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RESEARCH ARTICLE

Estimation of carbon sequestration potential in coconut plantations under different agro-ecological regions and land suitability classes

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Abstract: The study estimated the carbon sequestration potential of 25 year old Tall x Tall coconut (*Cocos nucifera* L. variety typica) plantations under S_2 (highly suitable for coconut) and S_4 (moderately suitable for coconut) soils in wet (WL_3, high moisture availability), intermediate (IL_{1a}, moderate moisture availability) and dry (DL_3, low moisture availability) agro-climatic conditions during May to September 2009. Variation in total carbon stock (plant and soil), total carbon input (measured as Gross Primary Production of coconut, GPP), total carbon output (measured as plant and soil respiration) and net carbon balance of ecosystems were assessed. Eight coconut palms and sample plots per site were used for estimations (two factor factorial with eight replicates). There is a significant agro-ecological region (AER) x land suitability class (LSC) effect on all the components of the carbon balance in a coconut plantation. The total ecosystem carbon stock ($B_{tot-eco}$) reduces along a decreasing moisture gradient from WL_3 to DL_3 and decreasing soil fertility gradient from S_2 to S_4. The GPP and $R_{tot-eco}$ do not show a reduction along a decreasing moisture gradient from WL_3 to DL_3 on S_2, whilst it shows a reduction from WL_3 to DL_3 on S_4. The net C balance reduces from WL_3 to DL_3 on S_4, whilst it does not reduce from WL_3 to DL_3 on S_2. C stock of the ecosystem varied between 32 and 72 Mg C ha^{-1} whilst the net carbon balance varied between 0.4 and 1.9 Mg C ha^{-1} $month^{-1}$ under different growth conditions. Of the measured components, GPP and maintenance respiration of coconut palms and soil respiration had greater contributions to the overall C balance of the system. This is the first report on carbon sequestration potential in coconut plantations of Sri Lanka.

Keywords: Agro-ecological region, carbon sequestration, *Cocos nucifera*, gross primary production, net carbon balance, palm respiration, soil respiration.

INTRODUCTION

Climate change is linked to a build up of greenhouse gases (GHGs) in the atmosphere enhancing the natural greenhouse effect. Carbon dioxide (CO_2) is, by far, the largest contributor to the anthropogenically enhanced greenhouse effect (De Costa, 1999; IPCC, 2007). Studies by the Intergovernmental Panel on Climate Change (IPCC) indicate that the likelihood of significant environmental and social damage increases if CO_2 concentration in the atmosphere exceeds about 550 ppm (from current level of 360–370 ppm). One of the options to mitigate the effects of global warming is to increase the sinks for GHGs. Forests and tree plantation crops are particularly important as carbon reservoirs because trees hold much more carbon per unit area than other types of vegetation (Lasco *et al*., 2002; Lamade & Bouillet, 2005). Coconut, being a perennial tree crop with 50-60 years of economic lifespan, has a potential to act as a carbon sink (Jayasekara & Jayasekara, 1995; Mialet-Serra *et al.,* 2005; Ranasinghe & Silva, 2007; Roupsard *et al*., 2008a,b). When accounting the contribution of terrestrial ecosystems to the global C cycle, measuring the productivity and carbon balance of various land uses is of great importance, particularly in the tropics.

In considering the carbon cycle of a coconut-based ecosystem, if there are no inputs from organic fertilizers, all the carbon inputs come from the Gross Primary Production (GPP; the sum of the photosynthesis of the plants of the ecosystem). A significant part of this carbon uptake is lost through autotrophic respiration

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(plant respiration; growth and maintenance respiration of different plant components). The fraction of GPP that is not lost through plant respiration is used to produce new biomass, thus contributing to the Net Primary Production (NPP; the sum of visible growth and litter production). The stand growth is the difference between NPP and litter production. Litter inputs to the soil are decomposed by soil micro organisms. The part that is not oxidized is transferred to the soil organic matter (SOM) pool. Emission of CO_2 through litter decomposition and subsequent SOM oxidation by soil micro organisms both contribute to the heterotrophic respiration. Therefore, the net ecosystem exchange of CO_2 between the plantation and the atmosphere is the difference between CO_2 uptake through photosynthesis, and CO_2 emission through ecosystem respiration (plant autotrophic respiration and soil heterotrophic respiration) (Roupsard *et al*., 2008b).

Carbon sequestration is an unexploited benefit of the coconut industry in Sri Lanka. Coconut plantations play a major role as a source of revenue to the country and also provide livelihoods to millions of people. Coconut is mainly cultivated in three agro-climatic zones (ACZ) of Sri Lanka, comprising about 30% in the Wet Zone, 50% in the Intermediate Zone and 20% in the Dry Zone. Within these ACZ, coconut is concentrated in seven agro-ecological regions (AER), namely, low country intermediate zone (IL_{1a}, IL_3), low country wet zone (WL_2, WL_3, WL_4), and low country dry zone (DL_3 and DL_5), and the total extent under coconut as at 2008 is 395,000 ha (MPA, 2008). In addition, new planting programmes of coconut are underway mainly in the northern and eastern provinces of Sri Lanka at a rate of about 10,000 – 15,000 ha per annum (Coconut Cultivation Board of Sri Lanka, *unpublished data*). Coconut can tolerate a range of climatic conditions, but performs well under a mean annual temperature of 27 – 29 ^{0}C and rainfall of 1250–2500 mm/year (Liyanage, 1999). The annual rainfall of the Dry Zone in the main coconut growing area (coconut triangle) is between 1000 – 1250 mm/yr, which can be regarded as the lower limit for coconut. However, solar radiation intensity in this area promotes high productivity when soil moisture and soil depth are not limited. In the Wet Zone of the coconut triangle, the mean annual rainfall is between 2250 – 2500 mm/yr, which is quite adequate for coconut. However, the solar radiation intensity in the Wet Zone is lower compared to the Dry Zone. The Intermediate Zone of the coconut triangle has the best combination of rainfall and solar radiation for the performance of coconut (Liyanage, 1999; Peiris *et al.,* 2008). Within an AER, there are different types of soils; some deep and coarse textured, some shallow and gravelly and others moderately deep and fine-textured. The productivity of coconut palm is different on these different types of soils and performs best in well drained, deep sandy loam soils. Coconut growing lands in Sri Lanka have been classified into five main land suitability classes (LSC) ranging from highly suitable (S_1, S_2), suitable (S_3), moderately suitable (S_4) and marginally suitable (S_5) (Somasiri *et al*., 1994). A high percentage of major coconut growing soils belong to S_2 and S_4 LSC. S_2 lands are deep to very deep (> 120 cm), sandy loam, imperfectly drained and highly fertile whilst S_4 lands are moderately deep (30 – 60 cm), sandy loam with gravel, well drained and less fertile soils. Potential yield in S_2 and S_4 lands are 12,500–15000 and 5000–10,000 nuts/ha/yr (Somasiri *et al.,* 1994). Therefore, the potential of carbon sequestration in a coconut plantation may vary with age, cultivar, soil fertility, agro climatic condition, management practices and type of intercrop. However, such information of coconut plantations is scarce. The net ecosystem carbon exchange of a twenty-year-old coconut plantation grown under near-optimal conditions (high fertility, no drought, high yielding variety) in Santo, Vanuatu was 4.7 – 8.1 t C ha^{-1} yr^{-1} (Roupsard *et al*., 2008b). In India, the values were reported as 8–32 t CO_2 ha^{-1} yr^{-1} (equal to 2–9 t C ha^{-1} yr^{-1}) (Anonymous, 2008).

The clean development mechanism (CDM) presents an opportunity for developing countries to get certified emission reductions for negotiations in the C market. Productivity and carbon balance of each type of land use in coconut are key issues for the CDM (Roupsard *et al*., 2008b). Scientific information on carbon sequestration potential by coconut plantations in Sri Lanka is not available to date. Therefore, the main objective of this study was to quantify and compare carbon sequestration potential in coconut plantations in S_2 and S_4 land suitability classes of three agro-ecological regions of Sri Lanka. In order to accomplish the objective, the study aimed at quantifying (a) current carbon stock in coconut, grass and top soil, (b) GPP of the total Eco-system, (c) NPP of the eco-system, (d) plant autotrophic respiration and soil heterotrophic respiration and (e) net ecosystem carbon exchange (balance) in coconut plantations.

