# LONG-TERM MONITORING OF NET ECOSYSTEM FLUX RATES OF $CO_2$ AND WATER VAPOUR IN A NATURAL RUBBER PLANTATION USING THE EDDY COVARIANCE TECHNIQUE

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Using the eddy covariance (EC) technique, flux of $CO_2$ and water vapour was continuously monitored for six years in a natural rubber plantation grown in central Kerala. The study period covered both immature and mature stages of the rubber trees (from $4^{th}$ to $9^{th}$ year of growth). The mean rate of $CO_2$ sequestration during the entire study period was 9.2g $CO_2$ $m^{-2}$ $day^{-1}$, equivalent to 33.6 tons $CO_2$ $ha^{-1}$ $yr^{-1}$. These rates were largely in agreement with the results obtained through the biomass inventory method. The highest rate was seen when the trees were in $5^{th}$ to $7^{th}$ year of growth, possibly indicating that this was the peak growth phase. As expected, it was evident that sequestration rates were the highest during those seasons of the year when sunlight was abundant and soil moisture was not deficient.

The mean rate of water loss through evapo-transpiration of water was 3.2 mm $day^{-1}$ and the ecosystem level mean water use efficiency ($WUE_{NEP}$) was 3.0g $CO_2$ $kg^{-1}$ water. Implications of the high rate of $CO_2$ sequestration of rubber plantations are discussed in the context of mitigating climate change. Similarly, the relevance of high WUE of rubber trees is discussed in the context of expanding rubber cultivation to newer and non-traditional areas where annual rainfall is lower than in the traditional regions.

**Keywords**: Biomass, $CO_2$ flux, Carbon sequestration, NEE, Rubber plantation, Water Use Efficiency

## INTRODUCTION

Terrestrial ecosystems are major repositories of atmospheric $CO_2$ (Keenan and Williams, 2018) and there is much more carbon stored in the soil than in the biomass of vegetation (Ontl and Schulte, 2012). It has been shown that actively growing managed ecosystems can have higher rates of carbon sequestration than many natural ecosystems (Sommer and Bossio, 2014; Epple *et al.*, 2016). For example, the Amazon forests normally have a carbon sequestration rate of 3-6 tons

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$CO_2$ $ha^{-1}$ $yr^{-1}$ while managed ecosystems such as farm forestry systems with multiple species of trees have a sequestration rate of 10-11 ton $CO_2$ $ha^{-1}$ $yr^{-1}$ (NASA, 2003; Chinsu and Chun-Hsiung, 2013). Many natural forests, including the Amazon forests do not have a remarkably high net rate of $CO_2$ sequestration compared to managed plantations as these forests have already reached their peak growth level. The Amazon forests are known to be net emitters of $CO_2$ during certain years when there is prolonged drought and high temperature. Much more catastrophic is the increasing frequency of incidence of wildfires happening in recent times that result in the release of huge amounts of $CO_2$ stored in the biomass of forests and other native vegetation into the atmosphere (Nobre *et al.*, 2016).

It is estimated that nearly 23 per cent of global emission of greenhouse gases is from agriculture and land use changes (IPCC, 2019). Houghton (2003) estimated that around 148.6 Pg C (Pg or petagrams = $10^{15}$ g) have been added to the atmosphere as a result of land use changes mainly due to the conversion of forest lands into agricultural land or new habitat developments. Carbon sequestration activities can help prevent global climate change by enhancing carbon storage in trees and soils (Bhadwal and Singh, 2002). Afforestation and reforestation programmes are actively promoted to mitigate rising concentration of $CO_2$ in the atmosphere and thus combat climate change (Chazdon and Brancalion, 2019) even as it is clear that this strategy alone is extremely inadequate to fully offset the anthropogenic emission of $CO_2$ and its rising concentration in the atmosphere (Marshall, 2020).

In this context, scientific information about the carbon sequestration potentials of various land use options assumes importance. Oxidation of the biomass either through the burning of biomass such as hay and other plant debris or through their natural decomposition in the soil at the end of the crop cycle as is the case with annual crops releases the carbon stored in the biomass back into the atmosphere. Therefore, unlike seasonal and annual crops, by virtue of their perennial nature $CO_2$ sequestered by tree plantations such as natural rubber (*Hevea brasiliensis*) is more permanent.

Biomass inventory method is commonly used for accounting the total amount of carbon stored in plant biomass, including natural rubber (Jacob, 2005; Annamalainathan and Jacob, 2019). These studies rely on allometric relations to scale incremental changes in the diameter of the tree trunk at breast height which is used to predict the biomass from which the amount of carbon stored in the trees is estimated. In this method bias may be introduced mainly due to omission of estimates of understory vegetation, carbon allocated below ground in root system and carbon exchange from the soil (Clark *et al.*, 2001). Eddy covariance (EC) technique is a more refined and precise method by which net rate of flux in $CO_2$ and water vapor can be measured in real time at the landscape level (Baldocchi, 2003). In an earlier study we measured the $CO_2$ and water vapour fluxes in an immature rubber plantation for a period of two years (4-5 years old plantation) and it was shown that the annual average net ecosystem exchange of $CO_2$ (NEE) was 11g $CO_2 m^{-2}$ $day^{-1}$ clearly indicating that rubber plantation is a potential sink for atmospheric $CO_2$ (Annamalainathan *et al.*, 2011). In the present study the carbon flux rates obtained for a continuous period of six years covering both the immature and mature phases of a rubber plantation using the EC technique were compared with carbon sequestration potentialof the same plantation calculated based on biomass inventory method and found concurrence with each other. Landscape level water use efficiency of rubber plantation was also estimated in the present study.

