.17 ± 0.02	Not collected	Not collected	3.24 ± 1.32
Floor litter (t ha^{-1})	5.23 ± 25	8.23 ± 2.15	34.91 ± 1.24	26.87 ± 3.86	4.76 ± 2.11
Litter extraction (t ha^{-1})	0.21 ± 0.04	2.83 ± 0.85	1.21 ± 1.23	1.56 ± 1.65	0.05 ± 0.01
Fuel wood extraction (t ha^{-1})	0.37 ± 65	1.78 ± 0.96	1.95 ± 0.23	1.47 ± .24	0.21 ± 0.05

Alnus-Cardamom (15-years age), Forest-Cardamom = 15-20 years age; # = Cardamom capsule,
* includes crops yield and mandarin fruit
$ includes crop residue

on agroforestry systems, adaptation strategies on revival of the system, and existence of pollinator species.

Results

Stand dynamics of different agroforestry systems

Tree density was remarkably high in forest-based agroforestry (843 ± 132), 4.26 times that of farm-based, 3.01 times of *Albizia*-mix tree mandarin, 2.02 of *Alnus*-cardamom and 1.17 times that of forest-cardamom agroforestry (Table 2). NPP was comparatively high in the *Alnus*-cardamom systems, nearly 3.60 times that of *Albizia*-mix tree-mandarin, 2.71 times more than farm-based and 2.45 and 1.49 times that of forest-cardamom and forest-based agroforestry, respectively. Agronomic yields were highest in the *Albizia*-mix tree-mandarin and farm-based system which included all the crops grown within a year. Cardamom yield ranged between 260 - 310 kg ha^{-1} $year^{-1}$.

NTFPs from agroforestry present a valuable source for household economies, as well as for augmenting the household diet. A total of 56 species of edible NTFPs were collected from the forest-based agroforestry, while 27 species from forest cardamom-based, 16 species from farm-based and 9 species from mandarin-based agroforestry systems were collected. Fodder collection from both trees (57 species) and ground fodder (61 species) was highest in forest-based agroforestry, followed by forest-cardamom, and then *Albizia*-mix tree-mandarin. A considerably high amount of dry crop residue was collected from the farm-based and *Albizia*-mix tree-mandarin agroforestry systems, which is traditionally stored in order to feed the farm animals during the lean season. Crop residue is not collected from the cardamom based agroforestry intentionally, as it would disrupt the natural nutrient cycle. About 90 % of the families have stall-fed animals, while 5 % graze in their private land.

Litter residue collected from agroforestry systems is primarily used for livestock bedding, which could be considered a traditional knowledge system (TKS), as it began in order to generate higher quality compost for crops. Litter is also used for mulching, especially in ginger, turmeric and yam seed bedding. Both farm-based and forest-based agroforestry contributed fairly high stand litter production. Extraction of fuel-wood for household usage was comparatively higher from the forest-based and farm-based. However, the greatest amount of fuel-wood extracted was

Table 3. Stand soil characteristics and nutrient availability. Values are means of three site replicates (± SE; *n* = 9).

