on each other as well as on plant productivity[16]. The present study recommends the use of co-inoculants as ecofriendly multipurpose bioinoculants. Development of such co-inoculants not only increases the fertility of soil, but they also act as PGPR or antagonists against phytopathogens, i.e. a bioinoculant with triple action.

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# Seasonal variability in soil-surface $CO_2$ efflux in selected young tree plantations in semi-arid eco-climate of Madurai

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The response of soil respiration (SR) to varying soil temperature and soil moisture was studied in three-year-old plantation sites of *Dalbergia sissoo, Dalbergia latifolia, Albizia lebbeck, Hardwickia binata* and *Cassia siamea* during 2005–06. Significant seasonal differences in SR rates were observed in each site ($P \leq 0.001$). The highest rates of soil $CO_2$ efflux were generally found during the rainy season and the lowest during summer in all the study sites. Highest SR rates were found in *D. sissoo*, $9.89 \pm 0.78\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ in November and December, followed by *H. binata*, $9.68 \pm 0.45\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ in September and October 2005, *A. lebbeck*, $8.84 \pm 0.43\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ between November 2005 and January 2006, *D. latifolia*, $7.6 \pm 0.12\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ in November and December 2005 and *C. siamea*, $7.3\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ in December 2005. There was a positive and significant ($P \leq 0.001$) relationship between SR rates and soil moisture in all the sites ($r^2$ above 0.60), except *C. siamea* ($r^2 = 0.30$). A poor relationship was observed between SR and soil temperature in all the sites ($r^2$ below 0.2). Examination of the seasonal pattern of SR rates suggests that much of the variability could be attributed to variations in soil moisture. There was a strong indication suggesting that the soil-water deficits served to reduce SR rates during summer and after subsequent rain events. Overall sensitivity of SR rate to soil moisture seems to be good for this semi-arid ecosystem.

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ATMOSPHERIC $CO_2$ concentrations have been increasing in response to the disruption of the global carbon cycle by anthropogenic activities such as deforestation, agricultural practices and burning of fossil fuels. This has resulted in large shifts among carbon pools[1]. The efflux of $CO_2$ from soil results from the combined rates of autotrophic (root) and heterotrophic (microbial and soil fauna) respiration. It is often called 'soil respiration' (SR). Globally, SR comprises a release of carbon to the atmosphere of approximately 80 Pg C $yr^{-1}$, to which the largest contributions come from tropical and subtropical broad-leaved forests[2]. This is 30–60 Pg C $yr^{-1}$ greater than the net primary productivity (NPP)[3]. While together these and other terrestrial ecosystems show significant inter-annual variability in gross primary productivity[4], the relative variation of global SR is lower, responding (globally) less strongly to water than to temperature[2]. Studies on soil carbon have received much attention because a small change in the soil carbon pool may significantly affect the global carbon cycle and climate system[5]. Therefore, SR is a major pathway for carbon to move from the terrestrial ecosystem to the atmosphere and even small changes can strongly influence the net ecosystem production (NEP)[6]. It is considered likely that global warming will increase SR, releasing more $CO_2$ that will further exacerbate warming as a large response to small climate changes[7]. Soil processes in arid and semi-arid lands have received considerably less attention, partly because of the relatively small organic C pools and fluxes in these regions[3]. Arid and semi-arid lands cover as much as one-third of the earth's surface[8], and the extent of arid and semi-arid lands may increase in response to climate change[9]. While large amounts of inorganic C are typically stored in soils in arid and semi-arid ecosystems, organic C pools are small[10]. Since organic matter C pools are so small, West et al.[11] concluded that soil organic C pools are a feature of arid and semi-arid lands that are sensitive to climate change.