## MATERIALS AND METHODS

### Eddy covariance technique for atmospheric flux analysis

Ecosystem level carbon dioxide (Fc) and water vapour fluxes (LE) of a rubber plantation were continuously measured for a period of six years by eddy covariance (EC) technique (Baldocchi, 2003). The rubber plantation was spread over more than 5 ha at the Central Experimental Station (CES) of Rubber Research Institute of India (RRII), Chethackal, Pathanamthitta District, Kerala (9° 26′N and 76° 48′E). The study area had different clones namely RRII 105, PB 260, RRII 430 and a few ortet clones. Latex was harvested from these trees when they attained a girth of 50 cm (150 cm above the bud union). The rubber trees were four year old when the observations began and when the experiment was over after six years, the average height of the trees was around 12 m and girth was 55 cm. An 18 m tall tower was erected in the middle of the rubber plantation on which various sensors of the EC apparatus were mounted at 4 m above the canopy. The description of EC technique, different sensors used, measurement of fluxes, data analysis and various correction factors required are explained elsewhere in our previous publication (Annamalainathan *et al*., 2011). General daily weather measurements namely rainfall, maximum and minimum temperatures, sunshine hours, *etc*. were collected from the nearby RRII weather station at CES, Chethackal.

### Accounting of tree biomass

The dry weight of above ground biomass was calculated using the Shorrock's regression model:

$$W= 0.002604\ G^{\wedge 2.7826}$$ (Shorrocks, 1965)

Where, G is trunk girth (cm) at the height of 150 cm from bud union.

Generally, root biomass was taken as 15-20 per cent of the shoot biomass. The amount of carbon stored in the trees was calculated from biomass increment of the trees and assuming that between 40 and 45 per cent of the dry biomass was carbon (Malhi *et al.,* 2001).

## RESULTS AND DISCUSSION

### $CO_2$ and water flux in rubber plantation

Daily flux of $CO_2$ (Fig. 1), sunlight intensity (Fig. 2a and 2b) and water vapor (Fig. 3) followed the typical expected diurnal pattern. $CO_2$ and water vapor fluxes increased in tandem with rising sunlight intensity in the morning hours, reached a peak by noon and declined to near-zero levels by early evening. There was a clearly discernible net efflux of $CO_2$ from the landscape in the night indicating night respiration of vegetation and soil, including possible release of $CO_2$ from decomposition of organic matter (Fig. 1), but this was only a small fraction of the total amount of $CO_2$ fixed during the day. On an average, the night respiration loss of $CO_2$ from the ecosystem was 2.3g $CO_2 m^{-2} day^{-1}$ and the net day time fixation was 11.5 g $CO_2$ $m^{-2}$ $day^{-1}$. There was a small but detectable quantity of water loss in the night (Fig. 3) reflecting night transpiration from the vegetation and surface evaporation from soil. On an average this rate was 0.3 mm as compared to an average rate of ecosystem water loss of 3.2 mm during the day. From the present data, it is not possible to partition the rate of water loss from the landscape between night transpiration by the rubber trees and evaporation from the soil surface. The night

