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Monoculture vs. mixed-species plantation impact on the soil quality of an ecologically sensitive area

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Abstract: Over the past four decades the Western Ghats of India, one of the eight hottest hotspots of biological diversity in the world, witnessed the transformation of its prime forests into other land-use types, mainly monoculture plantations. The present study evaluated the impact of conversion of natural forests to mixed-species (teak) and monoculture (rubber) plantations on the soil quality of a Typic Plinthohumults soil series in the Southern Western Ghats region of Kerala, India. The baseline physico-chemical and biological parameters of the different sites were analyzed using standard methods. To comprehend the impact of plantations on the overall soil quality, the soil quality index of the different land-uses was quantified using the forest as the reference land-use. Significant variations in different soil physical, chemical, and biological properties of plantation and forest soils were observed in the present study. The overall soil quality index was found to follow the order: forest (1.0) > teak plantations (0.9) > rubber plantations (0.6), thus signifying the negative impact monoculture rubber plantations had on the soil quality of the study area. The results emphasize the need for the development of better land management practices and mixed-species plantation systems such as the teak plantations in the present study which did not deteriorate the soil quality.

Keywords: mixed-species, monoculture, soil quality, Western Ghats.

Introduction

Land-use changes may be defined as the process by which humans transform the natural landscapes for economic benefits by assigning them functional roles (Paul and Rashid, 2017). Land-use land cover change (LULCC) due to its impact on local, regional, and global climatic processes is considered one of the major drivers of environmental change. Due to the rapid growth of the human population and its economies, every year large areas of natural forest continue to be cleared, degraded and converted to other land-uses (esp. monoculture plantations) to meet the growing demand for wood and fiber. Worldwide, environmental degradation caused by inappropriate land-uses has attracted widespread attention. Despite the recognized economic benefits, various authors have criticized the negative impact monoculture plantations have on the environment such as loss of soil productivity and fertility, disruption of hydrological cycles, and risks associated with the introduction of exotic species (Liu *et al.,* 2018). For instance, the monoculture plantations of spruce in southern Sweden were found to have lower resistance to biotic and abiotic disturbances aggravated by changing climates, as well as having other negative ecological and environmental impacts (Felton *et al.,* 2010). Studies have demonstrated that the conversion of tropical forests to other land-uses also affects the soil faunal structure and diversity (Nanganoa *et al.,* 2019; Singh *et al.,* 2019). Unlike monoculture plantations, mixed-species plantations due to their diversity are acclaimed as more environmental friendly, sustainable, and more resistant to damage inflicted by storms, pests, or diseases. In addition to their ability to prevent soil erosion and increase biodiversity, mixed-species plantations were also found to have higher yields and better growth performance when compared to monoculture plantations (Mutanal *et al.*, 2007). However in some conditions, due to asymmetric competition mixed-species plantations were found to reduce soil fertility and productivity. The agroforestry system, where woody perennials are grown along with crops and pastures on the same land and at the same time, also represents an important type of mixed-species system. Though such systems have very few drawbacks, their successful establishment is found to be very challenging and time-consuming. Additional restrictions on applying agroforestry systems include the lack of training and awareness among the farmers and land-owners (Liu *et al.,* 2018). To gain a better understanding of the suitability and sustainability of a land-use to its ecosystem, it is thus necessary to study the potential impact of that particular land-use on the ecosystem.

One of the most susceptible elements of the landscape to LULCC is the soil. Soil quality has been defined as “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” (Doran and Parkin, 1994). Thus the assessment of the soil quality under a specific land-use can serve as an invaluable tool in determining the sustainability of land management systems. Some of the proposed soil physical, chemical, and biological characteristics that may be used as indicators for soil quality include soil bulk density, soil temperature and moisture, soil texture, total organic carbon (TOC) and nitrogen (N), pH, electrical conductivity (EC), mineral N, phosphorus (P), potassium (K), microbial biomass C and N as well as soil respiration (Doran and Parkin, 1994). Microorganisms respond rapidly to environmental stresses due to the intimate relationship they have with their surroundings. They are key players in the decomposition of organic matter (OM) as well as the cycling of nutrients in the soil. In addition to these roles, they also alter the physical properties of the soil, through the production of extracellular polysaccharides, proteins, and other cellular debris which by acting as cementing agents stabilize soil aggregates (Nielsen and Winding, 2002). Glomalins are such thermostable, water-insoluble glycoproteins produced in copious amounts by arbuscular mycorrhizal fungi (AMF) which due to their recalcitrant nature are found responsible for soil aggregate stabilization (Wright and Upadhyaya, 1998).

The Western Ghats, a UNESCO world heritage site and one of the eight hottest hotspots of biological diversity in the world, constitute a chain of mountains running parallel to India’s western coast, traversing the states of Kerala, Tamil Nadu, Karnataka, Goa, Maharashtra, Gujarat Dadra and Nagar Haveli (Union Territory). The past four decades witnessed the prime forests of the Western Ghats being transformed into other land-use types, such as artificial surfaces (e.g. commercial establishments, hydroelectric projects, industries), and monoculture plantations. Between 1985 and 2018, the region lost 12% of its pristine forest cover with a simultaneous 11% increase in the non-forest cover. With an evergreen forest cover of only 11.3%, the other major land-use types of the Western Ghats now include permanent industrial crops (40%), arable land (17%), mining, and built-up (5%) area (Ramachandra and Bharath, 2019). Thus the conversion of natural forests to plantations such as acacia, eucalyptus, teak, and rubber, is an emerging land-use trend witnessed in the area. Though several studies have focused on the variations in the carbon sequestration potential (Ramachandra and Bharath, 2019) as well as the fertility characteristics (Ray and Thomas, 2012) of the soils under different land-uses of the Western Ghats, very few studies have taken into consideration the assessment of soil quality. Thus, the major objective of our study was to evaluate the impact of different land-uses (monoculture vs mixed-species plantations) on the soil quality of a selected soil series in the Southern Western Ghats region, notified as an ecologically sensitive area, of Kerala, India.