As a result of climate change and the increasingly recognized importance of the role of soils now and in the future, more efforts are being put into making better estimates of soil $CO_2$ efflux and to improve our understanding of the interactions between environmental variables and SR[12]. Despite the global significance as well as considerable scientific commitment to studies in this field over the past decades, there is still limited understanding of the factors controlling temporal and spatial variability of SR[13]. However, the relationships between SR and the two environmental variables, namely soil moisture and soil temperature vary in different ecosystems[1]. This variability calls for more measurements of SR to explore its environmental dependence on a regional scale. Detailed information on soil $CO_2$ fluxes and on factors that control these fluxes are needed to decide whether or not terrestrial ecosystems are carbon sinks or sources[14]. In semi-arid climate soils, the establishment of a plant cover is fundamental to avoid degradation and further desertification processes due to global warming. Much of the semi-arid and wastelands are converted to plantation sites[15]. Many studies revealed that the SR may vary with vegetation[16] and at the same time different plant communities frequently demonstrate differences in SR[17]. Uncertainties in the factors controlling SR in semi-arid ecosystems along with the likely increase in SR due to global warming, and how different plantation sites respond over a period prompted an experiment to: (i) observe seasonal variations of SR in these plantation sites and (ii) examine the relationship of SR with temperature and moisture.

The study was carried out in 2.5 ha area consisting of three-year-old plantations of *Dalbergia sissoo, Dalbergia latifolia, Albizia lebbeck, Hardwickia binata* and *Cassia siamea*. The plantation sites are located at the Biomass Research Centre, Madurai Kamaraj University, about 13 km west of Madurai. The study area is semi-arid and most of the rainfall occurred in November and December during 2005–06. However, there were also a few showers during October and rest of the study period (2005–06). The mean maximum temperature ranged between 29.5 and 43.6°C and minimum between 25 and 27.8°C. The soil at the site is lateric loam, with pH 8.5.

The SR was measured using the Licor 6400-09 soil $CO_2$ flux chamber. Before starting the measurement, ambient $CO_2$ concentration at the soil surface was measured. Once the chamber was installed, the $CO_2$ scrubber was used to draw $CO_2$ in the closed system down below the ambient concentration. When the scrubber was turned-off, soil $CO_2$ flux caused the $CO_2$ concentration in the chamber headspace to rise. Data were logged while the $CO_2$ concentration rose through the ambient level. The measurement cycles were repeated in various plantation sites.

A soil collar with a height of 4.4 cm and a diameter of 10.6 cm was inserted into the soil at each sampling spot. The collars were installed 24 h prior to the start of recording the measurements. The soil respiration chamber was set on top of these collars, allowing an undisturbed measurement of soil $CO_2$ flux rates. Soil $CO_2$ efflux was sampled in all the sites on three consecutive days in a month in each plot from May 2005 to April 2006. In each plantation site, six plots were randomly selected. Each measurement includes approximately 6–8 values.

Soil temperatures (0–10 cm depth) were measured next to each collar with a soil temperature probe connected to the Li 6400, along with $CO_2$ evolution measurements. Soil moisture was determined by gravimetric method. Thus, soil samples (0–5 cm) were collected from the plots in which SR measurements were made, weighed and oven-dried at 105°C to constant weight and weighed again.

Analysis of variance (one-way Anova) was performed to test the significance of differences in seasonal means of soil respiration rate, soil temperature and soil moisture. Linear regression analysis was carried out to examine the relationships between (i) soil $CO_2$ efflux and soil temperature, and (ii) soil $CO_2$ efflux and soil moisture.

The maximum soil $CO_2$ flux was observed in the plantation sites of *D. sissoo*, $9.89 \pm 0.78$ μmol m$^{-2}$ s$^{-1}$ in November and December 2005 followed by *H. binata*, $9.68 \pm 0.45$ μmol m$^{-2}$ s$^{-1}$ in September and October 2005, *A. lebbeck*, $8.84 \pm 0.43$ μmol m$^{-2}$ s$^{-1}$ between November 2005 and January 2006, *D. latifolia*, $7.6 \pm 0.12$ μmol m$^{-2}$ s$^{-1}$ in November and December 2005 and *C. siamea*, $7.26$ μmol m$^{-2}$ s$^{-1}$ in December 2006 (Figure 1).

