Natural rubber: a renewable industrial raw material with negative carbon footprint

K. Annamalainathan* **and James Jacob**

Rubber Research Institute of India, Kottayam 686 009, India

Using the lifecycle assessment method, we estimated the carbon footprint of natural rubber (NR) produced from 1 ha NR plantation with an economic lifecycle of 27 years and productivity of 1.5 MT dry rubber per ha per year. Lifecycle emissions due to farming operations added up to 26.5 MT of carbon dioxide per ha, most of which resulted from chemical fertilizers. Processing latex into ribbed smoked sheet (RSS) rubber and technically specified rubber (TSR) emitted more CO_2 due to higher energy requirements for drying compared to making concentrated latex (cenex). Thus, lifecycle emissions were the highest for processing RSS (27.8–41.6 MT CO_2) and TSR (13.3–22.9 MT CO_2) and the lowest for cenex (2.7–3.9 MT CO_2). However, the total amount of CO_2 sequestered during the entire lifecycle of the plantation was as high as 500 MT CO_2. This resulted in a negative carbon footprint of approximately –15, irrespective of the type of processed NR. This should make NR a much more preferred raw material for the rubber industry than synthetic rubber which has a much higher carbon footprint. Promoting production and consumption of NR will help decarbonize the global rubber industry and benefit millions of small and marginal NR growers around the world.

Keywords: Carbon dioxide emission, industrial raw material, lifecycle emissions, natural rubber, negative carbon footprint.

CARBON footprint of products and processes that contribute to economic growth is a major indicator of their environmental sustainability[1]. At a time when the world is seriously concerned about rising carbon dioxide (CO_2) emissions and global warming, this assumes much significance[2,3].

The rubber industry, which consumes both natural rubber (NR) and synthetic rubber (SR), is a major driver of economic growth[4]. Globally, about 65% of the total amount of rubber consumed by the industry is SR and the balance is NR. In India, the share of SR is roughly 30%, and NR is 70% (ref. 5). Increasing demand and rising deficit in domestic NR production may lead to more consumption of SR by the Indian rubber industry in the coming years. Since SR is produced from petroleum stocks, a rise in its consumption will invariably increase the carbon intensity of the rubber industry, which is at odds with India's stated intention to reduce the carbon intensity of the economy and attain net zero emission by 2070.

While the obviously large carbon footprint of petroleum-derived SR is generally known, there is a felt need for assessing the carbon footprint of NR even as there exists a substantial amount of data on the high carbon sequestration capacity of NR plantations[6–11]. In the present study, we have done a lifecycle analysis of carbon emissions from a 1 ha NR plantation grown in Kerala, a typical traditional rubber-growing region of India with an estimated productivity of 1.5 tonnes/ha/yr and an economic lifecycle of 27 years, including an immaturity period of seven years. Potential emissions from each agronomic activity, from nursery preparation to felling of old trees at the end of the plantation cycle and processing of latex into different marketable forms of NR, were estimated. Using data on CO_2 sequestration by rubber plantations published earlier, we show that NR has a highly favourable carbon footprint of –15, a significant finding with profound environmental and social implications.

Materials and methods

Sources of emissions associated with the production of latex and processing it into marketable forms of NR, namely ribbed smoked sheet rubber (RSS), technically specified rubber (TSR) and latex concentrate or centrifuged latex (cenex), can be grouped into direct and indirect emissions. These are calculated using the default IPCC emission factors and global warming potential of various greenhouse gases (GHGs)[12–16]. Direct emissions are those generated within the physical boundaries of the 1 ha plantation as a result of agronomic activities related to latex production and converting it into marketable forms of NR in processing factories (Figure 1). These are directly measurable and monitorable from the plantation and processing factory. Indirect emissions are those associated with the production of various inputs such as chemical fertilizers used in the plantations, their transportation, use of fuels and electricity to run any farm machinery, processing factories, etc.[14,15].