Soil Parameters (at 0-30 cm depth)	Agroforestry Systems				
	Farm-based	Forest-based	*Alnus*-Cardamom	Forest-Cardamom	*Albizia*-mixed tree-mandarin
Soil texture	*Sandy-loam*	*Sandy-loam*	*Silty, clay-loam*	*Silty, clay-loam*	*Silty-loam*
Bulk density (g cm^{-3})	0.87 ± 0.02	1.27 ± 0.05	0.98 ± 0.05	0.76 ± 0.03	0.82 ± 0.03
pH	6.54 ± 1.45	6.34 ± 1.64	4.56 ± 1.21	5.38 ± 1.43	6.23 ± 1.21
Moisture (%)	28.87 ± 7.27	16.76 ± 2.12	30.12 ± 6.23	27.86 ± 4.27	21.34 ± 5.32
Total Organic Carbon (%)	1.75 ± 0.45	3.68 ± 0.38	3.78 ± 0.61	2.78 ± 0.62	2.74 ± 0.45
Total Nitrogen (%)	0.21 ± 0.09	0.27 ± 0.10	0.29 ± 0.11	0.26 ± 0.09	0.27 ± 0.01
Total Phosphorus (%)	0.13 ± 0.08	0.12 ± 0.08	0.16 ± 0.09	0.10 ± 0.02	0.10 ± 0.006
Available Phosphorus (%)	0.006 ± 0.001	0.007 ± 0.002	0.006 ± 0.002	0.008 ± 0.002	0.007 ± 0.001
Soil nutrient contents					
Organic Carbon (Mg ha^{-1})	59.32 ± 23	77.54 ± 32	90.51 ± 24	92.58 ± 42	62.63 ± 21
Total Nitrogen (Mg ha^{-1})	3.12 ± 1.21	4.36 ± 1.51	7.65 ± 2.21	5.44 ± 1.54	4.40 ± 1.51
Total Phosphorus (Mg ha^{-1})	1.13 ± 0.54	1.34 ± 0.86	1.02 ± 0.79	1.24 ± 0.82	1.26 ± 0.42
Available Phosphorus (kg h^{-1})	138.52 ± 102	130.00 ± 104	164.26 ± 114	137.51 ± 65	144.54 ± 67

ANOVA for nutrient concentration: Sites- Mamley, Sumik and Kabi; Stands- Agorforestry Stands: pH- Sites NS; Stands $P < 0.0001$, Sites x Stands NS; Moisture- Sites NS, Stands $P < 0.0001$, Sites x Stands $P < 0.0001$; Organic-C- Sites NS, Stand $P < 0.0001$, Sites x Stands $P < 0.005$; Total-N- Sites NS, Stand $P < 0.0001$, Sites x Stands $P < 0.005$; Total-P- Sites NS, Stands $P < 0.0001$, Sites x Stands $P < 0.005$; Available Phosphorus- Sites NS, Stands $P < 0.0001$, Sites x Stands $P < 0.0001$.

utilized for curing of cardamom capsules in a traditional kiln, or *bhatti* (70 - 75 kg for drying 100 kg of raw cardamom).

Soil nutrient availability and fertility maintenance

Soil texture was classified as sandy loam in non-cardamom-based systems whereas cardamom-based agroforestry soils were composed of silty-clay-loam (Table 3). Mean bulk density of 0 - 30 cm soil from three study sites was comparatively higher in forest-based agroforestry. Soils were most acidic in *Alnus*-cardamom agroforestry systems followed by forest-cardamom systems. In the other stands, soil pH was higher (6.23 - 6.54). Organic-C was highest in forest-cardamom, while total N and P concentrations were highest in *Alnus*-cardamom, and low in farm-based agro-forestry. The range of soil organic-C, total-P and total-N availability was found to be highest in cardamom-based systems. Forest-based systems ranked second in organic-C and total-N, while soils from farm-based systems yielded higher total-P than forest-based systems. Available P proved highest in the forest cardamom, followed by farm-based, and then forest-based agroforestry systems. Moisture content, as a product of the soil water holding capacity (WHC) attributed to organic-C, was also highest in the *Alnus*-cardamom systems. Soil loss in cardamom-based agroforestry was lowest (32 kg ha^{-1}) while forest-based had higher (40 kg ha^{-1}) and soil loss in mandarin-mix-tree based agroforestry was highest (480 kg ha^{-1}).