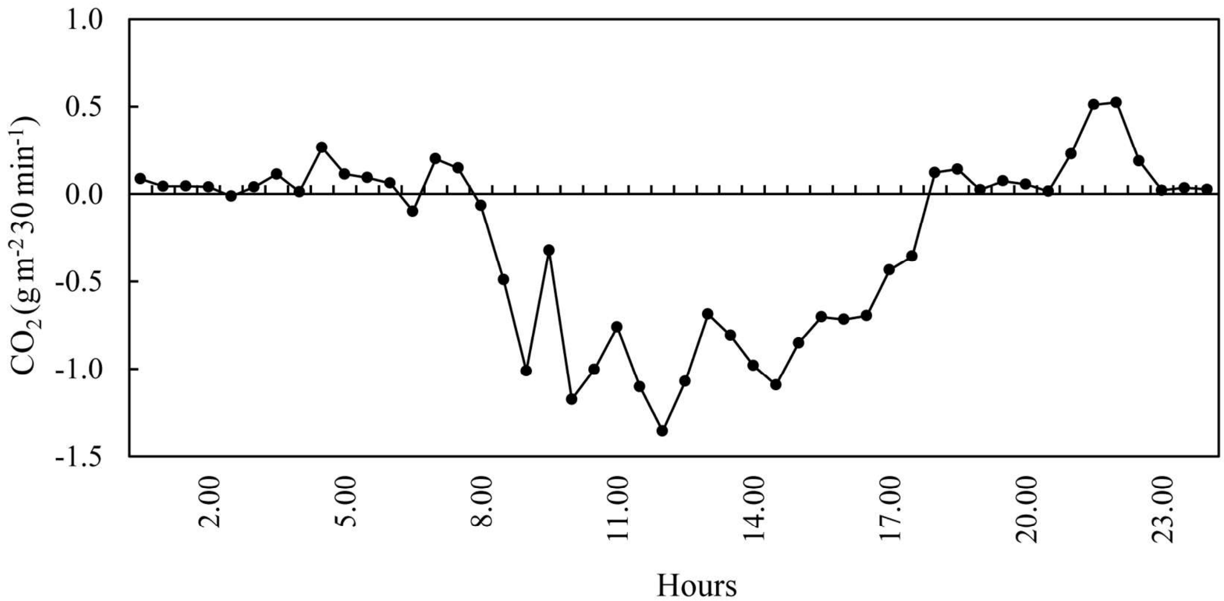


Fig. 1. Typical diurnal $CO_2$ flux in a rubber plantation grown in the traditional rubber growing region

time loss of water when there is no $CO_2$ fixation happening has implications for the water balance and water use efficiency of the ecosystem. A species that has more night transpiration is obviously not a desirable candidate for large scale planting in afforestation projects, particularly in areas where annual rainfall is poor. The present study indicated that nighttime water loss from rubber plantation was scanty

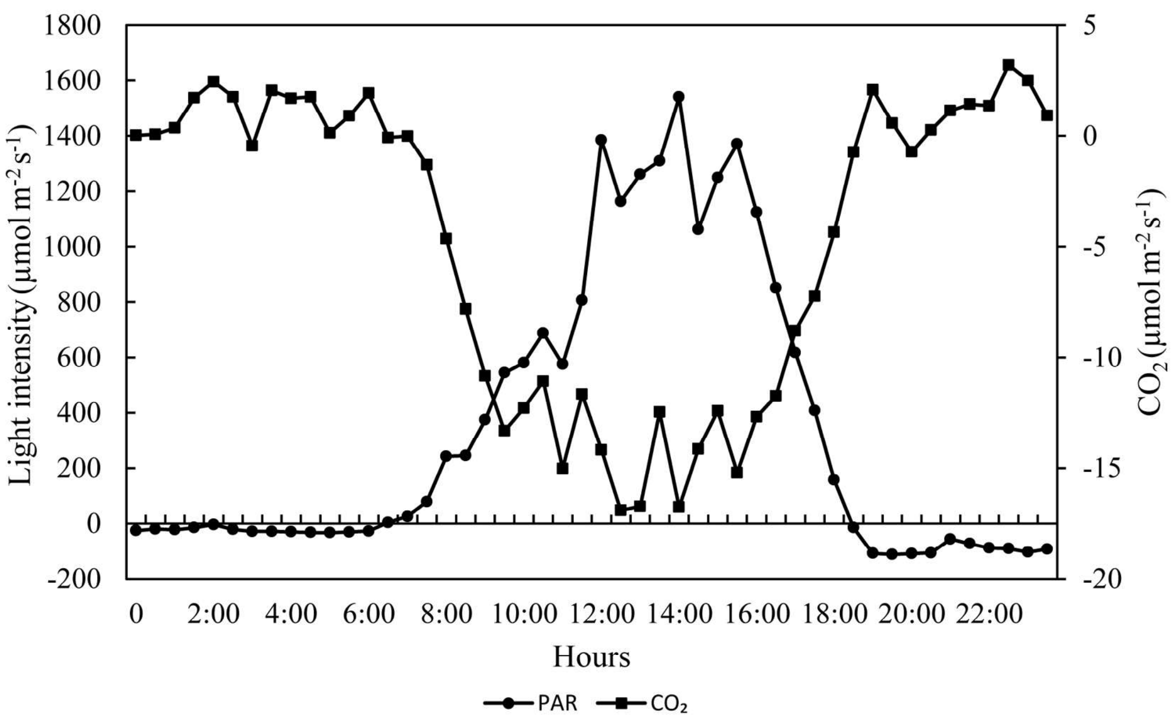


Fig. 2a. Diurnal sunlight intensity and canopy level $CO_2$ assimilation in a mature rubber plantation