Materials and Methods

Description of the study site

The study was carried out in the Southern Western Ghats region belonging to the Kollam district, of Kerala State in India (Fig. 1). The region is characterized by a humid tropical climate with annual precipitation of 3294 mm and average temperatures varying between 17 and 35ºC throughout the year. The hot season, which lasts from March to May, is followed by a bimodal pattern of rainfall consisting of the southwest monsoon (June to September) and northeast monsoon (October to November). The rest of the year is generally dry. The benchmark soils identified in the district include Neendakara (Psamments great groups), Varkala and Ummannoor (Ustults great groups), Sooranad (Ustepts great groups), Mylom (Fluvents great groups), and the Karavaloor soil series (Humults great groups). The sampling locations of the current investigation were restricted to the Karavaloor series, which is a member of clayey-skeletal, mixed, isohyperthermic, Typic Plinthohumults (Soil Survey Organization, 2007; Soil Survey Staff, 2015). The land-use types selected for the study included natural forest, teak, and rubber plantations. The series extends between 8º 45'- 9º 10' N and 76º 45'-77º15' E along the mid-upland and uplands of Pathanapuram Taluk.

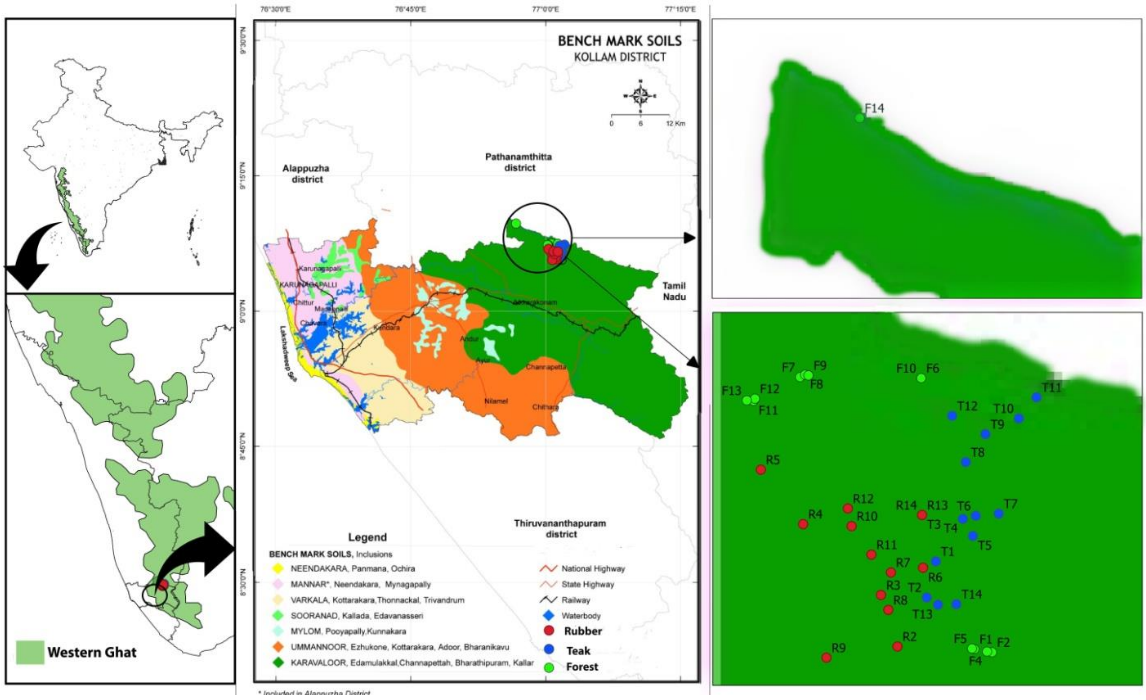

Fig. 1: Location of the study area shown on India's map

Description of the land-uses

There were 14 sampling sites for each of the selected land-use, thereby resulting in a total of 42 sites (Fig. 1). The sites were randomly selected in such a way that all the selected locations belonged to the Karavaloor soil series. Forest areas selected comprised of virgin semi-evergreen natural vegetation without significant anthropogenic intrusions. Teak plantations selected for the study were more than 30 years old and were previously also sites of teak plantations. Unlike rubber plantations, teak plantations had numerous other miscellaneous trees growing in between the teak trees (*Tectona grandis*). Some of the prominent miscellaneous species found in these plantations are *Terminalia tomentosa, Terminalia paniculata, Lagerstroemia lanceolata, Bridelia retusa, Artocarpus hirsutus, Polyalthia fragrans, Dalbergia latifolia, Grewia tiliaefolia, Bombax malabaricum, Careya arborea, Macaranga peltata, Anogeissus latifolia, Cassia fistula, Albizia odoratissima, Terminalia bellerica, Dillenia pentagyna, Schleichera oleosa, Aporosa lindleyana, Baccaurea courtallensis, Emblica officinalis, Cycas circinalis, Glycosmis pentaphylla, Helicteres isora, Eupatorium odoratum, Clerodendrum infortunatum, Phoenix spp.*, and *Cymbopogon spp.* The prescribed rotation age for the teak plantations is 60 yrs and other than silvicultural management practices, such as weeding, thinning, insect, and fire protection, the teak plantations received no other fertilization support. The rubber plantations of the study area were between 30-40 yrs old and were previously also sites of rubber plantations. The plantations were monocultures of *Hevea brasiliensis* with shade-tolerant grasses as natural cover. These plantations were fertilized twice every year (during the onset of southwest and northeastern monsoon) with a mixture of urea, rock phosphate, and muriate of potash (10:10:10). Latex harvesting was practiced in these plantations regularly. General information regarding the elevation of the different land-uses and soil texture is given in Table 1.

Table 1: General characteristics of the study site

LAND-USE	FOREST	TEAK	RUBBER
Elevation (m)	181.99 (±9.97)ab	168.63 (±9.16)b	197.76 (±6.39)a
Texture	Clay	Sandy Clay	Sandy Clay

Values are mean (N=14) with standard error in parenthesis. Means followed by different lowercase letters indicate significant differences among land uses type ($p<0.05$)

Sampling design and soil sampling

In January 2018, sampling was conducted in the selected land-uses at a depth of 20 cm from the soil surface using a 7.0 cm diameter stainless steel cylinder. Within a site (each approximately of 0.5-1.0 ha), five sampling points were selected at random locations, and the soil collected was then pooled and mixed thoroughly, to form a composite sample representing that particular site. Samples were then labeled as forest soils (F1-F14), teak soils (T1-T14), and rubber soils (R1-R14) with respect to each land-use (Fig. 1). Altogether, 42 composite samples (14 samples per land-use) were collected by the end of the sampling to represent the three land-uses in the study. The samples were air-dried, sieved, and stored for further physico-chemical analysis. The soil temperature, moisture, and electrical conductivity (EC) were recorded using a field-portable Stevens HydraProbe Soil Sensor.