METHODS AND MATERIALS

***Location, variety and climate*:** The study was conducted in six sites (parts of large coconut plantations covering more than 25 ha) representing three agro-ecological regions (AER); low country wet (WL_3), low country intermediate (IL_{1a}) and low country dry (DL_3) zones of Sri Lanka (latitude 7° 20' N, longitude 79° 53' E). In each AER, palms from two land suitability classes (LSC), S_2 and S_4 were selected and the distance between S_2 and S_4 sites within an AER was less than 5 km. Eight coconut palms [*Cocos nucifera* L*,* variety *typica,* (tall)] were randomly selected from each site (in forests, which are also perennial ecosystems and in mixed vegetations, the method of sampling for this type of studies is the 'sampling plot method'). However, coconut plantations in the present study are monocultures with grass cover. For experiments on coconut physiology, it is recommended to use single palm plots (which are as good as sampling from a plot) with adequate number of replicates (minimum six palms) (Kularatne *et al.,* 2006). Furthermore, this is the same approach taken by other groups working on the same type of research on coconut in other countries (Roupsard *et al*., 2008b). The plantations were of uniform age (25–26 years) and density (160 palms per ha), and were subjected to uniform agronomic and cultural practices (fertilized regularly and mulched manure circle). The coconut palms had a grass understory, which was maintained by regular slashing. The plantations were free of intercrops. The study was conducted during the period from May to September 2009.

Table 1: Location, soil characteristics and climatic conditions of the sites

Location	Soil type and LSC	AER
Urapola (Western Province)	Pallama series – S_2 Boralu series – S_4	WL_3
Wellawa (North-Western Province)	Kurunegala series – S_2 Kuliyapitiya series – S_4	IL_{1a}
Mangala Eliya & Madurankuliya (North-Western Province)	Mavillu series – S_2 Mampuri series – S_4	DL_3

The mean annual rainfall of WL_3, IL_{1a} and DL_3 over the last thirty years is 2224, 1662 and 1193 mm, respectively (Peiris *et al*., 2008). Sri Lanka receives rainfall throughout the year, with a bimodal seasonal distribution. The seasonal peaks vary by region with the peak of the main rainfall season occurring in October, November or December and the subsidiary peak occurring in April, May or June. Generally, the coconut growing areas are prone to droughts during the periods from January to March and July to September. The average maximum temperature ranges from 32–35 ºC, 29–35 ºC and 29–38 ºC, in WL_3, IL_{1a} and DL_3, respectively, and the highest values are recorded during February to May. The average minimum temperature ranges from 22–24 ºC, 20–26 ºC and 20–26 ºC in WL_3, IL_{1a} and DL_3, respectively, and the lowest is observed during December to February. The day time relative humidity generally ranges from 60–70%, 55–75% and 50–75% in WL_3, IL_{1a} and DL_3, respectively (Peiris *et al*., 2008).

***Characteristics of the selected soils (Somasiri et al., 1994)*:**

WL_3

Pallama series (S_2): Imperfectly drained to poorly drained, deep sandy loam, sandy clay loam to clay loam or sandy clay soil with few fine quartz, manganese nodules and plinthied.

Boralu series (S_4): Well drained, moderately deep, sandy loam, sandy clay loam to clay loam soil mixed with 40-50% ironstone gravel and few quartz gravel in sub soil.

IL_{1a}

Kurunegala series (S_2): Imperfectly drained, deep, sandy loam to sandy clay loam soil with few fine quartz, feldspar and occasionally ironstone grand.

Kuliyapitiya series (S_4): Well drained, moderately deep to deep, sandy loam to sandy clay loam soils with some quartz. Ironstone gravel and few feldspar in the sub soils.

DL_3

Mavillu series (S_2): Imperfectly drained, very deep, sandy loam to sandy clay loam soil.

Mampuri series (S_4) : Excessively drained , deep, coarse sand or sandy soil.

***Data collection*:** The data collection on coconut, grass cover and soil was conducted on eight randomly selected coconut palms or sample plots (35 x 35 cm) (for grass and soil measurements) per site during May to September 2009. For the determination of soil organic carbon and soil microbial respiration, core samples were collected from the centre of square (centre position of the four coconut palms, CS) at a depth of 0–20 cm (top soil). The below-ground biomass (roots) of coconut and grasses was not taken into account in the present study due to practical difficulties in the measurements and unavailability of reliable historical data on root: shoot ratio.

***Carbon stock in the ecosystem*:** Carbon stocks in biomass of coconut and grass (above-ground) and the top soils (0-20 cm depth) were determined using actual measurements and specific models.

***Coconut*:** The palms were climbed every month to count the number of nuts in each developing bunch (14–15 bunches per palm) and to measure the length of nuts along the long axis (two nuts per bunch). In each bunch, the dry weight per nut was estimated non-destructively by a fitted empirical equation developed for the Tall variety of coconut (Ranasinghe, 2008). The dry weight of each bunch was estimated by the mean nut weight and number of nuts per bunch and the total dry weight of nuts on a palm was obtained by summing up the weight of all the bunches. Stem density was estimated using the dry weight of stem core samples of a known volume and stem dry weight of a palm was estimated by multiplying the volume of the stem with the density (the shape of the coconut stem was assumed to be cylindrical and tapering of the stem towards the top was not taken into account. The same approach has been taken by many researchers working on coconut) (Friend & Corley, 1994; Navarro *et al*., 2008). Dry weight of total fronds per palm was estimated by using the actual dry weight of the most mature frond and the crown leaf load (Navarro *et al*., 2008). The carbon content of the dry mass was assumed to be 0.5 g C g_{DM}^{-1} (Matthews, 1993; Navarro *et al*., 2008). The total carbon stock per ha was determined by extrapolating the stock per palm for 160 palms.

***Grass cover*:** There was a periodically slashed and more or less uniformly distributed grass cover in all experimental sites except S_2 and S_4 sites in the DL_3 zone where only 50 - 60% of the surface was covered with grass (this was taken into account in the calculations). Above-ground grass dry matter in each site was assessed by harvesting randomly selected eight sub plots (pre-determined minimum plot size of 35 x 35 cm) adjacent to experimental coconut palms (2.5 m away from the base of the palm), taking oven dried weight (80º C for 48 hrs) and extrapolating it to the total area (per ha). Pre-determination of the minimum plot size was done on the basis of preliminary data collected on plots ranging from 10 x 10 cm to 200 x 200 cm sizes for estimating actual dry weight of grass cover in a coconut square excluding manure circle (four coconut palms in a 7.8 x 7.8 m square with each palm having a manure circle of 1.75 m radius from the base of the palm). The carbon content of the dry mass was assumed to be 0.5 g C g_{DM}^{-1} (Matthews, 1993).

***Top soil*:** Samples were collected from coconut centre of square (CS), at 0 –20 cm depth, using soil cores. 0.5 g of 2 mm sieved, air dried and ground soil samples were used to determine soil organic carbon content by wet oxidation method (Walkey & Black, 1934; Fernando, 1999). Using the soil organic carbon percentage, bulk density of the respective soils (Vidhana Arachchi, 2009); and total soil volume, total carbon stock per ha (0 –20 cm depth) was determined.

The total carbon stock in the ecosystem (minus the root carbon stock of coconut and grass) was determined by adding carbon in coconut palms, grass cover and soil.

***Gross Primary Production (GPP) of the ecosystem*:** Neglecting all inputs from organic fertilizer, it is assumed that all the carbon inputs of the ecosystem come from the Gross Primary Production (GPP, sum of photosynthesis of coconuts and grass). The rate of net photosynthesis of three fronds, representing the three whorls (upper, middle and lower) of the canopy of coconut palm was measured in the morning (between 9.00-12.00 h) and afternoon (between 13.00 – 16.00 h) in two consecutive days of every month (from May to September) by using a LI-COR 6200 Portable Photosynthesis system (LI-COR, USA). Using the mean photosynthesis rates over the period and leaf area of the three whorls of the canopy [leaf area of a single frond in each whorl was calculated using a model (Jayasekara & Mathes, 1992) and total leaf area of each three whorls were calculated based on the number of fronds in each whorl] and CO_2 assimilation period (8.00 – 16.00 h), amount of CO_2 fixed daily by different whorls of the canopy were estimated. Finally the values of three whorls of the canopy were summed up to estimate the total CO_2 fixed daily by a coconut palm (Jayasekara & Jayasekara, 1995). The total carbon fixed by coconuts cultivated in one ha of land was determined by extrapolating the single palm value for 160 palms. It can be argued that integrating daily photosynthesis values over a month can result in over- or under-estimation of GPP as the instantaneous photosynthesis rates can vary depending on the daily variation of meteorological variables. However, a more reliable model or method compared to the method used in the present study for estimating daily CO_2 assimilation by a leaf canopy is not available to date for coconut. Therefore, due to practical difficulties in taking extensive photosynthesis measurements daily, it was assumed that the two consecutive days of measurement represent the CO_2 assimilation rate of a palm during the respective month. GPP of the grass cover was not estimated in the present experiment (due to lack of a reliable methodology). Therefore, the total C fixed by the ecosystem is given as C fixed only by coconut palms (GPP of the ecosystem).