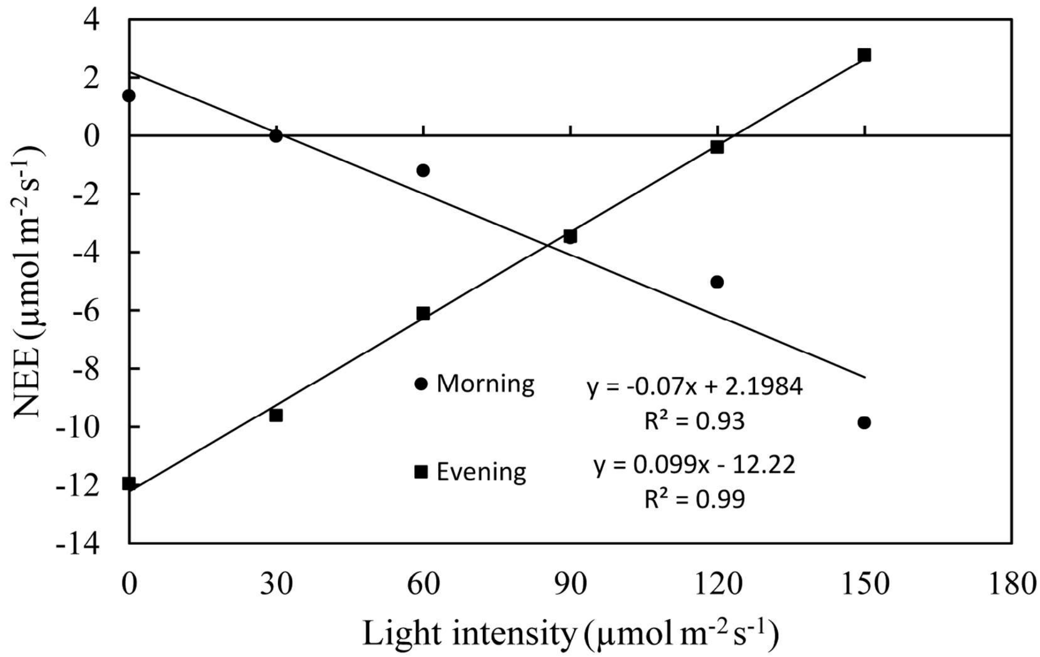


Fig. 2b. Relationship between light intensity during sunrise and sunset hours and Net Ecosystem Exchange of $CO_2$ in natural rubber plantation

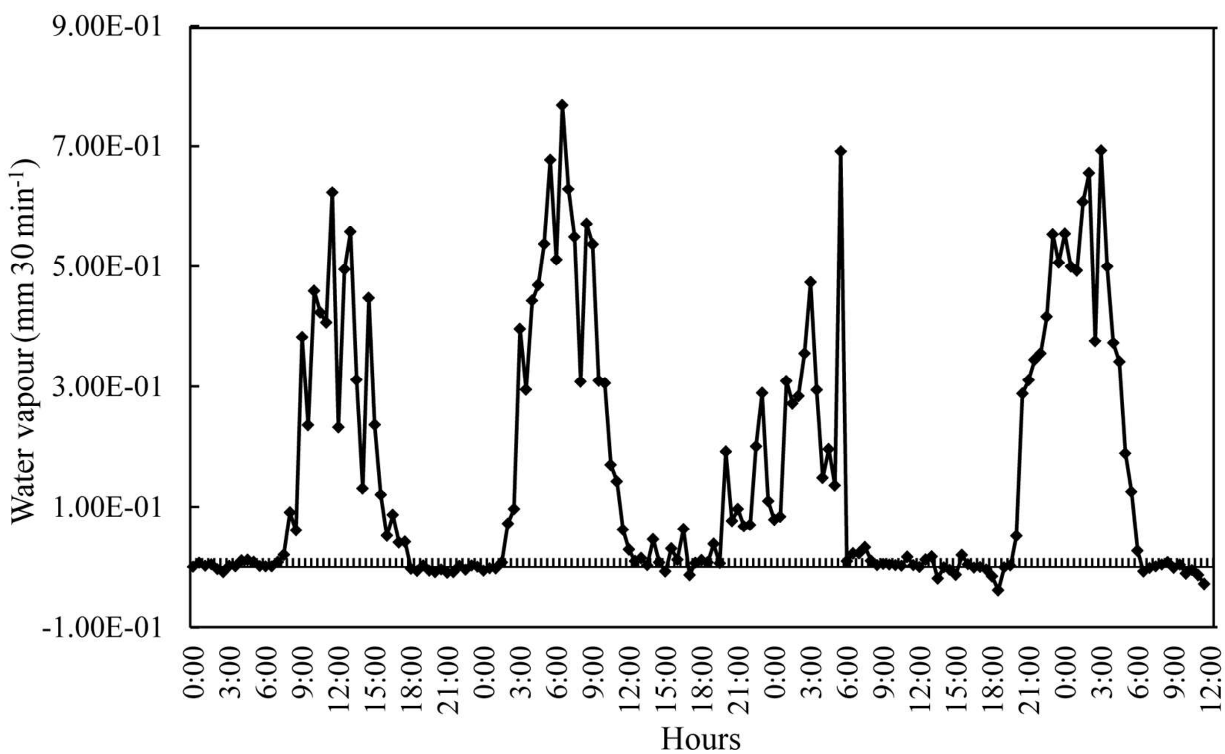


Fig. 3. Diurnal water vapour flux in the canopy of a mature rubber plantation

compared to day time ecosystem level evapotranspiration.