Soil fertility maintenance by N_2-fixing trees

N_2-fixation was calculated to annual nitrogen accretion for both *Alnus* and *Albizia* species, and annual input of nitrogen through biological fixation was calculated for each agroforestry system (Table 4). N_2-fixation rate per weight nodule was higher in *Alnus* than *Albizia*. Total nitrogen fixation was as high as 95.25 kg ha^{-1} $year^{-1}$ in the *Alnus*-cardamom agroforestry while forest-based agroforestry had about 59 kg ha^{-1} $year^{-1}$. Nitrogen fixation in farm-based and *Albizia*-mix tree-mandarin agroforestry was comparatively low bet-

Table 4. Tree density and biological nitrogen fixation by *Alnus nepalensis* and *Albizia* spp. in the agroforestry stands. Values are pooled from three site replicates (± SE).

Parameters	Farm-based agroforestry	Forest-based agroforestry	*Alnus*-Cardamom agroforestry	Forest-Cardamom agroforestry	*Albizia*-mixed tree-mandarin agroforestry
Agro-ecological range 800 - 1200 m					
Tree density (trees ha^{-1})					
Albizia spp.	40 ± 10	55 ± 20	76 ± 15	46 ± 12	72 ± 10
Alnus nepalensis	26 ± 9	192 ± 26	310 ± 30	–	25 ± 8
Nitrogen addition through fixation (Kg ha^{-1} year^{-1})					
Albizia spp.	7.92	10.89	15.73	9.52	13.61
Alnus nepalensis	6.51	48.00	77.52	–	6.25
Total	14.43	58.89	95.25	9.52	19.86
Agro-ecological range 1200–2100 m					
Tree density (trees ha^{-1})					
Albizia spp.	20 ± 6	32 ± 9	–	28 ± 9	26 ± 8
Alnus nepalensis	43 ± 10	56 ± 10	417 ± 17	–	32 ± 12
Nitrogen addition through fixation (Kg ha^{-1} year^{-1})					
Albizia spp.	4.14	6.62	–	6.00	4.91
Alnus nepalensis	12.04	15.68	116.76	–	8.96
Total	16.18	22.30	116.76	6.00	13.87

Average active 11 hours of day and C_2H_2:N_2 ration of 3:1 were used, Values were pooled for growing season, i.e. for the period of April to October 2009 - 2010.

ween 14 and 20 kg ha^{-1} year^{-1}. The highest amount of N_2-fixation was recorded in *Alnus*-cardamom agroforestry (116 kg ha^{-1} year^{-1}). Nitrogen input ranged between 14 - 22 kg ha^{-1} year^{-1} in *Albizia*-mix tree-mandarin, farm-based, forest-based agroforestry systems.

Energy input and output

The main inputs of energy were in the form of human labour (and oxen for ploughing, conversion 1 ox = 2 men) for land preparation, weeding and post-harvesting (Table 5). Inputs were high in the labour-intensive farm-based and *Albizia*-mix tree-mandarin agroforestry while inputs were low in cardamom-based systems. Cash inputs were thus relatively high in both. The high energy requirement for curing cardamom was met from the same system. The energy inputs in the form of human labour in comparison were very less in cardamom-based and least in forest-based agroforestry. Human labour input in cardamom-based systems hovered around 33.65 - 35.01 × 10^4 kJ ha^{-1}, which was comparatively low. Energy inputs as human labour in farm-based and *Albizia*-mix tree-mandarin agroforestry were high (172 - 181 × 10^4 kJ ha^{-1}).

The main outputs of the systems were analyzed in the form of agronomic yield, fuel-wood, fodder and NTFP extracted during two consecutive years (2008 & 2009) and values were pooled. Energy contribution as fuel-wood was highest from *Alnus*-cardamom, followed by forest-based and forest cardamom system. The total energy output from the agroforestry systems analyzed were relatively close- between 2606 - 3905 × 10^4 kJ ha^{-1}. The highest energy output was recorded from *Alnus*-cardamom, and lowest in *Albizia*-mix tree-mandarin agroforestry. Output in the form of cash was US$ 1895.45 in *Alnus*-cardamom, 11 times that of forest-based, 3.2 times that of farm-based, 1.6 times that of *Albizia*-mix tree-mandarin and approximately 1.5 times that of forest-cardamom agroforestry.