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Analysis of soil physical, chemical, and biological parameters

The texture, bulk density, pH, SOM, available N and P, exchangeable potassium (K), sodium (Na), calcium (Ca), and (Mg) were analyzed using the standard procedures (Maiti, 2003). The texture of the different soil samples was determined by using the international pipette method. Bulk density of the soil was determined by the core method for undisturbed soil samples using a 189.90 cm^3 stainless steel core, whereby the oven-dry weight of a known volume of the soil sample was determined and the mass per unit volume was calculated. A pH meter was used for the determination of the soil pH (soil to water w/v ratio of 1:2.5). The ignition of soil at high temperature (to up to 430ºC) gave a quantitative value of the SOM. Available N was estimated by employing the alkaline permanganate method using a Kjeldahl distillation assembly. Available P was determined following the widely used Bray's method, using a spectrophotometer. Exchangeable K and Na were extracted using ammonium acetate solution and the concentration was determined using a flame photometer. The exchangeable Ca and Mg in the ammonium acetate extracts were quantified following the EDTA titrimetry method. SOC content analysis was performed using the Skalar Primacs^{MCS} solid carbon analyzer. Glomalin content of the soil was quantified using the easily extractable glomalin (EEG) method (Wright and Upadhyaya, 1998).

Soil quality index calculations

Soil quality index (SQI) was determined following the three basic steps of (i) selection of the most critical soil quality indicators that best represents the soil function using principal component analysis (PCA), (ii) using the forest ecosystem as the reference land-use, the selected indicators are scored, and (iii) the scores are integrated into final SQI using the weighted additive SQI method (Andrews *et al.*, 2002).

Indicator selection

PCA and factor analysis was applied for the selection of a minimum data set (MDS) from the original untransformed soil indicators. Only principal components (PC) with eigenvalues more than 1 and those that could explain at least 5% of the variation in data were further subjected to factor analysis (varimax rotation). To avoid any redundancy in indicator selection within each PC, the attribute with the highest negative or positive factor loading was selected for further scoring (in instances where the factor loading of the second most weighted soil attribute was in very close proximity with the highest factor loading and when both attributes were highly correlated).

Indicator scoring

In the next step selected indicators were assigned a score ranging from 0 to 1 depending on their role in soil functioning. Critical limits for each soil attribute are generally chosen from a natural ecosystem such as grassland or natural forest (Liebig *et al.*, 2001). For the current investigation, the forest was selected as the reference land-use, as it was the less disturbed one compared with other land-uses. Indicators were then categorized based on whether the higher value obtained was considered "good" or "bad" with respect to soil function. For example, we used the "more is better" functions for indicators such as SOC, whereas we used the "less is better" function for indicators such as bulk density. The "optimum is better" function was used for indicators such as pH. To transform each indicator and assign it a score between 0 and 1, two unity-based normalization equations [Eqs. (1) and (2)] were used (Hinge *et al.*, 2019):

$$Y = \frac{X - a}{b - a}$$

Eq. (1)

$$Z = \frac{b - X}{b - a}$$

Eq. (2)

where Y and Z are the scores of each variable after transformation, X is the observed value of the soil attribute to be transformed, a is the minimum observed value of each soil attribute, b is the maximum observed value of the soil attribute. Eq. (1) was used for indicators categorized in the “more is better” function, while Eq. (2) was used for those in the “less is better” category. For the “optimum is better” indicators, observations were scored as “more is better” function (Eq. 1) up to the threshold value, and for observations above that threshold values, scores were given based on the “less is better” function (Eq. 2) (Liebig *et al.*, 2001; Singh *et al.*, 2014).

Soil quality indexing

The retained indicators after scoring were weighted based on PCA results. Each PC explained a certain amount of variation in the total data set [variance explained (%)]. This percentage divided by the total percentage explained by all the PCs with eigenvalues greater than 1, gave the weighted factor (W) for each soil attributes selected under a given PC. Finally, the weighted variable scores for each indicator under a particular land-use were summed up using the following equation (Andrews *et al.*,2002):

$$SQI = \int_{i=1}^{n} W_i \times S_i$$

Eq. (3)

where SQI is the weighted soil quality index, n is the number of indicators retained, W_i is the weighting factor from PCA, and S_i is the score for each variable. Higher SQI values indicated better soil quality and vice versa.

Statistical analysis

All statistical analysis was carried out using IBM SPSS Software Version 16. Statistical significance of the data was evaluated using Welch’s ANOVA followed by a Games-Howell Post Hoc test. All tests were set at a significance level of $p<0.05$. Correlations among soil quality indicators were analyzed using non-parametric Spearman’s rank correlation coefficients.

Results and Discussion

Soil physical parameters

The results of variations in the soil physical parameters of different land-uses are given in Table 2. Soil temperature, an important catalyst for soil physico-chemical and biological processes, depends on the ratio of energy absorbed by the soil to that lost from it (Onwuka, 2018). In the present study, the temperature of the soils measured between 1 and 2 pm varied from 26.2 – 32.5º C in the different land-use systems studied. The mean soil temperature was found to be highest in rubber plantations, followed by forest and then teak plantations. The one-way ANOVA of soil temperature across the different land-uses revealed a statistically significant effect (p<0.05), and the estimated partial eta squared value (η_p^2= 0.372) indicated that 37.2% of the variation in soil temperature could be attributed to differences in the land-use types. The temperature range observed in the site is quite similar to that observed in another study conducted in the Western Ghats (Ray and Thomas, 2012). The optimum soil conditions required for teak growth include slightly acidic to alkaline pH, with an abundance of bases especially Ca (Tanaka *et al.*, 1998). However, it is known that higher temperatures and precipitations in the humid tropical climate can decrease soil pH via leaching of nutrients and accumulation of sesquioxides (Shamshuddin and Daud, 2011). This corroborates the finding of comparatively lower temperature and alkaline pH observed in the teak plantations of the present study. Though the amount of solar radiation that the soil receives is one of the major factors influencing soil temperature, it must be noted that several other factors, such as soil color, mulch, moisture content, bulk density, OM content, vegetative cover, as well as the slope of the land surface also influence the soil temperature (Onwuka, 2018).