The dominant vegetation in the study site was natural rubber trees. But there were also other plants such as *Clidemiahirta*, *Centrosema pubescence*, *Lantana camera*, *Alternanthera braziliana*, *Cynodondactylon*, *Cenchruspurpureus etc*. that were growing in the field as weeds. The leguminous cover crop, *Pueraria phaseoloides* that was established in the immature phase of the plantation was not present during mature phase of the study period. In terms of the total standing biomass at the study site, the rubber trees accounted for more than 90 per cent. Since rubber trees were the dominant vegetation, it is concluded that most of the net $CO_2$ exchange of the ecosystem was contributed by these trees.

Almost on every day during the study period, the rubber plantation was a net sink of $CO_2$. However, on some days when the sky was mostly overcast, there was net emission of $CO_2$. Considering the entire study period, the rubber plantation acted as a significant sink of atmospheric $CO_2$. While the mean Reco (Ecosystem respiration) was 2.3g $CO_2$ $m^{-2}$ $day^{-1}$, the net rate of ecosystem exchange (NEE) was 9.2g $CO_2$ $m^{-2}$ $day^{-1}$ for the whole study period. These observations clearly indicated that the net $CO_2$ influx (*i.e.* photosynthetic $CO_2 m^{-2}$ $day^{-1}$ assimilation rate) was higher than the respiratory $CO_2$ efflux in the natural rubber ecosystem. The mean sequestration rate of the plantation was equivalent to 33.6 tons $CO_2 ha^{-1}$ $yr^{-1}$ and the range was 5- 14 g $CO_2$ $m^{-2}$ $day^{-1}$ (Fig. 4). The data showed that there was a slight decline in NEE in mature trees which was around 8.7 g $CO_2$ $m^{-2}$ $day^{-1}$, equivalent to 31.8 tons $CO_2$ $ha^{-1}$ $yr^{-1}$ (Fig 5a). This might be attributed to gradual plateauing of the growth curve of the rubber trees (Fig 5b), vanishing of the understory vegetation due

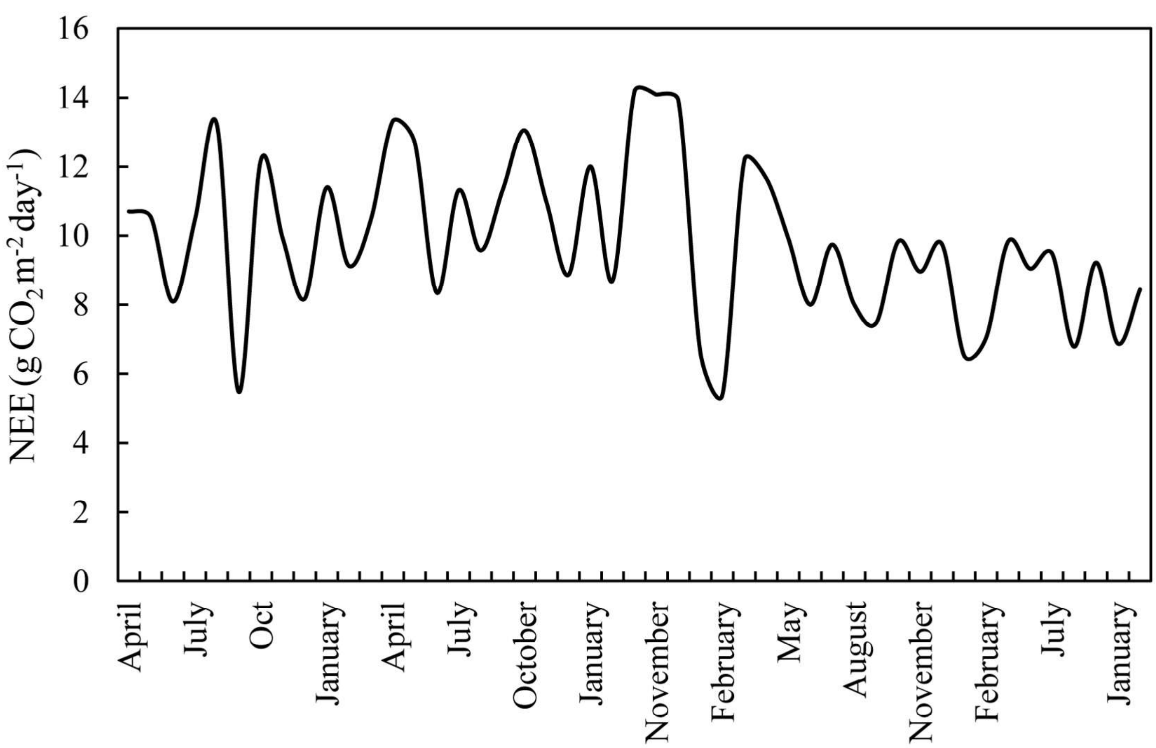


Fig. 4. Daily average NEE of $CO_2$ in an immature to mature rubber plantation (4th year to 9th year)