***Total Respiration of the ecosystem*:**

Plant autotrophic respiration (R_a) :

R_a of coconut palms was estimated by a general model proposed by de Wit *et al*., (1978), Penning de Vries *et al*., (1989) and Navarro *et al*., (2008). This R_a does not include root respiration (since the NPP and dry weight of roots are not known, the growth and maintenance respiration and hence R_a could not be estimated in the present study).

$$R_a = R_g + R_m = \alpha\, NPP + 0.4\beta B$$

R - respiration of coconut palm (g C m^{-2} day^{-1}), subscripts *a, g* and *m* denote autotrophic, growth and maintenance respiration, respectively; α - growth respiration coefficient (g C g_{DM}^{-1}), 0.67 for nuts, 0.32 for leaf and 0.25 for stem (Navarro *et al*., 2008); NPP- Net Primary Production of each organ (g DM m^{-2} day^{-1}); 0.4 - C: CH_2O molecular mass ratio; β - maintenance respiration coefficient (g CH_2O g DM^{-1} day^{-1}), 1.84 for nuts, 2.45 for leaf and 0.5 for stem (Navarro *et al*., 2008); B- biomass of the organ (g DM m^{-2}).

***NPP of coconut palm*:** The palms were climbed every month, the length of nuts along the long axis was measured (two nuts per bunch) and dry weight per nut of each bunch was estimated non-destructively by a fitted empirical relationship developed for Tall variety of coconut (Ranasinghe, 2008). The NPP of nuts in a given bunch (NPP_{bunch}) between time t_1 and t_2 was estimated by the following equation (Navarro *et al*., 2008);

$$NPP_{bunch} = N_{bunch\,(t_2)}\left[\frac{DM_{nut\,(t_2)} - DM_{nut\,(t_1)}}{t_2 - t_1}\right]$$

DM_{nut} - dry weight of a nut; $N_{bunch(t_2)}$ - total number of nuts in a bunch at time t_2

The NPP of all nuts on a palm (NPP_{nuts}) was obtained by summing up the NPP of all the bunches.

For determining the NPP_{stem}, vertical growth rate of stem was monitored by marking a line just below the leaf crown. The increased volume of the stem over the period (considering that there is no detectable increase in stem circumference over time) and stem density were used to determine the NPP_{stem}. The number of new leaves emerged per month was nearly one for each palm. Therefore, the dry weight of leaves was used to determine the NPP of leaves. R_g and R_m for each organ (nuts, leaves and stem) and total palm were calculated and the total autotrophic respiration per ha was estimated by extrapolating the per palm value for 160 palms. The growth and maintenance respiration of coconut root system and the grass cover (shoot and root) was not estimated in the present study.

***Soil respiration* (R_{soil}):** Samples to determine soil (microbial) respiration were collected from coconut centre of square (CS) using soil cores (at 0 – 20 cm depth) twice during the experimental period (June and July). Hundred grams of 2 mm sieved fresh soil samples were moistened with distilled water and CO_2 evolution at room temperature was determined after 7 d of incubation (Anderson & Ingram, 1989; Fernando, 1999). Since there was no significant difference between the CO_2 evolution rate of two months, the mean CO_2 evolution rate was used to determine the CO_2 evolution per ha as it was done for soil organic carbon determination.

Thus, the total ecosystem respiration ($R_{tot-eco}$) is given as autotrophic respiration of coconut palms (R_a) and soil heterotrophic respiration (R_{soil}).

***Meteorological data*:** Meteorological data of the research sites were obtained from nearby meteorological stations of the Coconut Research Institute and the Department of Meteorology, Colombo.

***Analysis of data*:** The data were analysed using the SAS statistical package with two-way ANOVA (PROC GLM, SAS version 8.2). AER and LSC were used as the main effects and if the two way interaction was not significant at $p \leq 0.05$ in ANOVA, means of the main effects (AER and LSC) were compared directly by LSD. If the two way interaction was significant at $p \leq 0.05$, appropriate two way values were used to make comparisons.

RESULTS AND DISCUSSION

Climate during the experimental period

During the course of the data collection, the mean monthly temperature (T_{mean}) was around 27–28 ºC and the duration of sunshine (SS) was around 7 hours per day in the three Agro Ecological Regions (Table 2). The mean monthly rainfall (RF) received by WL_3, IL_{1a} and DL_3 was 166, 86.2 and 31.3 mm, respectively. The mean solar radiation intensity in WL_3, IL_{1a} and DL_3 was 14.08, 16.29 and 18.02 MJ m^{-2} day^{-1}, respectively.

Carbon stock in the Eco-system (standing biomass)

Coconut (B_{palm})

There was a significant AER x LSC effect on total carbon stock of palms (B_{palm}) indicating that B_{palm} showed a different response to a decreasing moisture gradient on different LSCs (Figure 1). On S_2, which is highly suitable for coconut, B_{palm} did not show a significant reduction along a decreasing moisture gradient from WL_3 to DL_3. However, on moderately suitable S_4, B_{palm} was maximum in IL_{1a}, which has intermediate moisture availability. It is interesting to note that even in WL_3, where moisture availability is higher, B_{palm} on S_4 was significantly lower

Table 2: Monthly temperature, monthly rainfall (RF), daily sunshine hours (SS) and solar radiation intensity (SR, MJ $m^{-2} d^{-1}$) of WL_3, IL_{1a} and DL_3 during the experimental period (May – September 2009)

	May-09	June-09	July-09	August-09	Sept-09	Mean
WL_3						
T_{max} (ºC)	31.5	30.6	30.5	30.7	30.7	30.8
T_{min} (ºC)	22.7	23.7	23.3	24.5	23.2	23.5
T_{mean} (ºC)	27.1	27.2	26.9	27.6	27.0	27.2
RF (mm)	191.0	178.0	100.9	123.7	235.3	166
SS (hrs)	6.4	6.7	7.4	6.6	8.0	7.02
SR	13.51	13.83	14.33	13.63	15.09	14.08
IL_{1a}						
T_{max} (ºC)	32.4	31.1	30.9	31.5	30.8	31.3
T_{min} (ºC)	25.0	24.6	24.2	24.2	23.3	24.3
T_{mean} (ºC)	28.7	27.85	27.55	27.85	27.05	27.8
RF (mm)	37.2	97.8	67.7	85.5	142.8	86.2
SS (hrs)	6.5	6.7	6.5	6.3	6.9	6.6
SR	13.96	15.76	16.01	16.99	18.73	16.29
DL_3						
T_{max} (ºC)	32.7	32.2	31.8	32.2	32.6	32.3
T_{min} (ºC)	27.4	26.9	26.0	26.0	26.4	26.5
T_{mean} (ºC)	30.1	28.10	27.50	27.55	27.15	28.1
RF (mm)	16.0	31.7	6.7	94.1	8.2	31.3
SS (hrs)	6.8	7.4	6.3	7.3	8.4	7.24
SR	13.96	17.41	19.12	19.26	20.33	18.02

T_{max}: maximum, T_{min}: minimum, T_{mean}: mean

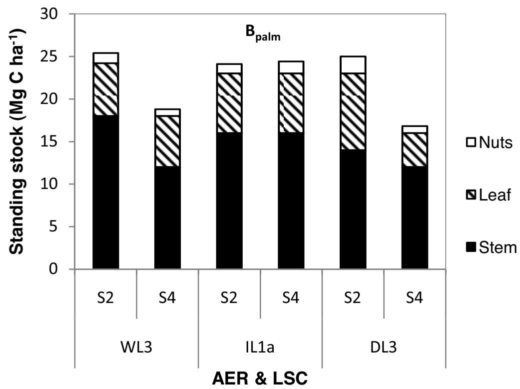
than its maximum in IL_{1a}. The possible reasons for these variations can be the higher depth of S_4 soils in IL_{1a} (Kuliyapitiya series) and lower water and nutrient retention ability of S_4 soils in DL_3 (Mampuri series with coarse sandy and sandy soil) compared to that of WL_3 (Boralu series). As a result of significantly greater B_{palm} on S_4 in IL_{1a}, there was no significant difference between B_{palm} on the two LSCs. In contrast, in both WL_3 and DL_3, B_{palm} on S_4 was significantly lower as compared to the respective values on S_2. Furthermore, out of the fractions of carbon in different components of the palm, coconut stem was found to be the main C storage organ, which stores about 56–70% of the total C stock of palms. Furthermore, on S_2, there was a significant reduction in the fraction of C stock in the stem (B_{palm}) along the decreasing moisture gradient from WL_3 to DL_3 whilst an opposite trend was observed on S_4 -grown palms. The pattern of variation in B_{leaf} showed an opposite trend on S_2 and S_4.