Soil moisture is considered an important physical parameter that influences the distribution and cycling of nutrients in natural soil systems, thereby determining the productivity and sustainability of the terrestrial ecosystem (Seo *et al.*, 2011; Yao *et al.*, 2016). It was found that the moisture content of the soil studied varied from 16.90 to 37.80 $m^3 \cdot m^{-3}$ in the different land-use systems. The variations observed in the moisture content of the soil might be associated with texture differences (Table 1) and the vegetation cover of the area. Though forest soils recorded the highest mean moisture content followed by teak and rubber plantations, the differences were not statistically significant (p<0.05, Table 2). However, several studies have reported conversion from forests to plantations to significantly decrease the moisture content of the soil (Ray and Thomas 2012; Yao *et al.*, 2016; Srivastava *et al.*, 2019). This is because vegetation cover greatly influences the soil moisture content by altering the rainfall interception, evapotranspiration, and surface shading of the region (Yao *et al.*, 2016). Bulk density, the soil matter contained in a unit volume of a soil sample is a quite variable parameter of the soil. High organic matter content is found to lower the bulk density, whereas compaction of soil increases it (Maiti, 2003). In the current investigation, the bulk density of the soil at 0-20 cm depth varied from 0.80 to 1.50 $g \cdot cm^{-3}$ under the different land-uses. Rubber plantations had the highest bulk density followed by teak plantations and forest. The results of one-way ANOVA revealed a statistically significant difference in the soil bulk density among land uses (p<0.05) and the estimated η_p^2 value indicated that 35.1% of the variability in bulk density could be explained by changes in the land-use type. Post hoc comparisons further revealed that differences in bulk density between forest and plantations to be statistically significant (p<0.05, Table 2). The high bulk density in the rubber plantations may be due to the intensive management practices usually practiced in such plantations. Site preparation operations using heavy machinery as well as tillage during the establishment and tending of plantations may have compacted the topsoil layer, thereby increasing the bulk density.

Increased bulk density in the plantations, when compared to forest soils, reflects the extent of soil degradation in the plantations. The results obtained in the study are consistent with several other similar studies (Lemenih *et al.,* 2005; Nanganoa *et al.,* 2019; Tellen and Yerima, 2018). High bulk density is an indicator of low soil porosity, which thereby restricts root growth and movement of air and water through the soil (Maiti, 2003). Such an increase in soil bulk density in plantations is a global concern due to the adverse impact it has on the soil environment and stand productivity.

Table 2: Soil physical characteristics in the different land-use systems

LAND USE	FOREST	TEAK	RUBBER
Temperature (^{o}C)	29.30 (±0.44)a	27.98 (±0.12)b	30.14 (±0.32)a
Moisture ($m^3 \cdot m^{-3}$)	28.08 (±1.29)a	26.30 (±0. 75)a	25.80 (±1.39)a
Bulk density ($g \cdot cm^{-3}$)	0.98 (±0.03) b	1.08 (±0.02)a	1.20 (±0.05)a

Values are mean (N=14) with standard error in parenthesis. Row entries followed by the same letters are not significantly different (p<0.05)

Soil chemical parameters

The various chemical properties of soils under different land-use systems are given in Table 3. Soil pH is an important chemical property that governs to a large extent the biochemical processes in the soil, further driving the intimate relation between soil and the supporting vegetation. The soil pH varied from 5 to 6.1 in the different land-use systems studied and the differences in the mean pH among the land-uses were found to be statistically significant ($p<0.05$). The estimated η_p^2 value revealed that 35.3% of the observed variability in mean pH could be attributed to the changes in the land-use types. Soils of the Western Ghats are moderately acidic in nature (Ray and Thomas, 2012; Nair *et al.,* 2019) and, in general, are found to favor the growth of diverse vegetations when compared to alkaline soils (Diaz-Maroto and Vila-Lameiro, 2007). Though the mean pH of forest and rubber plantations showed no statistically significant difference, their pH differed significantly ($p<0.05$) from that of teak plantations (Table 3). The soil pH observed in the teak plantations was similar to that observed in other studies (Singh *et al.,* 1990; Murugesh *et al.,* 1999; Choudhari and Prasad, 2018). The nutrient supply from the decomposition of teak leaf litter was found to replace the H and Al ions in soil exchangeable complexes by bases, thereby increasing soil pH (Suzuki *et al.*, 2007). The comparatively higher concentration of exchangeable bases in the soil due to teak's ability to act as cation pumps is the main reason for the increase in soil pH as evidenced in the present study.

Soil EC, an important indicator of soil health, is the measure of the amount of total soluble salts in soils. The EC of the soils of different land-use systems varied from 0.004 – 0.018 $S \cdot m^{-1}$ and followed the trend of teak plantations > forest > rubber plantations. One way ANOVA revealed the differences to be statistically significant ($p<0.05$) and the estimated η_p^2 value, further indicated that 27.3 % of the variability in the EC could be explained by the changes in the land-use systems. In general, all the soil samples in the different land-uses may be classified as non-saline. Post hoc comparisons conducted revealed, that the difference in EC between forest and teak plantations was not statistically significant. Instead, significant differences ($p< 0.05$) were observed among the EC of both forest and teak plantations with respect to rubber plantations (Table 3). Under the humid tropical climate, the low base saturation and acidic pH observed in the rubber plantations in our study, are indicative of a strong and prolonged leaching process. Studies have demonstrated that the conversion of forest to rubber plantations disrupts the otherwise efficient nutrient cycling via leaching (Kurniawan *et al.*, 2018; Liu *et al.*, 2019). Over time, the decreased nutrient availability in such plantations will make them more reliant on fertilization (Kurniawan *et al.*, 2018).