Consequently, the output: input ratio for energy was highest in the forest-based system (68.27) - about 3 times that of *Albizia*-mix tree-mandarin and 4 times that of farm-based agroforestry, whereas the other systems had much lower ratios (3.28 - 8.45). Output: input ratios in the form of cash were clearly the highest in cardamom-based agroforestry (*Alnus*-based systems having the highest), and proved to be the most

Table 5. Cost benefit analysis of agroforestry stands. Values are pooled from three site replicates. Energy = (x10^4 kJ ha^{-1}; Cash US$ ha^{-1}).

Input/Output	Farm-based Agroforestry		Forest-based Agroforestry		*Alnus*-Cardamom Agroforestry		Forest-Cardamom Agroforestry		*Albizia*-mixed tree-mandarin Agroforestry	
	Energy	Cash	Energy	Cash	Energy	Cash	Energy	Cash	Energy	Cash
Input										
Labour (land preparation)	115.50	200.50	15.12	18.36	–	–	–	–	60.75	82.04
Weeding	18.75	28.40	–	–	4.50	20.45	6.00	27.27	26.25	39.77
Harvest	31.50	45.45	10.75	11.36	5.25	23.86	6.75	30.68	19.50	29.54
Post-harvest	6.75	7.67	-	-	10.50	47.72	11.25	51.13	7.50	11.36
Fuel-wood collection	8.25	16.90	9.45	10.98	14.76	22.65	9.65	13.43	6.12	9.45
Fuel-wood for curing	–	–	–	–	1154.12	42.56	769.33	28.37	–	–
Total	180.75	298.92	35.02	40.70	1189.13	157.27	802.98	150.88	120.02	172.16
Output										
Agronomic yield	1242.03	545.46	–	–	712.32	1761.36	466.08	1140.00	1361.87	1136.37
Fuel-wood extraction	634.47	24.88	3095.42	121.36	3127.12	122.73	1876.20	73.63	36.52	14.32
Fodder (tree/ground)	650.64	11.54	876.49	15.24	–	–	612.34	9.21	532.87	8.43
NTFP/wild edibles	298.53	8.67	453.67	34.87	65.37	11.36	67.45	12.43	287.73	6.46
Total	2825.67	590.55	2390.95	171.47	3904.81	1895.45	3022.07	1275.22	2605.59	1165.58
Output: Input ratio	15.63	1.98	68.27	4.21	3.28	12.05	3.76	8.45	21.70	6.88

Human labour, 1 hour = 0.15 x 10^4 kJ (Freedman 1982), **Calculated at US $ 5.68 per kilogram of cardamom as per 2006 average rate. Cash conversion @ US $ 1 = Rupees 44.

energy efficient and economically prosperous for the communities, as well as the most cost effective among all agroforestry systems. The ratio of *Albizia*-mix tree-mandarin agroforestry (6.88) was closer to forest-cardamom (8.45) and also provided a relatively good economic return.

Climate change impacts

Detailed analysis of surveys regarding the farmers' perceptions on climate change revealed that there has been a subtle fluctuation in weather conditions which become more pronounced during the critical phase of crop season, thus altering the crop cycle (1980-present). Around 96 % of farmers observed that such fluctuations have impacted the productivity of crops (10 - 20 % decline), harvests, and post-harvest storage quality. As many as 92 % of farmers surveyed observed that climate change has contributed to unpredictable or erratic rainfall pattern, local springs and streams have dried (about 20 springs disappeared in the study sites within 10 years), crop species have migrated to higher elevations, shift in sowing and harvesting dates, and an emergence of diseases and pests in crops. The remaining 9 % reflected that such events could be due to human developments such as hydropower projects, road construction, etc. Almost all the farmers' interviewed reiterated that Sikkim Himalayan Agroecosystems along the gradients of altitudes are most vulnerable to climate change (Table 6).