The minimum rates of soil $CO_2$ efflux were observed during summer (March–May). It was $1.60 \pm 0.36$ μmol m$^{-2}$ s$^{-1}$ in the *D. sissoo* site, followed by $2.11 \pm 0.03$ μmol m$^{-2}$ s$^{-1}$ in the *C. siamea* site, $2.47 \pm 0.08$ μmol m$^{-2}$ s$^{-1}$ in the *A. lebbeck* site, $2.64 \pm 0.025$ μmol m$^{-2}$ s$^{-1}$ in the *H. binata* site and $3.047 \pm 0.5$ μmol m$^{-2}$ s$^{-1}$ in the *D. latifolia* site.

*D. latifolia* and *H. binata* sites showed a slightly different pattern in which SR rates declined from May to July, whereas there was an increase in SR rates in other plantation sites.

Both soil temperature and soil moisture content varied markedly with season. Maximum temperatures coincided with minimum water content in the summer and minimum temperatures were recorded during the rainy months when soil moisture was maximum (Figure 1). In order to analyse the effect of soil moisture and soil temperature, these two parameters were regressed against soil respiration (Figure 2).

Soil temperature varied in all the study sites, but was not statistically significant. In general, soil temperature was high during the start of the experiment in May 2005 and steadily decreased until the rainy season from October through December, reaching its minimum and then gradually increased through winter season until it reached a maximum in summer. Significant ($P < 0.001$) but weak correlation was observed between soil $CO_2$ efflux and soil temperature in all the study sites: *D. sissoo* ($r^2 = 0.16$), *D. latifolia* ($r^2 = 0.17$), *A. lebbeck* ($r^2 = 0.19$), *C. siamea* ($r^2 = 0.05$) and *H. binata* ($r^2 = 0.009$).

Soil moisture content over 0–5 cm depth ranged from 34% during the rainy season to 0.88% in summer. Soil moisture was low during summer, and below 3% from March until September. However, after the rains it increased sharply. Significant ($P < 0.001$) positive correlation was observed between soil $CO_2$ efflux and soil moisture in all the study sites: *A. lebbeck* ($r^2 = 0.70$), followed by *D. sissoo* ($r^2 = 0.67$), *D. latifolia* ($r^2 = 0.66$) and *H. binata* ($r^2 = 0.61$), whereas for *C. siamea* ($r^2 = 0.35$; $P = 0.043$).

Soil respiration together with soil temperature and soil moisture showed significant seasonal variations ($P \leq 0.001$) in all the study sites. In general, soil $CO_2$ efflux declined

during dry summer months and increased sharply with rainfall events and moderate fluxes were observed during other months. The overall SR did not vary significantly among the study sites, but significant differences ($P \leq 0.001$) were evident in the seasonal trend in each plantation site. Seasonal changes in soil microclimate play an important role in defining seasonal differences in soil $CO_2$ emissions within sites and climatic differences generate different SR rates among distant sites[3]. Earlier studies have revealed that SR also varies with vegetation and among
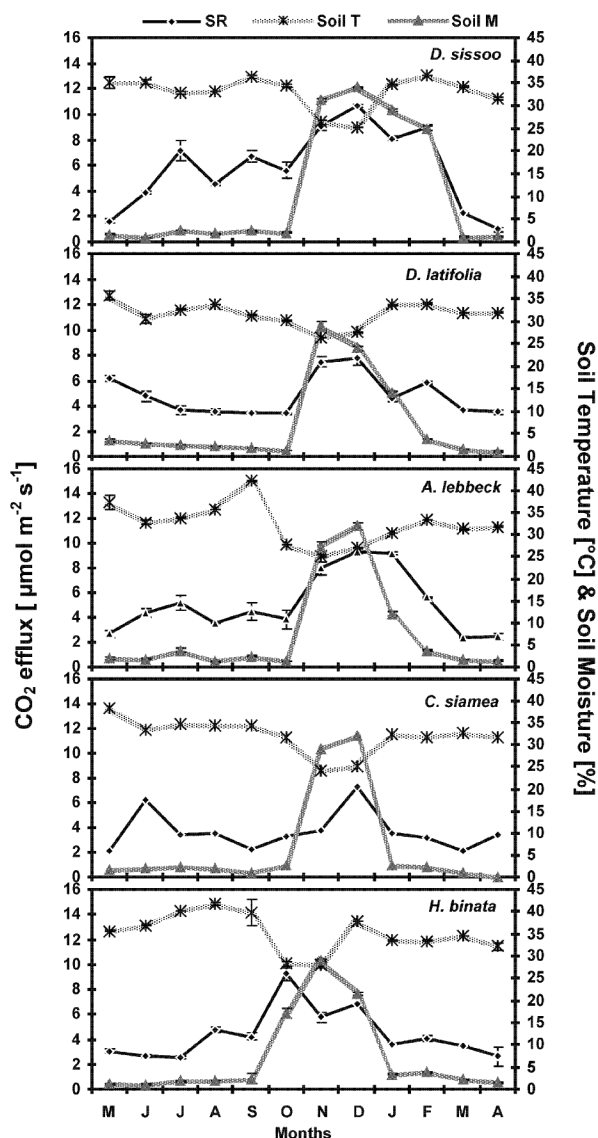