Grass cover

There was a significant AER x LSC effect on total carbon stock in the grass cover (B_{grass}) (Figure 2). The most striking factor is that B_{grass} was lower in DL_3, irrespective of the LSC, compared to the respective values in WL_3 and IL_{1a}. This may be mainly attributed to the lower growth of grass cover due to reduced soil moisture availability in the top soils in DL_3 compared to other two AERR (Figure 2, Table 2). Furthermore, on S_4, B_{grass} was not affected by the decreasing moisture availability from WL_3 to IL_{1a} whilst on S_2, B_{grass} showed the maximum value in IL_{1a}. This may be associated with the more suitable growth conditions for grass cover under higher light intensity in IL_{1a} (16.29 MJ $m^{-2} d^{-1}$) compared to WL_3 (14.08 MJ $m^{-2} d^{-1}$), and grasses on S_2 have taken the maximum advantage of it (Table 2).

Top soil

There was a significant AER x LSC effect on C stock in the top soils (B_{soil}) (Figure 2). B_{soil} showed a significant reduction along a decreasing moisture gradient from WL_3 to DL_3 and decreasing soil fertility gradient from S_2 to S_4, though the magnitude of difference between S_2 and S_4 varied with the AER. Furthermore, B_{soil} was



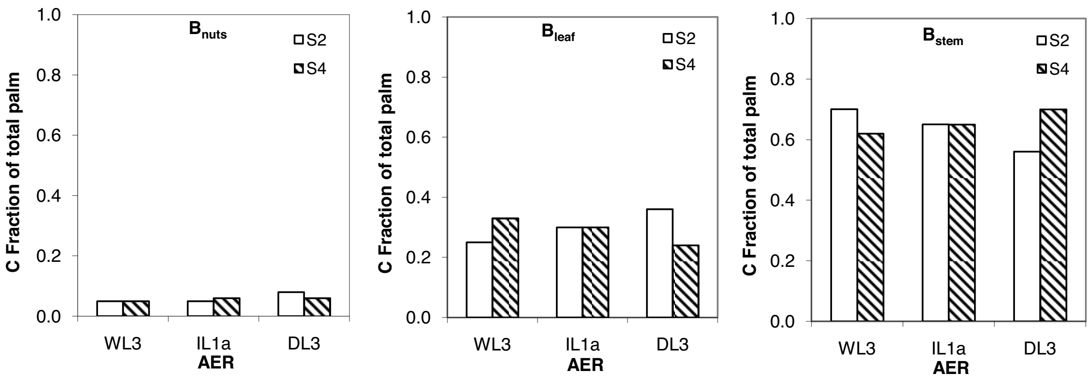


Figure 1: C stock of the whole palm (B_{palm}) (Mg C ha^{-1}) in terms of its components (stem, leaf, nuts), and the fraction of C in different components; nuts (B_{nut}), leaves (B_{leaf}) and stem (B_{stem}) on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3.

lowest in DL_3, irrespective of the LSC, compared to the respective values in WL_3 and IL_{1a} and this may be mainly attributed to the lower growth of grass (B_{grass}) in DL_3 and hence, reduced litter fall in DL_3 compared to other two AERs. It is interesting to note that, on S_4, there was a substantial reduction of B_{soil} in IL_{1a} compared to the values in WL_3, although the litter production by the grass cover was more or less equal on two soils. This may be possibly attributed to the increased decomposition of litter on S_4, in IL_{1a} (Kuliyapitiya soil series) under a favourable environment for microbial activity [moderate soil moisture availability (Fernando, 1999) and higher soil temperatures (30.7 ºC in IL_{1a} *vs* 30.3 ºC in WL_3)] (see Figure 6a for highest microbial activity on S_4 in IL_{1a}) compared to S_4 in WL_3 (Boralu soil series, which had a lower microbial activity compared to S_4 in IL_{1a}).

Total ecosystem

There were significant AER and LSC effects on total ecosystem carbon stock ($B_{tot-eco}$)(Figure 3). It showed a significant reduction on S_4, which is moderately suitable for coconut as compared to respective values on S_2 plantations, which are highly suitable for coconut. Furthermore, ($B_{tot-eco}$) decreased along a decreasing moisture gradient from WL_3 to DL_3.

$B_{tot-eco}$ in the six different eco-systems ranged from 32 Mg C ha^{-1} (S_4 of DL_3) to 72 Mg C ha^{-1} (S_2 of WL_3). This wide range of C stock may be mainly attributed to variations in agro-ecological condition of the region, physical, chemical and biological factors of soils therein resulting differences in palm growth, litter production and

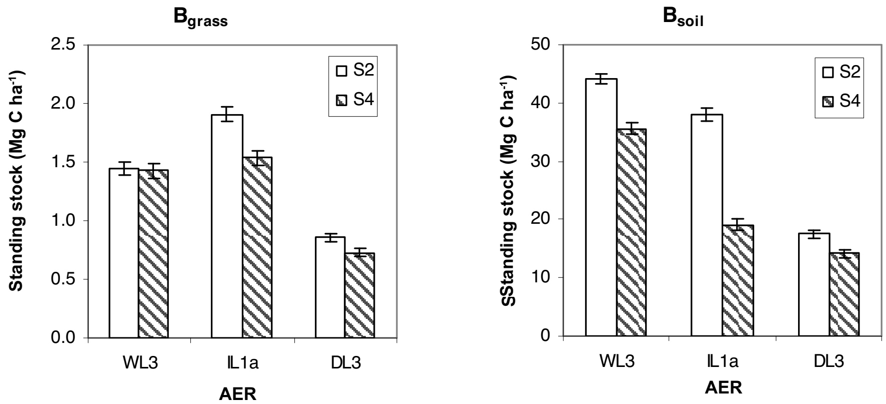


Figure 2: C stock (Mg C ha^{-1}) of grass cover (B_{grass}) and top soil (B_{soil}) on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3 (values are means ± standard error of mean)

litter decomposition. In a case study, Vanuatu Red Dwarf x Vanuatu Tall high-yielding coconut hybrid (19–22 yr old) grown under optimal conditions had a total palm C stock of 34.13 Mg C ha^{-1} out of which 5.0 Mg C ha^{-1} was found in course and fine roots (Navarro *et al*., 2008). In the same study, the grass cover had about 1.8 Mg C ha^{-1} and, consequently, the total carbon stock in coconut and grass was about 36 Mg C ha^{-1}. In the present study, total palm C stocks varied from 17–25 Mg C ha^{-1}, depending on the AER and LSC. The lower values compared to the values reported in the literature (Navarro *et al*., 2008) may be attributed to several reasons. The key reasons would be that the palms were not grown under optimum conditions and C stocks in the roots of coconut were not estimated in the present study. Average carbon storage by agro-forestry systems has been estimated as 9, 21, 50 and 63 Mg C ha^{-1} in the semi-arid, sub-humid, humid and temperate regions respectively (Montagnini and Nair, 2004). In the, present study, the contribution of carbon stock in coconut palms (B_{palm}) and sub soil (B_{soil}) to the total ecosystem C stock ($B_{tot-eco}$) varied with the AER. Whilst the C stock in coconut palms accounted for about 35, 45 and 55% of the total eco-system C stock, soil carbon stock accounted for about 63, 52 and 42% in the WL_3, IL_{1a} and DL_3, respectively. Grasses (B_{grass}) contributed to only 2–3% in the carbon stock of ecosystems irrespective of the AER or LSC. Roupsard *et al.,* (2008b) also pointed out the presence of more C stocks in the soils of coconut plantations compared to that in the biomass of coconut. Soils are the largest carbon reservoir of the terrestrial carbon cycle and the current global stock of organic carbon is estimated to be 1,500–1,550 Pg (Lal, 2004). Of the C stocks in the coconut palm, 55–70% was stored in the stem (long-term C sinks) and the balance was stored in leaf canopy and fruits (short-term C sinks). Carbon stocks in the litter were not determined in the present study.