Discussion

Agri-silvipastoral systems have developed over generations as traditional land use practices in the Sikkim Himalaya. Tree density, basal area, biomass

Table 6. Farmers' perception of climate change in the Sikkim Himalaya.

Attributes in the agrodiversity landscapes	Perceived climate change impacts			
	High	Medium	Low	Negligible
Rice, Maize, wheat, oil seeds	■			
Large cardamom	■			
Ginger	■			
Mandarin orange	■			
Drinking water sources and springs	■			
Fodder trees	■			
Fruit crops		■		
Tubers/yams		■		
Pulses/beans		■		
Agroforestery trees			■	
Broom grass			■	
Livestock			■	
Underutilized/Lesser known crops			■	
Medicinal plants in cultivated systems			■	
Finger millet, buckwheat			■	
Grass fodder for animals				■
NTFPs in the agroforestry systems				■

and NPP were comparatively high in the forest-based and cardamom-based agroforestry providing the highest amount of fuel-wood, fodder and litter. These agroforestry systems are largely closed loop and the diverse species are ecologically adapted and interdependent, while proving to be economically viable production systems. The extraction of litter for bedding livestock, mulching and bedding ginger, turmeric, and yams clearly show that agroforestry plays a crucial role as a traditional support scheme in the agricultural sector. Nutrient cycling from the forest to the field constitutes an important fertility transfer, helping maintain agricultural productivity, promoting genetic diversity, and bringing overall systemic resilience to the agroecosystem. Indeed, livestock species and their associated gut bacteria represent the interface between cultivated land and uncultivated forest land, efficiently transforming nutrient-dense forest litter into readily available plant nutrients.

The integration of crops, trees, and livestock is a multifunctional production system critical for sustaining farm-based and *Albizia*-mixed tree-mandarin agroforestry in marginal landscapes. Crop-livestock interactions are important for multiple benefits, as animals are required for many farming operations. Animal manures improve income and yield potentials within organic agriculture systems by introducing soil nutrients e.g. total-N, total-P, organic-C and available-P, which are high in the *Alnus*-cardamom and forest-cardamom litter and subsequently accumulate to enrich the soil in humus. The organic matter in *Albizia*-mixed tree-mandarin and farm-based agroforestry were also high due to the addition of animal manures to the system. Nutrient losses however, were reported to be very high in these systems due to heavy topsoil erosion during the monsoon season (Sharma *et al.* 2001; Sharma *et al.* 2007). Vulnerability to soil nutrient depletion through erosion was most common in farm-based and *Albizia*-mix tree-mandarin agroforestry, whereas cardamom-based and forest-based were found to be relatively self sustainable systems, cycling nutrients among more dense vegetation and reducing droplet impact.

Nutrient availability in the farm-based and *Albizia*-mixed tree-mandarin agroforestry was fairly low. This could easily be attributed to the issue of topsoil erosion, biomass removal as well as nutrients exiting the system in the form of agronomic yield. Both farm-based and *Albizia*-mix tree-mandarin agroforestry are nutrient exhaustive, whereas cardamom and forest-based agroforestry tend to show high soil, water, and nutrient-conserving ability. This was reflected in an improvement to the input: output ratio, and prove to be appropriate niche-based land use systems. The improved soil nutrient status was attributed to the nitrogen fixing species *Alnus* and *Albizia,* which serve to add nitrogen through fixation and nutrient rich litter to the system. Farmers' traditional ecological knowledge of soil fertility maintenance through mulching, green manuring and the incorporation of N_2-fixing species is an adaptive innovative practice, and thus should be valued from a developmental perspective. This case can be compared with the community forestry in Nepal where the lower organic C and total N could be due to the higher rate of litter raking and biomass extraction (Baral & Katzensteiner 2015). The litter/

crop biomass is transferred back to the croplands in the form of organic residues/manure, mulch, animal feed and bedding materials via livestock for soil fertility maintenance.