SOM, formed via the physical, chemical, biological transformation of plant and animal residues, is the most important component that serves as a reservoir of nutrients and water for the soil. The SOM content of the different land-use systems ranged between 3.87 and 10.99%, with forests having the highest content, followed by teak and then rubber plantations. The overall SOM content depicted significant variation (p<0.05), with changes in the land-use type (Table 3), and the estimated η_p^2 value of 0.40 indicated that 40% of the variability observed in SOM content may be attributed to changes in the land-use type. While the SOM content of the forest was found to differ significantly (p<0.05) from that of both the plantations, no significant difference was found in the SOM content between the plantations (Table 3). The increased biodiversity of the forest ecosystem with the dense understory vegetations may explain the increased OM content of the forest soils. Leaf litter is one of the major sources of OM. The litterfall in forest ecosystems in Kerala was found to be in the range of 12.18 to 14.43 tonnes per hectare per·year (Kumar and Deepu, 1992), while that in teak was 5.5 to 12.1 tonnes per hectare per·year (O'Connell and Sankaran, 1997). In the case of rubber plantations, the litterfall was found to be only about 6 tonnes per hectare per·year (Krishnakumar and Potty, 1992). This would explain the pattern of SOM found within the three land uses in the present study.

The SOC content plays a crucial role in soil fertility by stimulating primary production through its positive effect on the soil's physical, chemical, and biological properties (Panakoulia *et al.*, 2017). The observed range in variations of SOC content (2.25-5.32%) in the present study is comparatively higher than that generally observed in the Karavaloor series (Soil Survey Organization, 2007). The estimated η_p^2 value of 0.463 suggests that 46.3% of the variability in SOC content can be explained by changes in the land-use types. There were significant differences (p<0.05) in the mean SOC content between forest and the plantations, with forest soils having the highest SOC concentration (Table 3). The results obtained in the present study followed a pattern similar to that of SOM concentration as SOC is a major component of SOM. Changes in the land-use patterns, such as conversion from natural landscapes to managed ecosystem, agricultural practices with low external input, and soil-degrading land uses tend to deplete the soil C stocks which was accumulated over long periods, consequently increasing the concentration of CO_2 in the atmosphere. The SOC plays a significant role in the fertility and C sequestration capacity of the soil (Lal, 2004). Since SOC plays a crucial role in many of the soil functions and ecosystem processes (Schjønning *et al.*, 2018), a significant decrease in its content in plantation soils may be considered as one of the negative impacts of land-use change on soil fertility. Due to the disturbance of soil aggregates during the site preparation and establishment of plantations, conversion of forest to plantations was found to decrease the SOC content in several other studies too (Guo and Gifford, 2002; Ray and Thomas, 2012; Stockmann *et al.*, 2013).

The available N content in the soils of different land-use systems ranged between 501.76 and 752.64 $kg \cdot ha^{-1}$ and followed the trend of rubber plantations > teak plantations > forest. The estimated η_p^2 value of 0.142 indicated that 14.2% of the variability observed in the overall available N content in the soil could be explained by the variability of land-uses. Post hoc comparisons revealed significant differences (p<0.05) in the available N content of forest and rubber plantations (Table 3). Tropical forests are abundant with legumes, which in turn house copious amounts of heterotrophic soil microbes and rhizobia. The abundant occurrence of these soil microbes causes the high rates of N fixation, thereby increasing the natural availability of N in tropical forest soils when compared to temperate forests. Thus, in general, tropical forests tend to recycle and have great amounts of available N in their soils (Hedin *et al.*, 2009). In the present study, the higher concentration of available N in the rubber plantations when compared to forests may be attributed to the fertilization activities conducted twice every year. Similar results were also observed in another study (Li *et al.*, 2012) conducted in the tropical rain forests and adjacent rubber plantations of Yunnan Province, southwest China. Such deposition of N is found to be increasing dramatically in the tropics and is predicted to continually increase in the coming decades (Galloway *et al.*, 2004). Although several studies propose this to cause an increase in foliar N concentration, which consequently increases the photosynthetic C gain (Wright *et al.*, 2004; Hietz *et al.*, 2011) several other studies hypothesize that such N deposition would acidify the soils and alter the availability of other nutrients, with a potentially negative effect on plant growth (Matson *et al.*, 1999; Corre *et al.*, 2010). Intensive fertilization of crops without synchronizing it with plant demand would increase the nitrate leaching as well as the emission of nitrous oxide to the environment.

The available P content in the land-uses varied between 55.62 and 116.07 $kg \cdot ha^{1}$, with teak plantations having the highest, followed by rubber plantations and forest. However, the differences obtained were not statistically significant (Table 3). Though several studies consider the primary production in tropical rainforests to be P-limited (Elser *et al.*, 1996; Kitayama and Aiba 2002; Ray and Thomas 2012), as per the nutrient management plan of the State (Department of Agriculture, 2019) the available P content in the present study was found to be high in all the land-use systems. The available K content of the different land-uses ranged between 164.64 and 926.24 $kg \cdot ha^{1}$ with the mean available K content highest for soils of teak plantations, and lowest for rubber plantation soils. The estimated η_p^2 value of 0.141 suggested that 14.1% of the variability observed was due to the changes in the land-use types. The difference in the mean available K content between the plantations was found to be statistically significant ($p<0.05$). As per the nutrient management plan of the State (Department of Agriculture, 2019), the available K content of all the studied land-use systems was high. It was noticed that despite the fertilization of the rubber plantations, the concentration of K in these plantations remained lower than that of forest and teak plantations. The results obtained in relation to rubber plantations were quite similar to another study conducted in an adjacent soil series (Ray and Thomas, 2012). The comparatively low concentrations of K in rubber plantations may be either due to the excessive uptake of K by the rubber trees (Jessy, 2011) or due to excessive leaching of K from the soils (Ray and Thomas, 2012). When compared to rubber plantations, the high concentrations of K in teak plantation soils can be explained by the nutrient supply via the decomposition of teak leaf litter which has K in the second-highest concentration among other nutrients in it (Suzuki *et al.*, 2007).