GPP of the ecosystem

There was a significant AER x LSC effect on the GPP of the ecosystem (Figure 4). On highly suitable soils (S_2), GPP did not show a significant reduction along a decreasing moisture gradient from WL_3 to DL_3. However, on moderately suitable soils (S_4), GPP showed a significant reduction from WL_3 to DL_3. Moreover, GPP on S_4 was higher than that on S_2 in the WL_3, where moisture availability is high, whilst the effect was opposite in DL_3 where moisture availability is low. In IL_{1a}, where moisture availability is moderate, GPP did not show a significant difference between the two LSC. These results are mainly attributed to the comparable rate of photosynthesis and leaf area index (LAI) of coconut palms in IL_{1a}, irrespective of LSC (Table 3). These results comply with the observation that photosynthesis rates, leaf area index and hence the GPP of coconut are less sensitive to LSC when there is no severe soil moisture stress as observed in WL_3 and IL_{1a} (Table 2). The higher rate of photosynthesis (though the difference was not significant) and leaf area index of palms grown on moderately suitable soils (S_4) compared to that on highly suitable soils (S_2) in WL_3 (Table 3) may have resulted a higher GPP of former compared to latter. This may be an adaptation measure of S_4 grown palms when the moisture availability is high (in WL_3) to compensate the reduction of assimilate production during moisture stressed periods.

This effect was reflected not only in photosynthesis but also in leaf production rate and nut setting of these palms during the same period. For an example, the number of set nuts per palm on S_4 was similar or higher than that on S_2 during May - August period whilst it was significantly lower on S_4 compared to S_2 during the periods with environment stress (February - March period) (*C. S. Ranasinghe, unpublished data*). However, this mechanism does not seem to be taking place on S_4 in IL_{1a}, where the moisture availability is moderate and the reasons for the observed differences have to be explored in future studies. In DL_3, where the moisture availability is low, the rate of photosynthesis was significantly lower compared to that in WL_3 and the leaf area index of palms on S_4 was lower compared to that on S_2 and palms in the other two AERs. This may be a key reason for the differences in GPP in the DL_3 (Figure 4). If the data collection of this study covered a reasonably dry period of the year such as February and March, the response of GPP along a decreasing moisture gradient on two LSC would have been different and, therefore, studies are in progress to assess these aspects. GPP by the grass cover was not measured in the present study, thus, the GPP of coconut palms ($GPP_{coconut}$) was considered as the GPP of the total ecosystem. For the purpose of comparison, if the highest GPP value observed in the palms of WL_3 (2.9 Mg C ha^{-1} $month^{-1}$) is extrapolated for the whole year, it will be equal to a value of about 34.8 Mg C ha^{-1} yr^{-1}, which is comparable to the GPP value of 39.0 Mg C ha^{-1} yr^{-1}, obtained by Eddy-covariance method, for a high yielding coconut plantation under optimal conditions (Navarro *et al*., 2008).

Net Primary Production (NPP) of coconut palms

There were significant AER x LSC effects on the NPP_{palm} and all of its components (Figure 5). The NPP_{nut}, NPP_{leaf}, NPP_{stem} and NPP_{palm} were not affected by the land suitability class or decreasing moisture gradient from WL_3 to IL_{1a}. However, despite the low moisture availability, the palms on highly suitable soils (S_2) in DL_3 show a significantly higher NPP_{palm} mainly due to significantly higher NPP_{nut} of these palms compared to the respective values under other growth conditions. This was mainly attributed to higher fruit load in these palms compared to others (data not presented). Navarro *et al.,* (2008) also reported that NPP_{nut} appear to be a key driver for whole tree NPP (NPP_{palm}), and NPP_{leaf} and NPP_{stem} appear to be remarkably constant. Furthermore,

Table 3: Mean rate of photosynthesis (A) and leaf area index (LAI) of coconut palms on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3

AER	LSC	A (µmol CO_2 $m^{-2}s^{-1}$)	LAI
WL_3	S_2	9.256 ± 0.639	2.391 ± 0.158
	S_4	10.238 ± 0.500	2.713 ± 0.121
IL_{1a}	S_2	6.404 ± 0.729	3.180 ± 0.120
	S_4	6.260 ± 0.624	3.261 ± 0.186
DL_3	S_2	7.319 ± 0.356	2.720 ± 0.179
	S_4	6.559 ± 0.356	1.774 ± 0.126

Note: Values are means of 8 palms ± standard error of means.

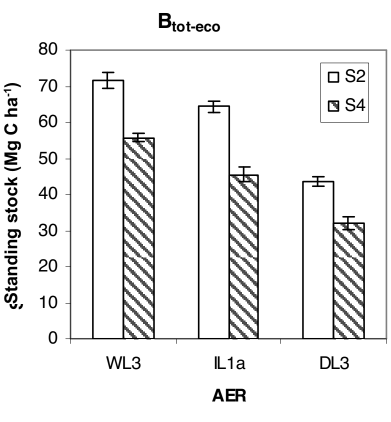


Figure 3: C stock (Mg C ha^{-1}) of the total ecosystem ($B_{tot-eco}$) on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3 (values are means ± standard error of mean)

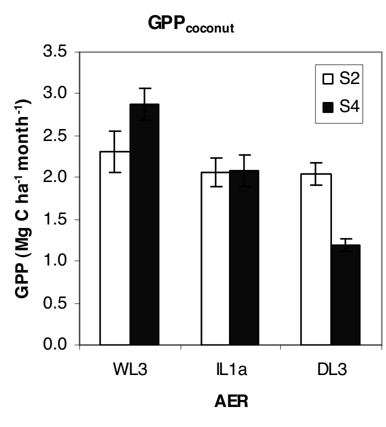


Figure 4: Gross Primary Production (GPP) of coconut palms (Mg C ha^{-1} $month^{-1}$) on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3 (values are means ± standard error of mean)

they pointed out that fruit production in coconut is poorly linked to photosynthesis rate, which may be reasonably true for the present study as well. Leaf NPP (NPP_{leaf}) comprised the highest percentage (40–66%) of palm NPP (NPP_{palm}), followed by NPP_{nut} (28–50%) and NPP_{stem} (6–12%). However, NPP_{nut} comprised a higher percentage of NPP_{palm} than NPP_{leaf} in S_2 of the DL_3. With a high-yielding coconut hybrid, Navarro *et al.,* (2008) also found a higher NPP_{nut} compared to NPP_{leaf} under optimal conditions. In their study, the NPP_{palm} (including NPP_{roots}) was 11.99 Mg C ha^{-1} yr^{-1}. If the highest NPP_{palm} observed in the present study (0.612 Mg C ha^{-1} month^{-1}) is extrapolated for the whole year, it will reach to a value of about 7.4 Mg C ha^{-1} yr^{-1} (excluding roots), which is comparable to the values shown by Navarro *et al.,* (2008).

Respiration of the ecosystem

Autotrophic respiration of palms [$R_{a(palm)}$]

There were significant AER x LSC effects on the total respiration of palms [$R_{a(palm)}$] and all of its components, growth respiration (R_g) and maintenance respiration (R_m) indicating that palm respiration showed differential responses to a decreasing moisture gradient on different LSCs (Figure 6a). Similar to NPP of palms, R_g , R_m and $R_{a(palm)}$ were not affected by the land suitability class or decreasing moisture gradient from WL_3 to IL_{1a}. However, the palms on highly suitable soils (S_2) in DL_3 showed a significantly higher $R_{a(palm)}$ mainly due to significantly higher R_m of these palms compared to the respective values under other growth conditions. This