Input of nitrogen through biological fixation by *Albizia* and *Alnus* was much higher in the cardamom-based (95 - 116 kg ha^{-1} $year^{-1}$) than non-cardamom-based (6 - 22 kg ha^{-1} $year^{-1}$) agroforestry. N_2-fixing *Albizia* and *Alnus* in agroforestry and incorporated in croplands contributes directly to soil fertility and increased productivity and yield (Sharma *et al.* 2001, 2002a). Other associated agroforestry species such as *Erythrina indica, Schima wallichii, Sauraria napalensis, Litsea cubeba, Ficus* spp., *Artocarpus lacoocha*, *Thysanolema maxima,* and *Dendrocalamus* sp. are both ecologically adapted as well as socially accepted species widely incorporated in agroforestry systems for their varying ecosystem services and diverse NTFPs.

Inclusion of *Alnus* and *Albizia* species into agroforestry helps to mitigate many of the risks inherent to practicing agriculture in the vulnerable mountain watersheds of Sikkim. The supporting and regulating ecosystem services include, among others, enhancing soil conservation, providing appropriate shade to understory crops, regulating the soil moisture regime and thus high-altitude aquifer conservation, and enriching soil nutrient availability for crops. Cropping patterns in farm-based and *Albizia*-mix tree-mandarin agroforestry are designed in multi-storied canopy configurations, often interplanting trees with bushes, shrubs, grasses, and vines in order to maximize productivity on limited arable lands.

Annual output: input ratios in the range of agroforestry systems clearly illustrated that cardamom-based systems were less labour-intensive than farm-based and *Albizia*-mix tree-mandarin agroforestry systems. The quantum of energy input was more in cardamom-based agroforestry, as these systems required fuel-wood for cardamom curing. Subsequently, output was also higher in these systems followed by forest-based agroforestry. The energy demand in hill-farm household is integral with these agroforestry systems. In recent years, acute energy shortage has been actualized in villages with fewer agroforestry systems as the main farming system. Energy transfer in the form of litter, sequestration of atmospheric N and C, and heat sink capacity in these agroforestry systems is an additional supporting role which should be considered. The cash benefits from cardamom-based systems equalled 8 to 12 times that of input, whereas *Albizia*-mix tree-mandarin agroforestry had about 7 times that of input. This clearly reflects that the cardamom-based and *Albizia*-mix tree-mandarin agroforestry provide sustainable economic benefits as both the crops are comparative advantage crops with established international market.

Upland terraced rice fields in Sikkim are frequently managed with trees lining either side of the slope. The tree-lined terraces are traditionally designed to offer multifunctional attributes and protection to the upland rice cultivation slopes. This is a unique characteristic of mountain agroecosystem management via indigenous knowledge systems developed by the local communities themselves. Agroforestry elements, in addition, lend support with water conservation and flood control, and provide nutrient and biomass to the rice paddy and farm.

Agrobiodiversity was richest in farm-based, *Albizia*-mix tree-mandarin-based and forest-based agroforestry. A number of underutilized and lesser known crops and wild varieties, including medicinal herbs grown in agroforestry systems, have traditionally served as the basic dietary elements to the people of Sikkim (Sharma & Dhakal 2011; Sharma *et al.* 2016). It is only in the recent past that a few of these crops such as cardamom have found their way into the niche markets as a source of economic return for the rural poor. Due to its unique biodiversity and endemism in the Eastern Himalaya, Sikkim is considered one of the 34 biodiversity hot-spots of the world (CI 2005). Traditional agroforestry also serves to enhance biodiversity corridors and wildlife movements by creating more continuity between forest land and cultivated farmland (Sharma *et al.* 2008). Lately, food production in urban areas has taken wider importance. A significant lesson that can be learned from the study of Mosina and Maroyi (2016) is that food plants in urban domestic gardens contribute to livelihoods of local people through provision of ecosystem services, food supplements and income generation.