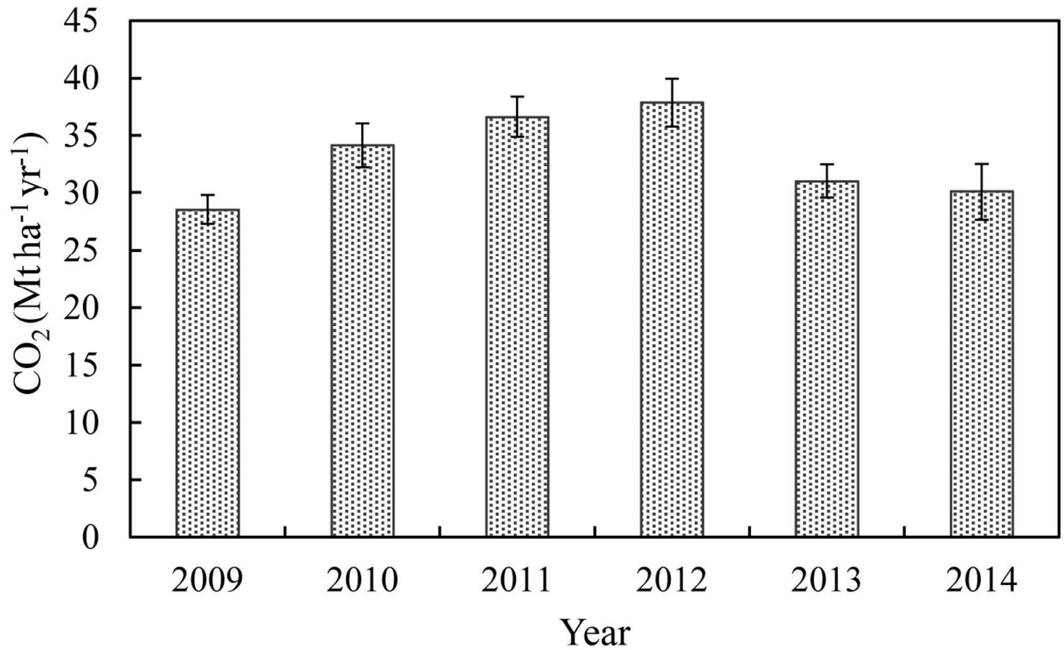


Fig. 5a. Annual NEE (Net Ecosystem Exchange of $CO_2$) projected for one hectare area estimated from eddy covariance flux data for six years in an immature (untapped 2009-2012) to mature rubber plantation (trees under latex tapping 2013 and 2014)

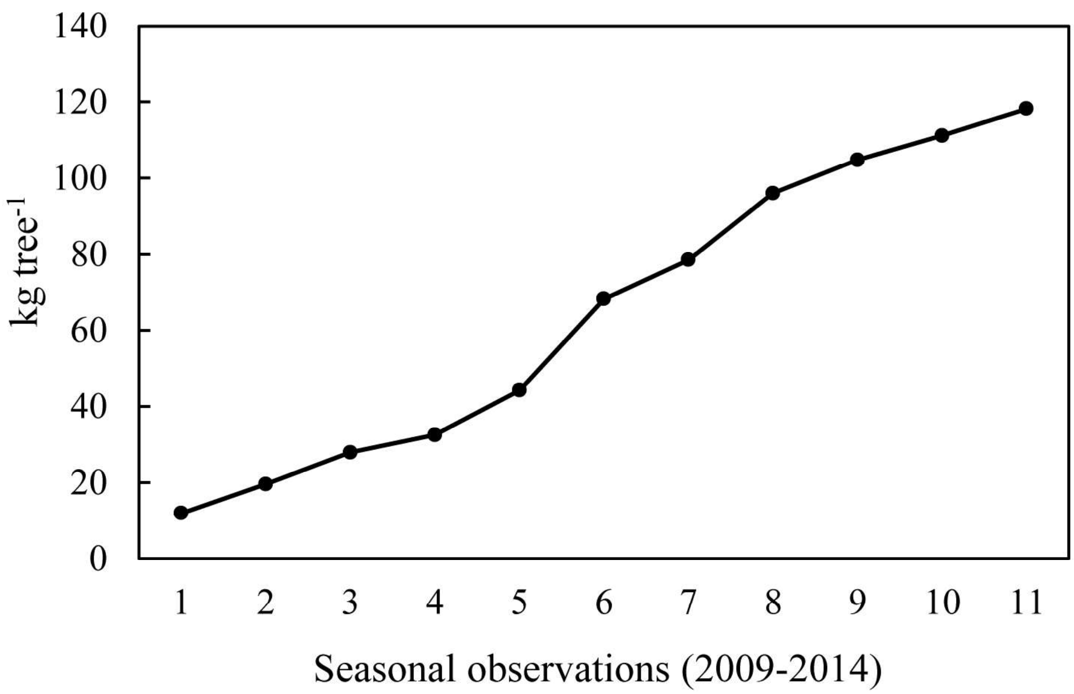


Fig. 5b. Seasonal shoot biomass increase in an immature ($4^{th}$ year) of planting to mature rubber plantation ($9^{th}$ year) at CES, Chethackal