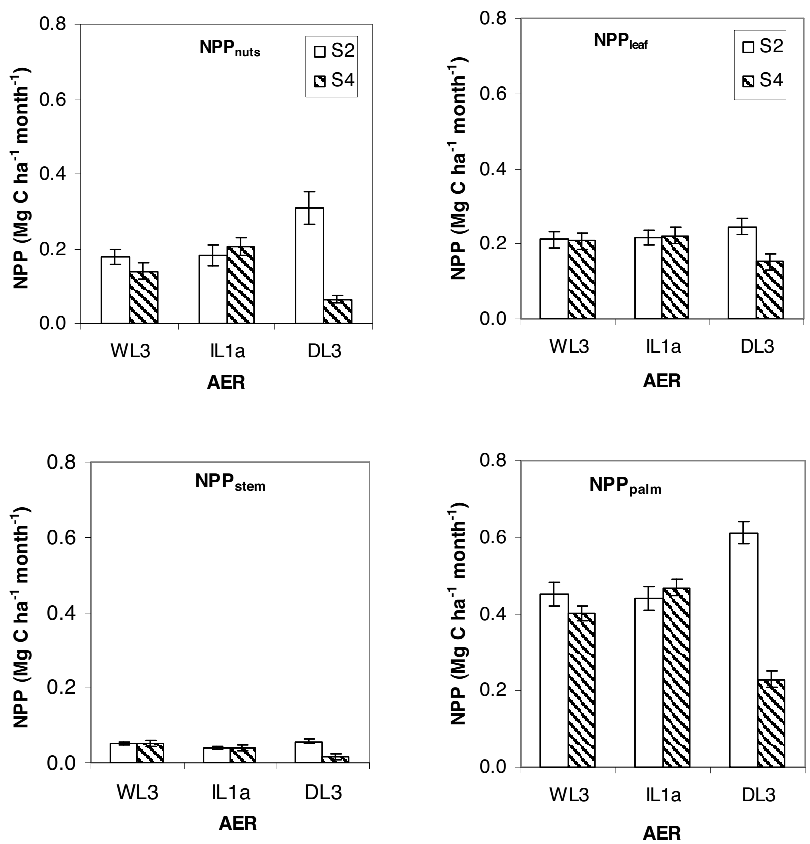


Figure 5: Net Primary Production (Mg C ha^{-1}month^{-1}) of nuts (NPP_{nut}), leaves (NPP_{leaf}), stem (NPP_{stem}) and total coconut palm (NPP_{palm}) on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3 (values are means ± standard error of mean)

was mainly attributed to greater dry weight of stem and higher nut load of these palms compared to other growth conditions (data not shown). Maintenance respiration (R_m) of coconut palms was about five fold higher than the R_g irrespective of the land suitability class or moisture availability (AER).

The data on R_g, R_m and total respiration of different compartments of coconut palm are presented in Tables 4a and 4b. With the exception of maintenance (R_m) and total (R_a) respiration of nuts and stems, on S_4 in WL_3, the above mentioned variation in $R_{a(palm)}$ and R_m of palms is reflected in the corresponding variations of R_g, R_m and R_a of nuts, leaves and stem components on two LSC and three AER. With regard to the growth (R_g) and maintenance respiration (R_m) of different organs, R_g was maximum in nuts, followed by leaves and stem whilst R_m was maximum in leaves, followed by stem and nuts, irrespective of the AER and LSC. R_m is primarily determined by the standing biomass and the stems have higher standing biomass than the leaves (Figure 1). Therefore, one would expect to have a higher R_m for stem compared to that of leaves, which is opposite to the observations in the present study. The main reason for this deviation is the higher maintenance respiration coefficient (β) of leaves (2.45) as compared to that of

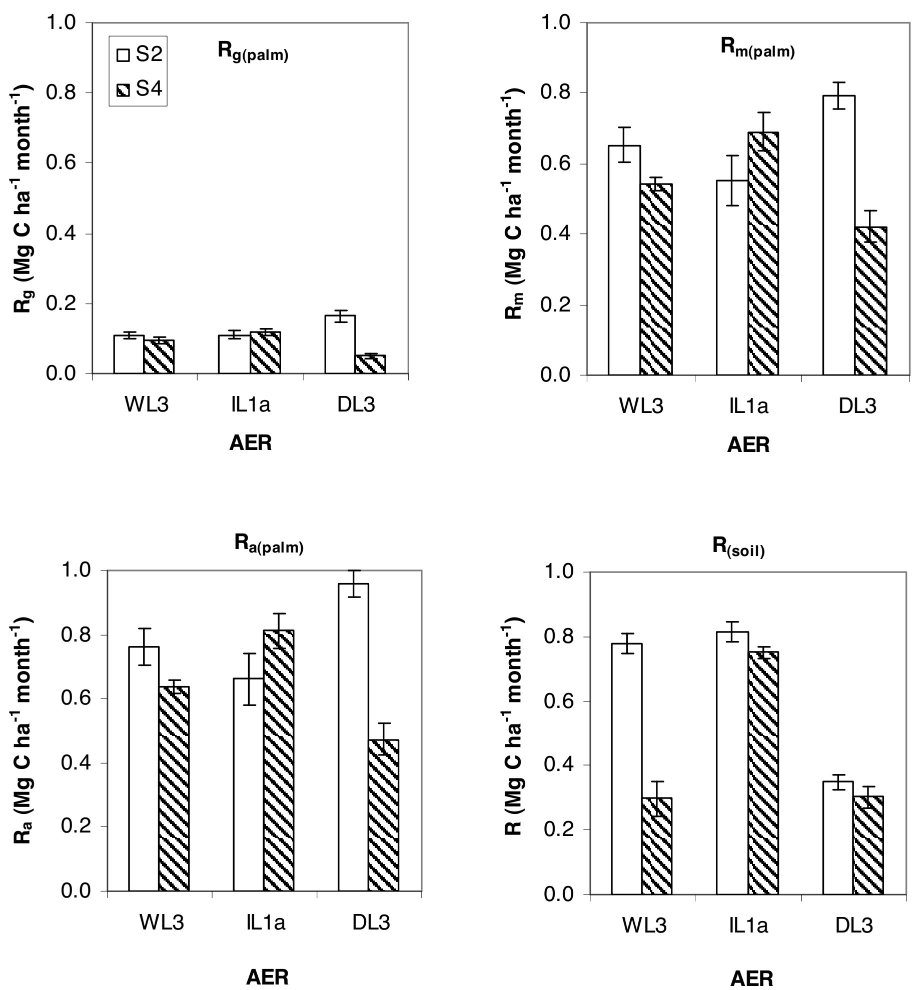


Figure 6a: Growth Respiration, [$R_{g\,(palm)}$] (Mg C ha^{-1}month^{-1}), maintenance respiration [$R_{m\,(palm)}$] and total respiration [$R_{a\,(palm)}$] of coconut palms and soil respiration [$R_{(soil)}$] on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3 (values are means ± standard error of mean).

stems (0.5). According to the equation for computation of β, it has coefficients for conversion of nitrogen to protein, protein turnover, dry matter content in nitrogen and cost induced by ionic gradients (de Wit *et al.,* 1978) and these values are higher for leaves than for stem.

Consequently, the respiration of leaves comprised the highest percentage (52–63 %) of palm autotrophic respiration, followed by that of stem (18–30%) and nuts (14–21 %). The autotrophic respiration of the grass cover $R_{a\,(grass)}$ was not estimated in the present study. Thus, the R_a of coconut palms is considered as the R_a of the ecosystem. For a high yielding coconut hybrid grown under optimal conditions, $R_{a\,(palm)}$ was 20.96 Mg C ha^{-1} yr^{-1} out of which about 6 Mg C ha^{-1} yr^{-1} was attributed to the respiration of root and inflorescences (Navarro *et al.,* 2008). If the highest $R_{a\,(palm)}$ observed in the present study (0.958 Mg C ha^{-1} $month^{-1}$) is extrapolated for the whole year, it will reach to a value of about 11.5 Mg C ha^{-1} yr^{-1} (excluding root and inflorescence respiration) which is little lower than the values shown by Navarro *et al.,* (2008).

Heterotrophic respiration of soil (R_{soil})

There was a significant AER x LSC effect on soil microbial respiration (R_{soil}) indicating that R_{soil} showed differential responses to a decreasing moisture gradient on different LSCs (Figure 6a). On S_2, which is highly suitable for coconut, R_{soil} did not show a significant reduction along a decreasing moisture gradient from WL_3 to IL_{1a}. However, on moderately suitable S_4, R_{soil} was maximum in IL_{1a}, which has intermediate moisture availability. In contrast, in WL_3, where moisture availability is higher, R_{soil} on S_4 was significantly lower as compared to the respective values on S_2. As a result of significantly greater R_{soil} on S_4 in IL_{1a}, there was no significant difference between R_{soil} on the two LSCs. It is interesting to note that even in WL_3, where moisture availability is higher, R_{soil} of S_4 was significantly lower than its maximum in IL_{1a} and equal to the respective values on S_2 and S_4 in DL_3. Soil microbial respiration can vary with the soil temperature and soil water content, depending on the type of plantation (Jiang *et al.,* 2005). Therefore, key reasons for low R_{soil} in DL_3 may be the low moisture availability and higher temperature compared to other two AERs. However, the main reasons for low R_{soil} on S_4 of WL_3 would be less suitable soil physical and chemical characteristics for microbial activity in the *Boralu* soil series (Fernando, 1999).