Agroforestry systems in Sikkim are both dynamic and vulnerable. Several indicators govern the dynamics of change. Cardamom-based agroforestry systems were exposed to extreme shortage of moisture regime due to frequent and prolonged drought events over the years. This fact was compounded by a shift in cultivation practices of cardamom which saw a decrease in tree intercropping in favour of a maximized planting on more open terraces. Similarly, climate change induced vulnerabilities are acute to other agroforestry systems as well in the form of land degradation, untimely seasons, invasive species, nutrient depletion, viral infestation, poverty etc. The alternating climatic influences have also been reported in south western Nigeria where variations of climatic events such as heavy rainfall have resulted into soil erosion and flooding (Ayanlade 2016). Vulnerabilities are supported by low organizational capacity, lack of awareness and lack of policy focus. Changing social-ecological and social-economic dimensions are a major concern across the Eastern Himalayas to the Central Himalayas (Maikhuri *et al*. 2001; Sharma & Rai 2012). Shifts in land-use practices and market focus have led to some serious vulnerabilities causing major threat to the cultivated systems and traditional systems, aggravated further by loss of agrobiodiversity in the region (Arunachalam *et al.* 2002; Maikhuri *et al.* 2001; Sharma & Rai 2012). Now more than ever there is a call for designing policies to address these complex challenges that affect all of society.

Recognition of cultural values, belief systems, traditional ecological knowledge systems, and the organizational capacity of indigenous communities is imperative. Appropriate management strategies facilitated through a participatory approach would gear up the sustainable development processes in the mountain farming systems of Sikkim. Agroforestry systems in the Sikkim Himalaya have high ecological adaptability, resilience and opportunities for future sustainability. Traditional communities trade agroforestry products in global markets and contribute to reduce global warming through carbon sequestration in the systems they have developed. These agroforestry systems are locally adapted, socially acceptable land use practices which are proven to be economically viable, while simultaneously helping to conserve soil, regulate ground water recharge and create habitat connectivity for native biodiversity and genetic diversity. In this way, the benefits extend far beyond the potential for enhancing food and economic security of the farmers, and should be considered valuable models for future sustainable development partnerships between the Government of Sikkim Horticulture and Cash Crops Development Department, Forest and Wildlife Department, farmers, scientists and extensions agents, NGO's, and marketing agents.

Conclusion

The traditional agroforestry systems illustrated in this paper are examples of mixed cropping polycultures where soil nutrient usage is maximized, crop biodiversity is maintained, risk of crop loss is minimized, diversity of food crop and nutrition is enhanced, and regeneration of soil is favoured. The government of Sikkim has given due importance to the promotion of horticulture and floriculture sector through various policy changes and programmes while agroforestry, a locally developed, ecologically adapted system of production, has been utterly less prioritized.

Social-ecological and social-cultural evaluation of these ingenious agroforestry systems reveal that these systems are fundamental to the livelihood of rural communities and can help mitigate the increasing impacts of climate change in the future. They provide provisioning and regulating ecosystem services from local to global level (Farber *et al.* 2002). Conservation of broader biodiversity, ecosystem sustainability and poverty eradication should be linked up with agroforestry systems for a true vision for sustainable development to be met in Sikkim. They should be approached in parallel with adequate research, policies and incentives as well as incorporated within the institutional framework. The policy makers have the challenge of integrating poverty issues linked with the institutionalization of these agroforestry systems for economic gain and improvement of food security in the region.

Acknowledgements

The authors are grateful to the Director, G. B. Pant Institute of Himalayan Environment and Development, and The Mountain Institute-India for providing facilities. This project was funded by Indian council of Agricultural Research, New Delhi. Authors are thankful to Jagannath Dhakal for his assistance in the field experiments and sample collection.

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(Received on 28.05.2014 and accepted after revisions, on 06.05.2015)