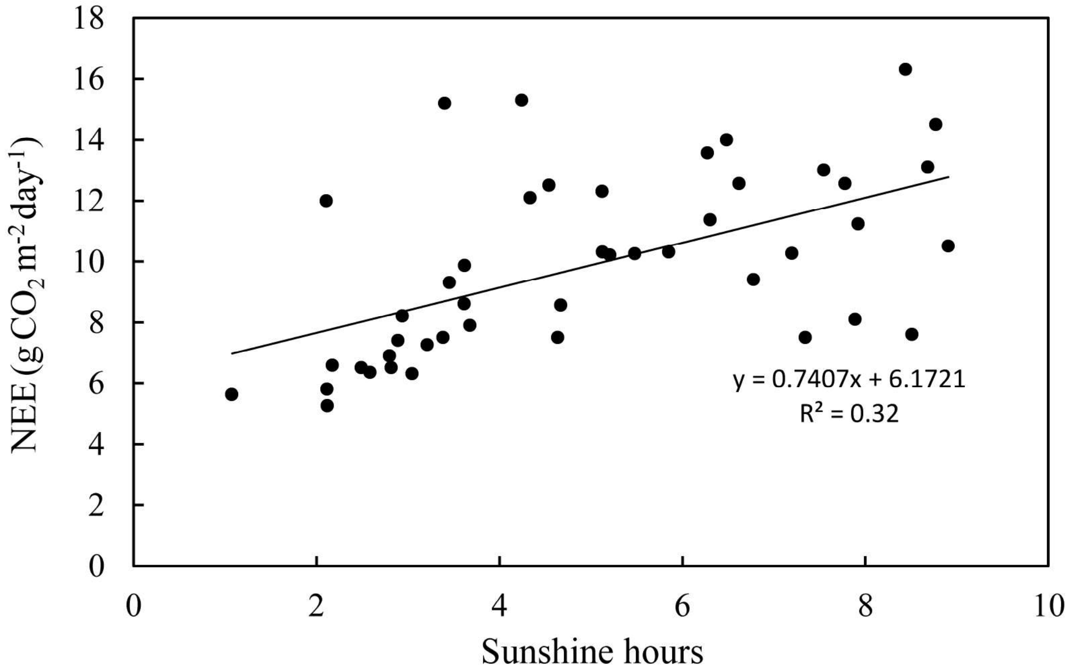


Fig. 6. Relationship between mean NEE and Sunshine hours in a mature rubber plantation

to increasing shade under the mature rubber trees or variations due to climatic reasons. Hence, this observation cannot be interpreted as an effect of tapping the mature trees.

The evapo-transpiration (ET) at the landscape level was calculated from latent heat of vapourization (LE) as net evaporative water loss from the rubber plantation per day during the study period. Mean ET was 3-4 mm day$^{-1}$ and this included water lost through transpiration from the rubber trees and the understory vegetation and evaporation from the soil surface (Fig. 3).

A closer analysis revealed that when sunlight intensity decreased during the course of the day due to normal diurnal changes or due to clouds, $CO_2$ sequestration was immediately reduced, and ecosystem water loss declined rather slowly. Ecosystem carbon exchange declined during sunset much faster than it increased in the morning during sunrise (Fig. 2b). In an earlier study, we found that the rate of water mining by rubber trees (estimated based on xylem sap flow measurements) did not decline concurrently with declining light intensity for a long time after the trees have started experiencing a shaded condition and during sunset hour in the evening and the rate of decline in xylem sap flow (water mining by the trees) during sunset was much slower than the rate at which it increased during sunrise (Annamalainathan *et al.*, 2013). Therefore, transient shading of canopy due to cloud movements *etc.* leads to reduction in water use efficiency because of greater decrease in $CO_2$ fixation than transpiration at the level of whole plant. As expected, there was a close association between canopy level $CO_2$ sequestration and sunshine hours (Fig. 6). Apart from sunshine hours and sunlight intensity, availability of soil moisture, VPD

Table 1. **Canopy level mean water use efficiency (WUE) in a rubber plantation in the traditional rubber growing region**

| | Net ecosystem exchange of $CO_2$ (NEE) ($g\ m^{-2}\ day^{-1}$) | Evapotranspiration ET ($mm\ day^{-1}$) | Ecosystem level $WUE_{NEP}$ $g\ CO_2\ kg^{-1}\ H_2O$ |
|---|---|---|---|
| January | 8.5 ±0.60 | 2.4 ±0.12 | 3.5 |
| February | 7.6 ±0.56 | 2.3 ±0.20 | 3.3 |
| March | 10.8 ±0.70 | 3.1 ±0.13 | 3.5 |
| April | 11.8 ±0.45 | 3.9 ±0.15 | 3.0 |
| May | 11.4 ±0.50 | 3.5 ±0.13 | 3.3 |
| June | 8.5±0.54 | 3.8 ±0.12 | 2.2 |
| July | 10.9 ±0.80 | 3.6 ±0.12 | 3.0 |
| August | 10.6 ±0.74 | 3.3 ±0.14 | 3.2 |
| September | 8.4 ±0.65 | 3.0 ±0.20 | 2.8 |
| October | 12.1 ±0.56 | 3.1 ±0.18 | 3.9 |
| November | 10.3 ±0.90 | 2.5 ±0.15 | 4.0 |
| December | 9.3 ±0.50 | 2.6 ±0.15 | 3.6 |

*etc*. are also important factors determining both $CO_2$ sequestration and water loss during different seasons of the year.