Furthermore, in the present study, soil microbial respiration was estimated with moistened soil samples under *ex-situ* (laboratory) conditions and the values would have been slightly different if the respiration data were collected *in-situ* under field conditions. Moreover, the total soil respiration of an ecosystem consists of two components, soil microbial respiration and root respiration (Jiang *et al*., 2005), and the latter was not measured or estimated in the present study as reliable data on NPP and dry weight of coconut root system were not available. Hence, if the root respiration of coconut and grasses was also included in the R_{soil}, the CO_2 efflux from soil respiration would have been higher compared to the observed values in the present study.

There was a significant AER x LSC effect on total respiration of the ecosystem ($R_{tot-eco}$) indicating that $R_{tot-eco}$ showed a differential response to a decreasing moisture gradient on different LSCs (Figure 6b). On S_2, which is highly suitable for coconut, $R_{tot-eco}$ did not show a significant reduction along a decreasing moisture gradient from WL_3 to DL_3. However, on moderately suitable S_4, $R_{tot-eco}$ was maximum in IL_{1a}, which has intermediate moisture availability. In WL_3,

Table 4a: Growth (R_g) and maintenance (R_m) respiration of different plant organs of coconut palm on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3

AER	LSC	R_g (Mg C ha^{-1} $month^{-1}$)			R_m (Mg C ha^{-1} $month^{-1}$)		
		Nuts	Leaves	Stem	Nuts	Leaves	Stem
WL_3	S_2	0.065 ± 0.007	0.037 ± 0.002	0.007 ± 0.002	0.053 ± 0.006	0.379 ± 0.036	0.220 ± 0.016
	S_4	0.051 ± 0.008	0.036 ± 0.002	0.007 ± 0.001	0.039 ± 0.004	0.363 ± 0.014	0.140 ± 0.007
IL_{1a}	S_2	0.066 ± 0.010	0.038 ± 0.001	0.006 ± 0.001	0.051 ± 0.007	0.308 ± 0.070	0.192 ± 0.013
	S_4	0.075 ± 0.008	0.039 ± 0.002	0.006 ± 0.001	0.061 ± 0.005	0.437 ± 0.034	0.193 ± 0.017
DL_3	S_2	0.113 ± 0.016	0.043 ± 0.003	0.008 ± 0.001	0.091 ± 0.006	0.534 ± 0.035	0.169 ± 0.010
	S_4	0.024 ± 0.004	0.027 ± 0.002	0.002 ± 0.000	0.043 ± 0.009	0.241 ± 0.024	0.144 ± 0.011

Note: Values are means of 8 palms ± standard error of means

Table 4b: Total (R_a) respiration ($R_g + R_m$) of different plant organs of coconut palm under S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3

AER	LSC	R_a (Mg C ha^{-1} month^{-1}) Nuts	Leaves	Stem
WL_3	S_2	0.118 ± 0.01 (15%)	0.416 ± 0.04 (55%)	0.227 ± 0.02 (30%)
	S_4	0.090 ± 0.01 (14%)	0.400 ± 0.02 (63%)	0.147 ± 0.01 (23%)
IL_{1a}	S_2	0.118 ± 0.02 (18%)	0.346 ± 0.07 (52%)	0.197 ± 0.01 (30%)
	S_4	0.136 ± 0.01 (17%)	0.476 ± 0.04 (59%)	0.198 ± 0.02 (24%)
DL_3	S_2	0.204 ± 0.02 (21%)	0.577 ± 0.04 (61%)	0.177 ±0.01 (18%)
	S_4	0.066 ± 0.01 (14%)	0.267 ± 0.03 (56%)	0.146 ± 0.01 (30%)

Note: Values are means of 8 palms ± standard error of means. Percentage contribution to total palm respiration is given in the parentheses.

where moisture availability is higher, $R_{tot-eco}$ on S_4 was significantly lower than its maximum in IL_{1a} and this is mainly attributed to the significantly low R_{soil} on S_4 in WL_3. A significantly low R_{soil} and $R_{a(palm)}$ has resulted in the significantly lower R_{soil} on S_4 in DL_3. Since the R_{soil} and $R_{a(palm)}$ on S_4 in IL_{1a} were comparable with that on S_2, there was no significant difference in $R_{tot-eco}$ between two LSC in IL_{1a}. If the data collection of this study covered a reasonably dry period of the year such as February and March, the response of $R_{a(palm)}$, R_{soil} and $R_{tot-eco}$ along a decreasing moisture gradient on two LSC would have been different and, therefore, studies are in progress to assess these aspects during different seasons of the year. The contribution of $R_{a(palm)}$ and R_{soil} to the $R_{tot-eco}$ varied with the AER. $R_{a(palm)}$ comprised 59, 48 and 67% of $R_{tot-eco}$ in WL_3, IL_{1a} and DL_3, respectively. The highest contribution of $R_{a(palm)}$ to $R_{tot-eco}$ in the DL_3 was mainly attributed to high respiration rates of the palms on S_2 LSC resulted from high NPP.

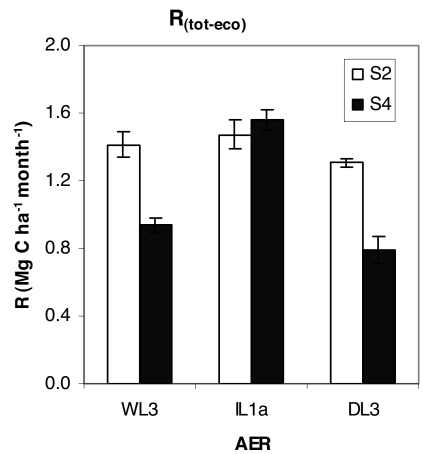


Figure 6b: Total ecosystem respiration [$R_{(tot-eco)}$] on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3
Note: values are means ± standard error of mean

Final carbon balance

Coconut plantations in all three AER on two LSC have the potential to act as carbon sinks and the net carbon exchange rates (C sequestration rates) were in the range of 0.4 –1.9 Mg C ha^{-1} month^{-1} (Table 5). There was a significant AER x LSC effect on net carbon exchange (balance) of ecosystems confirming that components of C balance show a differential response to a decreasing moisture gradient on different LSCs. On S_4, which is moderately suitable for coconut, net C balance reduced along a decreasing moisture gradient from WL_3 to DL_3. However, on highly suitable S_2, the C balance did not show a significant reduction along a decreasing moisture gradient from WL_3 to DL_3. The most striking result of this study was the significantly greater net C balance on moderately suitable S_4 compared to highly suitable S_2 in the WL_3 (Table 5). In the present study, the S_4 in WL_3 belongs to Boralu series in which the moisture retention ability and soil microbial activity are significantly lower compared to the S_4 soils in IL_{1a} (Fernando, 1999). Similarly in DL_3, the S_4 soils belongs to *Mampuri* series, in which the moisture retention ability and soil microbial activity are again significantly lower compared to Kuliyapitiya series (Fernando, 1999). Therefore, the high net C balance on S_4 compared to S_2 in the WL_3 was associated with a higher GPP, which is less sensitive to LSC when the soil moisture is not limiting (when there is adequate rainfall, Table 2), and lower R_{soil} (Figure 6a) which is even equal to that of DL_3, on *Boralu* series soils (S_4) in WL_3. However, this pattern of GPP and soil respiration can vary with the environmental conditions, especially during the periods with very heavy rainfall (November-December) and low rainfall associated with high temperatures (February-March). Therefore, the seasonal and inter-annual variations in GPP, plant and soil respiration and net ecosystem carbon balance of coconut plantations on different LSC in different AER are being studied for developing a scientific database on C sequestration potential of coconut in Sri Lanka.

Although coconut is a multipurpose perennial tree crop that can sequester C for about 70 years and has the possibility of growing in tropical environments as C sinks, little attention has been paid to collect scientific data on carbon sequestration potential in coconut plantations. Detail C balance study assessments remain scarce for coconut plantations, except the recent case study published for a high yielding variety grown under optimal conditions in Vanuatu (Roupsard *et al*., 2006; Roupsard *et al*., 2008b; Navarro *et al*., 2008). They estimated a mean net ecosystem carbon balance of 3–8 Mg C ha^{-1} $year^{-1}$ for a 19–20 year-old coconut plantation under optimum fertility and water conditions. Thus, this value has to be considered only as the maximum estimation for a coconut plantation. For small-holder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} (Montagnini & Nair, 2004). According to the current C market, an average value of US$ 11 per Mg of CO_2 can be used to estimate the annual revenue that can be obtained from net ecosystem carbon exchange (NEE) in coconut plantations. In the present study, mean NEE of C was 9.3 Mg C ha^{-1} yr^{-1}, which is equivalent to 34.03 Mg CO_2 sequestered per ha^{-1} yr^{-1}. Therefore, a coconut plantation of 25-26 years of age has C credits (per ha) worth of US$ 375 (equivalent to SLR 41, 250.00). The total net revenue per ha could be worked out by the difference between the present scenario (with C project) and the baseline scenario.