The available Na content in the soil of the different land-use systems varied between 54 and 228.50 ppm. The η_p^2 value of 0.376 predicts that 37.6% of the variability observed in the concentration of available Na was due to changes in the land-use types. Significant differences ($p<0.05$) were noted in the concentration of available Na, with teak plantations having the highest concentration and rubber plantations having the lowest (Table 3). The extractable Ca concentration of the different land-uses was in the range 12.54-114.77 ppm, with the highest concentration observed in teak plantations and lowest in rubber plantations. The estimated η_p^2 value of 0.550 depicts that 55% of the variability in the extractable Ca concentration may be attributed to land-use changes. Though no significant differences were observed in the extractable Ca concentration between forest and teak, significant differences ($p<0.05$) were reported with respect to rubber plantations. The extractable Mg concentration in the different land-uses varied between 1.34-5.59 ppm with the estimated η_p^2 value indicating that 41.8% of the variability observed in Mg concentration may be due to changes in the land-use types. Teak plantations with the highest soil Mg concentration differed significantly ($p<0.05$) from that of rubber plantations as well as forests.

As evidenced in the present study and several other studies (Balagopalan and Jose, 1982; Salifu and Meyer, 1998), the high concentrations of exchangeable bases (Ca, Mg, K, Na) in the soils under teak plantations is due to the tendency of teak trees to add more bases to the surface soil. Teak tree roots by acting as cation pumps increase pH and cation availability in the surface soil by taking up high levels of cations from lower soil layers (Salifu and Meyer, 1998). These nutrients taken up by the tree are re-circulated to the soil as plant residues, which then release the nutrients into the surface soil via the mineralization of the SOM (Owusu-Bennoah *et al.,* 2000). The results of our study confirm the fact that teak is a species with high nutrient requirements and grows in well-drained and low acidic soils with high chemical fertility (Kumar, 2011; Lawal *et al.,* 2014; Fernández-Moya *et al.,* 2015). On the contrary, the low concentration of these bases in rubber plantations depicts the deterioration of soil fertility as a result of conversion to monoculture plantations. A decrease in the soil cation exchange capacity and concentration of exchangeable bases of rubber plantations relative to forest soils have been observed in several other studies also (Orimoloye *et al.,* 2010; Allen *et al.,* 2015). Excessive N fertilization, as seen in rubber plantations, may negatively impact soil fertility via the leaching of base cations (Allen *et al.,* 2015).

Table 3: Chemical properties of soil under different land-use systems.

LAND USE	FOREST	TEAK	RUBBER
pH	5.34 (±0.03)b	5.64 (±0.07)a	5.32 (±0.06)b
EC ($S\cdot m^{-1}$)	0.011 (±0.001)a	0.013 (±0.001)a	0.008 (±0.001)b
SOM (%)	7.61 (±0.44)a	5.48(±0.37)b	5.34(±0.25)b
SOC (%)	4.41 (±0.17)a	3.18 (±0.21)b	3.10(±0.14)b
Available N ($kg\cdot ha^{-1}$)	564.48 (±21.80)b	609.28 (±22.22)ab	627.20 (±0.00)a
Available P ($kg\cdot ha^{-1}$)	66.41 (±2.81)a	77.38 (±6.03)a	68.31 (±2.86)a
Available K ($kg\cdot ha^{-1}$)	493.52 (±60.16)ab	599.04 (±59.39)a	402.32 (±44.37)b
Available Na (ppm)	116.96 (±11.78)a	153.60 (±12.73)a	81.89 (±5.32)b
Extractable Ca (ppm)	68.58 (±5.05)a	69.32 (±6.30)a	27.02 (±2.93)b
Extractable Mg (ppm)	2.76 (±0.20)b	4.26 (±0.28)a	3.02 (±0.14)b

Values are mean (N=14) with standard error in parenthesis. Row entries followed by different lowercase letters indicate significant differences among land-use types (p<0.05).

Soil biological parameter

AMF are soil microorganisms that are important in the biogeochemical cycling of both organic and inorganic nutrients in the soil. They play a crucial role in soil fertility by forming symbiotic associations with most cultivated plants, further influencing the development, nutrient uptake, above-ground productivity, and water relations of the plant community (Jeffries *et al.,* 2003). They promote the formation and stability of soil aggregates by producing a special immunoreactive glycoprotein called glomalin and several studies use this to estimate the AMF biomass in soil (Wright and Upadhyaya 1998; Rosier *et al.,* 2006). The soil EEG content of the different land-uses in the present study was in the range of 48.12-105.50 $\mu g\cdot ml^{-1}$, with forest soils having the highest concentration, while rubber plantations had the least (Table 4). The η_p^2 value of 0.351 suggests that 35.1%

of the variability observed in the glomalin content was due to changes in the land-use systems. Significant differences (p<0.05) were observed between the glomalin content of the forest and plantation soils. While several studies have shown SOC content to be an important regulator for glomalin accumulation in surface soils (Wang *et al.*, 2015; Wang *et al.*, 2017, Zhong *et al.*, 2017) several others propose glomalin to be linked to aggregate stability and consequent C storage (Wright and Upadhyaya, 1998; Zhang *et al.*, 2017). Similarly, in the present study, the high SOC content in the forest soils may explain the high concentration of glomalin or vice versa. Apart from SOC content, several other factors such as bulk density, pH, nitrogen, and EC also regulate the concentration of glomalin in the soil (Wang *et al.*, 2015; Wang *et al.*, 2017). The comparatively low levels of glomalin content observed in the plantation soils may be attributed to several factors including reduced C levels and decline in plant diversity, as well as site management practices such as mineral fertilization (de Souza *et al.*, 2013; Vasconcellos *et al.*, 2016).

Table 4: Glomalin content under different land-use types.