**Landscape level water use efficiency**

Water use efficiency (WUE) is defined in different ways. From a physiological perspective, it is the ratio of the number of moles of carbon fixed by the leaf through photosynthesis per unit amount of water transpired by the leaf. From an agronomic point of view, WUE can be better defined as the ratio of the total amount of biomass or economic yield harvested to the cumulate amount of water consumed by the crop from sowing to harvest (Medrano *et al*., 2015). From a broader ecological perspective, it is the amount of $CO_2$ sequestered per unit amount of water lost from a given landscape (Hatfield and Dold, 2019). In the present study, we estimated the landscape-level WUE of the rubber plantation for the entire period of the study and this was 3.0g $CO_2$ $kg^{-1}$ $H_2O$ (Table 1). This was comparatively less during the south west monsoon season indicating low rate of canopy level $CO_2$ assimilation (possibly due to limiting sunlight intensity) per unit amount of transpiration during intensive rainy days. Landscape-level WUE of rubber plantations is better than many other ecosystems like grasslands, conifers and other plantation crops (Tong *et al*., 2019; Annamalainathan *et al*., 2020). Tree and forest ecosystems generally have higher WUE than cultivated annual crops and grasslands (Hatfield and Dold, 2019). It is highly desirable to consider the WUE aspect of rubber plantations when rubber cultivation is expanded to newer areas in the country, particularly to regions where water is relatively scarce. It is predicted that water will become an increasingly limiting factor for crop growth and productivity in the decades ahead. In a perennial tree crop like natural rubber whose economic life cycle is as long as 25-30 years, WUE should be an important consideration while planning expansion of its cultivation.

This assumes greater relevance in the context of the general presumption among many that rubber tree is a water guzzler.

**Biomass inventory method**

The amount of carbon sequestered by the rubber trees was estimated by accounting the annual shoot biomass increment (Shorrocks, 1965). According to this method, the $CO_2$ sequestration in tree shoot biomass was around 22-25 ton $CO_2$ $ha^{-1}$ $yr^{-1}$ for the entire study period (excluding the carbon present in the rubber harvested from the trees and biomass of the roots of the rubber trees and sequestration by other vegetation present inside the rubber plantation). Considering that about 20 per cent of the total biomass of rubber trees is present in the roots, the mean rate of carbon sequestration by the rubber trees comes to nearly 26.4 to 30 ton $ha^{-1}yr^{-1}$ which is close to the rate measured through the EC method (Fig 5a). An earlier biomass inventory study involving different clones showed that a mature stand of rubber plantation converted almost 20-30 tons $CO_2$ $ha^{-1}$ $yr^{-1}$ into shoot biomass and rubber yield (Annamalainathan *et al*., 2020). The total amount of carbon sequestered during the entire life cycle of a 25 year-old rubber plantation was worked out to be 142 tons C $ha^{-1}$ using the biomass inventory method (Jacob, 2003). According to Sivakumaran *et al*., (2000) rubber plantation can sequester around 139 to 318 tons C $ha^{-1}$over a life cycle of 27 to 29 years. Based on EC study, the net ecosystem exchange in an immature rubber plantation was 9-11g $CO_2$ $m^{-2}$ $day^{-1}$ which is equivalent to around 34 tons of $CO_2$ $ha^{-1}$ $yr^{-1}$ (Annamalainathan *et al*., 2011). In another study the above ground and below ground biomass of rubber trees was estimated through destructive method and it was found that the rate of carbon sequestration was around 27.5 MT $CO_2$ $ha^{-1}$ $yr^{-1}$ (Ambily and Ulaganathan, 2015). A life cycle analysis of a rubber cultivation indicated high organic carbon content in rubber soils (Blagodatsky *et al*., 2016). There was a decline in the organic carbon content of the soil during the immature period of rubber as the soil was exposed to direct sunlight that caused accelerated oxidation of the organic matter or as a result erosion of the top soil. But this was recouped when the trees matured (Abraham and Philip, 2017). The present results indicate that carbon buildup in the soil was the result of high rate of $CO_2$ sequestration by the rubber trees.

In conclusion, results of the present study based on continuous field measurements for six years establish the high rates of $CO_2$ sequestration and water use efficiency by rubber plantations and these findings have important ecological implications. While planting rubber or other trees may not be adequate to fully offset the current rate of increase in the concentration of $CO_2$ in the atmosphere, it should not escape the attention of policymakers that increased use of synthetic rubbers in place of natural rubber will lead to more emission of $CO_2$ as the former comes with a much larger carbon footprint (George *et al.*, 2006). Allowing natural or cultivated plants to thrive in the understory of mature rubber plantations as in the case of a homestead is known to improve the microclimate and soil conditions even as growth and productivity of rubber trees are unaffected (Hoffner, 2021; Jessy *et al*., 2017) and these vegetations also will positively contribute towards carbon sequestration of the entire ecosystem.

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