**Figure 1.** Seasonal pattern of soil $CO_2$ efflux rate, soil temperature and soil moisture in young tree plantation sites of *Dalbergia sissoo, D. latifolia, Albizia lebbeck, Cassia siamea* and *Hardwickia binata* measured from May 2005 to April 2006. Each point (mean ± SE) represents average of 6–8 values in six replicate measurements. Seasonal pattern shows significant differences at $P \leq 0.001$.
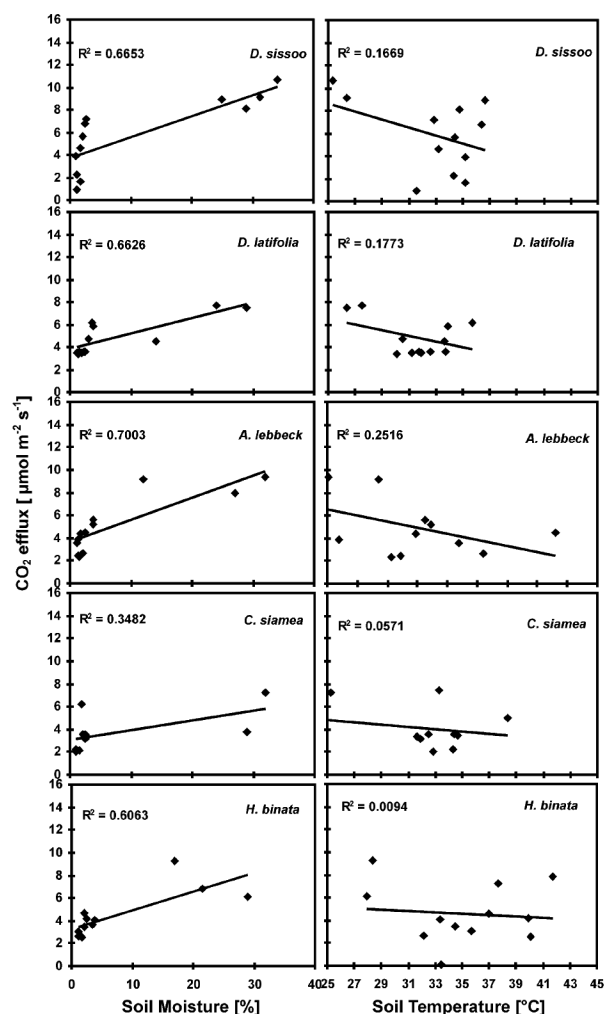
**Figure 2.** Relationship between soil $CO_2$ efflux rate and soil moisture; soil $CO_2$ efflux rate and soil temperature of young tree plantation sites of *D. sissoo*, *D. latifolia*, *A. lebbeck*, *C. siamea* and *H. binata* measured from May 2005 to April 2006.

major biome types significantly[16], and side-by-side comparisons of different plant communities frequently demonstrate differences in SR[17]. Such findings indicate that vegetation type is an important determinant of SR rate and therefore changes in vegetation have the potential to modify the responses of soils to environmental change.