LAND-USE TYPE	FOREST	TEAK	RUBBER
Glomalin content ($\mu g \cdot ml^{-1}$)	89.36±2.31a	74.46±3.63b	68.66±3.74b

Values are mean (N=14) with standard error in parenthesis. Means followed by different lowercase letters indicate significant differences among land uses type (p<0.05)

Correlation between the different soil properties

Correlation between the soil properties under different land-uses revealed a significant correlation in 29 soil variable pairs (Table 5). However, among these 29 variables, a strong correlation was observed only in 2 pairs. As expected, the SOM content showed a strong significant positive correlation (r= 0.984) with the SOC content, as the latter is a component of SOM. Similar relationships were observed also in other studies (Bianchi *et al.*, 2008; Périé and Ouimet, 2008; Azlan *et al.*, 2012). A strong positive correlation (r= 0.875) was reported between the concentration of available K^+ and Na^+ ions under the different land-uses studied. It is found that high concentrations of Na^+ have the potential to desorb and leach inherited and applied K^+ from the soil however making it readily available to plants over a specific period (Jalali and Merrikhpour, 2008; Wakeel, 2013). This is attributable to the similar physicochemical properties of Na^+ and K^+, which make them compete with each other for the high-affinity potassium transporters (HKTs) and nonselective cation channels (NSCCs) in plants. Thus excessive amounts of K^+ in the soil were found to increase its influx into the plants while decreasing the Na^+ influx (Wakeel, 2013). A moderate positive correlation was observed between EC and moisture content (r=0.664). Several other studies also observed higher EC to be associated with moist soils (Zhou *et al.*, 2001; Binley *et al.*, 2002; Dafalla *et al.*, 2018). A moderate negative correlation was observed between bulk density and SOC content (r=-0.637) as well as SOM content (r=-0.609). The structural properties of soil are largely determined by the degree of aggregation and by the interacting influence of texture mainly due to the incorporated OM. Thus, OM content being a major factor affecting bulk density, it has long been recognized that the determination of the OM content may be used to estimate the bulk density of the soil (Saini, 1966; Adams, 1973). As observed in the current investigation, several studies reported an increase in OM content to decrease soil bulk density (Périé and Ouimet, 2008; Nascente *et al.*, 2015).

Table 5: Correlation among soil attributes collected from the three land-uses

	pH	Temp.	BD	Moisture	EC	SOC	SOM
pH	1						
Temp.	-0.286	1					
BD	0.137	0.036	1				
Moisture	0.094	-0.154	0.029	1			
EC	**.463****	**-.499****	0.031	**.664****	1		
SOC	-0.272	0.013	**-.637****	-0.059	-0.14	1	
SOM	-0.27	-0.029	**-.609****	-0.104	-0.16	**.984****	1
Avail. N	0.066	0.052	0.032	-0.285	-0.09	-0.08	-0.08
Avail. P	0.036	0.016	0.093	-0.226	-0.13	0.043	0.049
Avail. K	**.575****	**-.309***	-0.047	0.229	**.400****	0.079	0.063
Extr. Ca	**.468****	**-.358***	**-.396****	0.075	**.447****	**.306***	0.297
Extr. Mg	**.478****	-0.277	-0.082	-0.242	0.115	-0.04	0.008
Avail. Na	**.533****	**-.530****	-0.156	0.195	**.438****	0.183	0.201
Glmln	**-.351***	0.016	**-.373***	0.004	-0.03	**.380***	**.349***

***Correlation is significant at the 0.01 level (2-tailed)*
** Correlation is significant at the 0.05 level (2-tailed)*

Table 5 (Cont.)

	Avail. N	Avail. P	Avail. K	Extr. Ca	Extr. Mg	Avail. Na	Glmln
pH							
Temp.							
BD							
Moisture							
EC							
SOC							
SOM							
Avail. N	1						
Avail. P	-0.08	1					
Avail. K	0.013	0	1				
Extr. Ca	**-.305***	0.166	**.401****	1			
Extr. Mg	0.167	0.005	0.286	**.423****	1		
Avail. Na	-0.02	0.053	**.875****	**.519****	**.383***	1	
Glmln	-0.224	**-.392***	-0.167	0.109	-0.29	-0.07	1

***Correlation is significant at the 0.01 level (2-tailed)*
** Correlation is significant at the 0.05 level (2-tailed)*

Soil quality index for different land-uses

So far, although we have discussed how the different LULCC in the present study affected the various soil physico-chemical and biological parameters, it is difficult to conclude about the effect of the same on the overall soil quality by looking at a large number of variables at a time. To meet this objective, SQI was calculated for the different land-use types. To facilitate the easy understanding of the large dataset, a MDS was selected by the application of PCA followed by varimax rotation to all selected soil indicators. Results of the analysis grouped the soil data set into 4 PCs with eigenvalues greater than 1, explaining together 71% of the variance in the data set. Table 6 represents the rotated factor loadings, i.e., the correlation between soil variables and the factors (PCs). The communalities column in it indicates how much variance in a particular soil property has been accounted for in the extracted factors (Hinge *et al.,* 2019). Under PC1, available Na, K, pH, and EC were the highest weighing indicators with rotated factor loadings greater than 0.7. However, because available Na and K were found to be highly correlated (r= 0.875 and p<0.01) (Table 5), to avoid any redundancy in indicator selection only available Na with the highest correlation sum was selected. So, under PC-1, the soil attributes retained were available Na, EC, and pH. Likewise, in PC-2, only SOC and bulk density were selected, as SOC and SOM were highly correlated (r= 0.984 and p<0.001). The soil attributes moisture and available N were selected from PC-3 and PC-4, respectively. Thus the selected MDS, in the present study, included available Na, EC, pH, SOC, bulk density, moisture, and available N. For the calculation of SQI, these indicators were then transformed into scores ranging between 0 to 1 using Eqs. (1) and (2).

Table 6: Result of PCA after varimax rotation for chosen soil properties

	Components				
	PC-1	PC-2	PC-3	PC-4	Communalities
pH	**.764**	-.342	.209	-.124	.759
Temperature in ºC	-.577	-.088	.128	.104	.368
Bulk density in g/cm3	-.115	**-.759**	-.038	.118	.605
Moisture in m3 m-3	.234	-.162	**-.791**	-.241	.765
Electrical conductivity in S/m	**.706**	-.190	-.525	-.202	.851
SOC	.041	**.937**	.064	.009	.884
SOM in %	.068	**.927**	.108	.040	.877
Available N in kg/ha	.046	-.094	.097	**.897**	.825
Available P in kg/ha	.223	-.038	.673	-.132	.521
Available K in kg/ha	.795	.092	.008	.229	.693
Calcium in ppm	.681	.325	.193	-.415	.780
Magnesium in ppm	.610	-.134	.453	.061	.599
Available Na in ppm	**.887**	.198	.085	.161	.859
Glomalin in µg/ml	-.192	.582	-.393	-.142	.550
Eigenvalues	3.832	3.021	1.845	1.237	
Variance explained (%)	27.372	21.579	13.179	8.839	
Cumulative variance explained (%)	27.372	48.951	62.131	70.969	