Table 5: Summary carbon balance of the ecosystems (means of 8 palms ± standard error of means): C stock, GPP, respiration and carbon sequestration Rate (CSR) of plantations on S_2 and S_4 land suitability classes in WL_3, IL_{1a} and DL_3

AER	LSC		Coconut palm	Grass cover	Soil	Ecosystem
WL_3	S_2	C stock (Mg C ha^{-1})	25.96 ± 1.73	1.45 ± 0.06	44.17 ± 0.88	71.57 ± 2.21
		GPP (Mg C ha^{-1} $month^{-1}$)	2.31 ± 0.25	nm		2.31 ± 0.25
		Resp (Mg C ha^{-1} $month^{-1}$)	0.782 ± 0.06	nm	0.778 ± 0.03	1.414 ± 0.08
		CSR (Mg C ha^{-1} $month^{-1}$)				0.90 ± 0.30
	S_4	C stock (Mg C ha^{-1})	18.73 ± 0.66	1.43 ± 0.06	35.54 ± 1.03	55.70 ± 1.13
		GPP (Mg C ha^{-1} $month^{-1}$)	2.88 ± 0.19	nm		2.88 ± 0.19
		Resp (Mg C ha^{-1} $month^{-1}$)	0.637 ± 0.02	nm	0.298 ± 0.06	0.936 ± 0.04
		CSR (Mg C ha^{-1} $month^{-1}$)				1.94 ± 0.17
IL_{1a}	S_2	C stock (Mg C ha^{-1})	24.48 ± 1.28	1.91 ± 0.06	37.89 ± 1.15	64.28 ± 1.55
		GPP (Mg C ha^{-1} $month^{-1}$)	2.07 ± 0.17	nm		2.07 ± 0.17
		Resp (Mg C ha^{-1} $month^{-1}$)	0.661 ± 0.08	nm	0.814 ± 0.03	1.475 ± 0.08
		CSR (Mg C ha^{-1} $month^{-1}$)				0.59 ± 0.21
	S4	C stock (Mg C ha^{-1})	24.89 ± 1.96	1.54 ± 0.06	19.05 ± 0.96	45.47 ± 1.94
		GPP (Mg C ha^{-1} $month^{-1}$)	2.08 ± 0.19	nm		2.08 ± 0.19
		Resp (Mg C ha^{-1} $month^{-1}$)	0.811 ± 0.06	nm	0.751 ± 0.02	1.562 ± 0.06
		CSR (Mg C ha^{-1} $month^{-1}$)				0.52 ± 0.25
DL_3	S_2	C stock (Mg C ha^{-1})	25.21 ± 1.17	0.86 ± 0.04	17.47 ± 0.68	43.53 ± 1.48
		GPP (Mg C ha^{-1} $month^{-1}$)	2.04 ± 0.14	nm		2.04 ± 0.14
		Resp (Mg C ha^{-1} $month^{-1}$)	0.958 ± 0.04	nm	0.349 ± 0.02	1.307 ± 0.03
		CSR (Mg C ha^{-1} $month^{-1}$)				0.73 ± 0.27
	S_4	C stock (Mg C ha^{-1})	17.09 ± 1.41	0.73 ± 0.03	14.15 ± 0.77	31.96 ± 1.80
		GPP (Mg C ha^{-1} $month^{-1}$)	1.19 ± 0.08	nm		1.19 ± 0.08
		Resp (Mg C ha^{-1} $month^{-1}$)	0.473 ± 0.05	nm	0.303 ± 0.03	0.789 ± 0.08
		CSR (Mg C ha^{-1} $month^{-1}$)				0.40 ± 0.19

nm: not measured

In addition to the factors studied here, net ecosystem C exchange or the C sequestration potential of coconut plantations (ecosystem) may vary with the age of plantation, cover crop, inter-crop, variety, type of management etc. *Gliricidia Sepium*, which has a higher CO_2 fixation rate than coconut, is recommended to grow under coconut plantations as a bio-fertilizer and a bio-fuel in all three AERs of Sri Lanka (Fernando & Jayalath, 2003; Gunathilake, 2004). Tea, banana, pineapple, cashew, cinnamon, cocoa and coffee are recommended to grow as intercrops in coconut plantations as it is more profitable to grow coconut as a multi-cropping system than a monocrop (Liyanage, 1999). For the sustainability of coconut plantations under stressed conditions, the soil fertility management is of utmost importance. In all six experimental sites, the soil organic carbon content and the soil microbial activity were higher in the manure circle (1.75 m away from the bole of the palm, mulched with coconut fronds and husks) than the centre of square where the sampling was done in the present study (data not presented). That clearly indicates the impact of management practices on the soil C stock and C sequestration potential of coconut plantations. Furthermore, growing leguminous cover crops improves soil organic carbon content, soil moisture holding capacity, soil microbial activity, soil fertility and finally the productivity of coconut plantations (Fernando, 1999; Dinesh *et al*., 2006). Also the palm water status and coconut yield in S_4 soils can be improved by surface mulching with coconut coir dust and irrigation (Ranasinghe *et al.,* 2003; Jayalath *et al.,* 2005; Nainanayake *et al*., 2008). Therefore, if the C sequestration data are available for different coconut-based ecosystems, the ecosystems with higher carbon sequestration indices can be screened for each land use so that those can be prioritized in new planting programmes. Therefore, work has already started to estimate the C sequestration potential of coconut based ecosystems and its impact on financial and economic viability of coconut plantations during its economic life span.

Simplifying assumptions made in the estimation of C balance

Our estimates of total C stocks, C input (GPP) and C output (respiration) and consequently the net C balance of the ecosystem were dependant on the following limitations and assumptions.

The results of this study were based on the data collected during a specific period in which a moderate rainfall and temperature was prevalent in major coconut growing areas (from May to September in 2009). However, the components of C balance (especially GPP and soil respiration) can vary with the environmental conditions (high rainfall, severe drought).

Total C stocks of the ecosystem

C stock in the roots of coconut and grasses were not taken into account due to practical difficulties in the measurements and unavailability of reliable historical data on root: shoot ratio. Soil C stock was limited to the depth of 0–20 cm and therefore, the C stocks in the soil layers deeper than 20 cm were not estimated in the present study.

Estimation of CO_2 input to the ecosystem (GPP)

A light response photosynthesis model to estimate daily total of CO_2 assimilation by the coconut palm canopy is not available at present. Therefore, monthly GPP of coconut palms was estimated by integrating daily photosynthetic assimilation measured as instantaneous rate of photosynthesis of three whorls of leaf canopy in the morning and afternoon during two consecutive days. It was assumed that these measurements represent the CO_2 assimilation rate per palm over a month. CO_2 uptake by the understorey grass cover was not taken in to account in the present study and hence, if the CO_2 uptake by grasses was also included in the GPP, the CO_2 uptake by the ecosystem would have been higher compared to the observed values in the present study.

Estimation of CO_2 output from the ecosystem (plant and soil respiration)

The growth and maintenance respiration of coconut root system and the shoot and root of grass cover were not taken into account in the study due to practical difficulties. Hence, if the root respiration parameters were also included in the R_{soil}, the CO_2 efflux from soil respiration would have been higher and net ecosystem C balance would have been slightly different compared to the observed values in the present study. Although the actual soil moisture levels under field conditions in the three AERs are different, the measurements of soil (microbial) respiration were taken at a similar moisture level *ex-situ* (incubation experiment under laboratory conditions). Therefore, the soil microbial respiration revealed in this study can be considered as the 'potential' rates that necessarily reflect the microbial population under *in situ* conditions due to soil moisture and temperature of different AER and LSC during this period (the equipment facilities for *in-situ* measurement of soil respiration were not available during the experimental period).

The carbon content of the dry mass of each plant component was assumed to be 0.5 g C g_{DM}.

CONCLUSION

The total C stock of a coconut plantation reduces along a decreasing moisture gradient and soil fertility gradient. Carbon input and output of the ecosystems do not reduce along the decreasing moisture gradient on highly suitable soils whilst the values reduce on moderately suitable soils. Consequently, coconut plantations under all six growth conditions have the potential to sequester carbon and the net carbon exchange rates were in the range of 0.4 –1.9 Mg C ha^{-1} $month^{-1}$.

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