The range of SR rates recorded in the present study is similar to the ranges reported in other studies[18]. Similar seasonal trends in SR have also been observed elsewhere. For example, Conant *et al.*[7] showed that SR in semi-arid ecosystems increases with both C pool size and mean annual precipitation, but decreases with increase in mean annual temperature.

The poor relationship between soil $CO_2$ efflux and temperature frequently occurred when soil moisture content was low, which indicates that soil moisture was almost acting as a limiting factor for soil $CO_2$ efflux. Our results are in agreement with those of Davidson *et al.*[19] and Sotta *et al.*[20]. Variation in SR occurs in response to changes in soil temperature and moisture, reflecting the biochemical basis of the component respiratory processes that occur simultaneously at different depths within the soil profile[19]. Davidson *et al.*[19] concluded that respiratory processes in the soil are also strongly influenced by soil moisture, with drier soils tending to yield lower $CO_2$ effluxes. The poor relationship must be a response of both plant and soil microbial metabolism to water stress[21]. The increased hydraulic resistance requires restrictions in transpiration and thus causes stomatal closure and a reduction in photosynthesis. As a result, the population of microbes rhizosphere and the fine-root production diminishes. The drying effect alone reduces the soil efflux[20]. In light of rising temperatures caused by global warming, soil respiration in the plantation sites will be maintained at a relatively constant rate owing to the so called 'temperature acclimation'[22]. Temperature acclimation, otherwise a self-adjustment of the site, is responsible for the observed decrease in SR rates in our study. Temperature acclimation in these plantation sites may possibly be caused by differences in substrate quantity and quality, as suggested by Luo *et al.*[22]. Studies by Zhou *et al.*[23] revealed that microbial communities associated with species may vary and such variation could also affect the SR rate.

Most long-term global modelling studies have included soil temperature as the sole variable determining SR. However, annual SR fluxes in the Mediterranean and semi-arid ecosystems in general, are highly sensitive to soil moisture[24].

When combined with periods of rewetting, i.e. immediately after the rain, the rate of soil $CO_2$ efflux increased considerably. It was possible in our study to observe the effect of drying and successive rewetting in the soil $CO_2$ efflux. The effect of summer drought became apparent as soil moisture content fell below 3%. The limiting effect of soil moisture on SR was clear as SR responded quickly and sharply to each rain event, reaching its highest values and then decreasing to pre-rain values. Soil moisture may limit SR in two ways; either by limiting aeration and thus the diffusivity of air when it is high, or by stressing the soil microbial communities and root respiration when it is low. In our study site, soil moisture did not reach a high limiting value, but strongly limited SR during summer months when the soil moisture content dropped below 3% over 0–10 cm depth. Similar phenomena have been observed elsewhere; for example, Holt *et al.*[25] observed a threefold increase in SR immediately after heavy rains. Law *et al.*[18] found a similar phenomenon in ponderosa pine forest during a summer drought, but the increase in SR had disappeared after 24 h of the rainfall event. When the very dry soil was rewetted by rain (slight showers during September and October followed by heavy rains in Novem-

ber and December), the efflux was higher. The stimulation may partly result from the displacement of air rich in $CO_2$ from within the soil and from the activity of microbes that oxidize the carbon dissolved in water. However, the main effect is likely to result from stimulation of soil organic matter decomposition after a period of drying, together with the rapid response of microbial biomass to increase in soil moisture[26]. This phenomenon is often called the 'Birch effect', following the initial investigations by Birch[26]. The drop from high soil temperature to optimum for the bacterial activity may be one of the reasons for the high efflux rates during this period[20]. The initial higher rate of $CO_2$ efflux, which results from high microbial activity, reduced subsequently. This reduction was observed from January 2006 onwards in all the plantation sites. Similar observations were made by Rey et al.[12] in Mediterranean oak forest and by Sotta et al.[20] in a tropical forest in the Central Amazon which showed that low water content limits the response of SR to temperature. Lopez et al.[27], who studied the effect of drought on fine-root dynamics in a Mediterranean forest in Spain, suggested that soil-water availability is the main variable controlling root growth in these ecosystems and not soil temperature as in many temperate forests. Similar slopes of soil moisture dependence regressions for all the species (except C. siamea) suggest that SR in such plantations responds similarly to soil moisture.