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Note: Indicators retained for SQI assessment are denoted in bold

Critical limits were set using the forest as the reference land-use and the final SQI equation for the different land-uses based on the weighted factor obtained from the eigenvalues of the PCA in the study area was [Eq. (4)]:

$$\mathrm{SQI} = 0.386_{\mathrm{pH}} + 0.386_{\mathrm{EC}} + 0.386_{\mathrm{Avail.Na}} + 0.304_{\mathrm{SOC}} + 0.304_{\mathrm{BD}} + 0.186_{\mathrm{Moisture}} + 0.124_{\mathrm{Avail.N}}$$

Eq. (4)

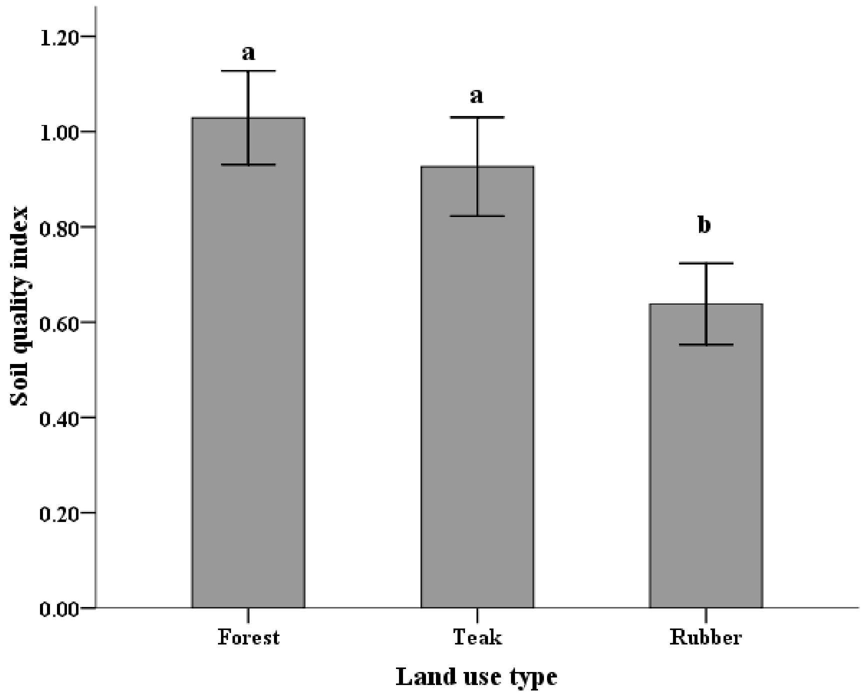

Fig. 2: Soil quality index of different land-uses. Means with different letters indicate significant difference at $p < 0.05$. Values are mean ± standard error

Estimated SQI ratings showed significant variation across the different land-use types (Fig. 2). The overall SQI of the different land-use types were in the following order: Forest (1.0) > Teak plantations (0.9) > Rubber plantations (0.6). There was no significant difference in the SQI value of forest and teak plantations, thus suggesting the similarity of soil quality in these land-uses. Unlike rubber plantations, which were monocultures, teak plantations had mixed trees growing in between, and this might have possibly contributed to their better soil quality. While land-uses with SQI greater than 0.80 are considered to have high soil quality, those having SQI less than 0.40 are considered to have low soil quality. Land uses having SQI values in between the above-mentioned ranges (0.40<SQI< 0.80) are assessed to have medium soil quality (Hinge *et al.,* 2019). Thus, in the current investigation, teak plantations (mixed-species plantation) had a high soil quality comparable to that of forest soil, whereas rubber plantations (monoculture plantations) had a medium soil quality. The percentage contribution of each of the soil attributes to the SQI of the different land-uses followed the order: bulk density (20.7%) > EC (20.2%) > Avail. Na (14.7%) > SOC (14.6%) > pH (13.3%) > Moisture (10.4%) > Avail. N (6.2%). The comparatively high bulk density and low EC of the rubber plantations explained the medium soil quality observed in this land-use. In rubber plantations, human activities such as trampling and weeding with herbicides may result in the compaction of soil and reduced formation of large pores. Reduction in soil porosity in turn is found to increase surface runoff and consequent soil erosion due to a serious reduction in infiltration and percolation (Giertz *et al.*, 2005). Increased surface runoff and strong leaching may explain the low EC in rubber plantations, despite fertilization conducted twice every year. The variations in the other soil attributes in the different land-use systems have been elucidated in the foregoing discussions. It is evident from the current investigation that the conversion of natural forests to monoculture rubber plantations deteriorates soil quality. However, the conversion to mixed-species teak plantations did not significantly affect soil quality.

Conclusion

The present study found LULCC to significantly impact the physico-chemical and biological parameters of the soil. Conversion of natural forests to plantations increased soil bulk density as a result of compaction of soil during the site preparation. Teak trees, due to their ability to act as a cation pump, increased the pH of the soil when compared to that of natural forest and rubber plantations. This also explained the high concentration of exchangeable bases in the soils of the teak plantation. The SOM and consequent SOC content were found to be highest for natural forests due to high biodiversity and increased leaf litter input. Intensive fertilization of already N-rich tropical soil increased the concentration of available N in the rubber plantations, which in turn may increase nitrate leaching as well as the emission of nitrous oxide to the environment. Excessive uptake or leaching of K from the soils of rubber plantations resulted in relatively low available K content. The SQI assessment helped provide a bird's eye view of the general status of the soil quality of the different land-uses. Interestingly, the SQI developed found the mixed-species teak plantations to have high soil quality similar to that of forest soils, while the monoculture rubber plantations, due to serious land degradation, had a medium soil quality. The results stress the negative impact monoculture plantations and excessive fertilization have on the soil quality, implying the need for the development of mixed agroforestry systems and better land management practices in an ecologically sensitive area such as the Western Ghats. Under the prevailing land-use types, the study demonstrates the use of SQI as a sensitive tool to assess the effect of land management practices on soil function. It may also be noted that the methods used to compute SQI can be used successfully on other land-use types, via selecting site-specific soil characteristics for a MDS, scoring indicators as per their performance of the respective soil function, and finally, combining the scored values into an integrative index.

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