The similar reflect trends of SR to soil moisture can be explained, in part, by the similar seasonality of soil moisture which is driven by the same climatic conditions in these plantations. In contrast, differences in soil moisture dependency in the case of C. siamea, can be explained by the heterogeneity of respirators among these plantation sites[28]. It is evident that different respirators have various soil moisture dependencies. More soil moisture may be needed in such plantation sites to maintain the activities of abundant respirators[29]. Although the mean SR rates in five plantation sites did not differ significantly, statistically significant ($P \leq 0.001$) differences were evident in seasonal trends in all plantation sites. This is in accordance with the findings of Adachi et al.[30] in different tropical ecosystems.

The similarity in the efflux rates in the sites of D. latifolia and H. binata, which differ from the other study sites from May to July, may be due to difference in their potential growth rates. This capacity is strictly limited by soil microclimate and nutrients. Singh et al.[31] reported that nutrient-poor ecosystems showed a reciprocal relationship between microbial biomass and plant growth rate, due to which they can differ significantly in their influence on soil properties as well as on soil fertility. Further, the quantity and quality of litter input into the soil, the difference in the leaf texture and differential rates of litter decomposition[32] may also be the reasons for their differential efflux rates when compared with the other study sites.

The present study suggests that SR in the semi-arid ecosystem is largely controlled by soil moisture. Unlike results from more mesic systems, increase in soil temperature (with corresponding decrease in soil moisture) led to net decrease in SR throughout the experiment. Changes in precipitation rather than temperature during this active portion of the year will have the greatest potential to affect total SR rates. SR rates in the semi-arid ecosystem will be maintained at a relatively low value owing to the so-called temperature acclimation.

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# Influences of look angle and look direction of space-borne SAR sensor in geological feature delineation in Metasedimentary terrain of Kurnool Group of rocks, Andhra Pradesh

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The role of look angle and look direction of space-borne SAR sensors in enhancing signatures of geological elements is an important aspect of study. In the present study, two different look angle (IS2 and IS4) data of ENVISAT ASAR are compared to evaluate the significance of look angle in enhancing different lithovariants and structures of the Proterozoic metasedimentary terrain. The ascending and descending modes of data acquisition of ENVISAT ASAR also help to study the significance of look direction in enhancing or subduing geological features. Geometric distortion is similar in both look angles. Low-dipping sedimentary terrain with steep mesa, butte and cuesta ridges creates layover on images of IS2 (18°–25°) and IS4 (28°–36°) acquisition of ENVISAT, but low look angle facilitates less shadow zones at the back slope portion and helps in finding important geological structures. Alternate polarization channels of ENVISAT ASAR are useful in enhancing the lithovaraints based on polarization signatures characteristically developed over each rock type due to variation in surface roughness and moisture content of each rock type. Separabilty of one rock type from another based on polarization signatures is better in low look-angle data. Drainages on the other hand, are enhanced in high look-angle data as the specular surface of drainage returns appreciable energy in low look-angle acquisition. In the present study it is found that lineaments of variable trends can be mapped better from dual look-direction data.

**Keywords:** Image fusion, litho unit, look angle, look direction, sedimentary terrain.

IMAGING radars are operated in the microwave range of the electromagnetic spectrum[1] at wavelengths from about 1 cm to 1 m. SAR provides valuable information on surface roughness, soil moisture, topography and drainage pattern of a terrain[2]. SAR also has limited capabilities to penetrate through the soil cover and thereby can provide valuable information about *in situ* rock type and subsurface structure. Moreover, SAR techniques have the efficiency to provide relatively coarser resolution where minor details and variations are suppressed. Owing to this

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