Agronomic operations in a plantation include preparation of nursery beds, growing young plants in plastic containers in the nursery and watering, preparation of the main field which includes weeding, terracing, pitting, planting, application of fertilizers, plant protection measures, latex harvesting and collection, and processing the latex into RSS, TSR or

---

*For correspondence. (e-mail: annamalainathan1963@gmail.com)

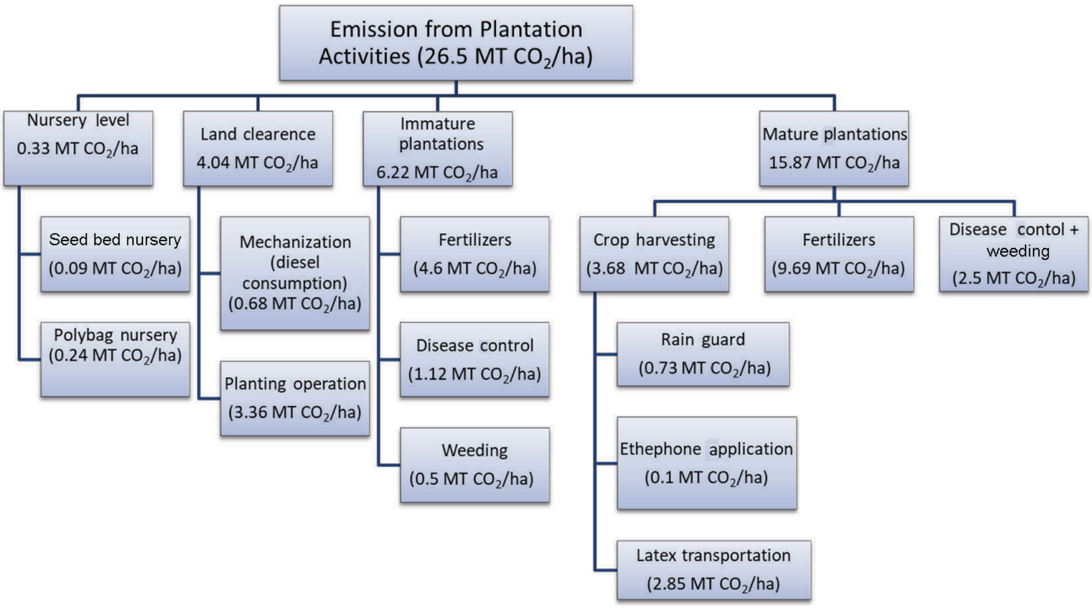

Figure 1. Schematic diagram showing the sources of emission from various farm activities in rubber plantations. Values in parentheses indicate possible emissions from individual farm activities. (See the 'Results and discussion' section for more details.)

cenex[17]. For assessing lifecycle emissions, it was assumed that all the standard agronomic practices recommended for scientific cultivation of NR were adopted for growing this crop in 1 ha, and processing the latex harvested for its full economic lifecycle of 27 years (including the immaturity period of the first seven years)[17].

The rate of net carbon sequestration was continuously monitored for several years in an NR plantation grown in Kerala[9,11,18]. A mean sequestration rate of 25 MT CO_2/ha/yr (from the seventh year onwards) was used in the present analysis to calculate the total lifecycle CO_2 sequestration by 1 ha of NR plantation. Data on the type and quantity of fuels used to process latex into marketable forms of NR such as RSS, TSR and cenex were collected from latex-processing factories, and their respective emission factors, and global warming potential were used to compute the corresponding emissions during processing[12,13,16].

Results and discussion

Assuming that all standard recommended practices were adopted for growing NR in 1 ha, potential lifecycle emissions from each farm activity and when the latex was processed into RSS, TSR or cenex were estimated, and the carbon footprint of NR was calculated.

Emissions from the nursery and preparation of the main field

For a standard planting requirement of 500 seedlings per hectare area in the main field, the seedbed nursery may start with 1000 seeds, and only the best 500 plants are eventually planted in the main field. Compost, charcoal powder, chemical fertilizers, pesticides, etc. used in the seedbed nursery are potential sources of emission. The estimated total emission from the seedbed nursery was about 87 kg CO_2 (Table 1). In the next step, seedlings were grown in LDPE polybags or plastic root trainer cups in the nursery before being transplanted in the main field when the plants had sufficiently grown. For raising 1000 nursery plants, around 20 kg of polythene materials is required. These polybags are non-reusable and have a high carbon footprint. Plastic root trainer cups, which also come with a positive carbon footprint, are used for raising nursery plants. Root trainer cups can be reused 5 to 6 times. Estimated total emission from the seedling nursery was 241 kg CO_2 (Table 2).

The mainland preparations include clearing old plantations, light burning of debris after felling, terracing, lining, pitting, etc. (Table 3). Nowadays, most of these activities are carried out by heavy-duty machinery. Transporting wood logs, pit-making, transportation of planting materials and fertilizers, etc. consume fossil fuels like diesel or petrol. Typical values for general farm practices were considered for estimating emissions from the mainland preparation, and the total emission was about 4 MT CO_2 (Table 3).

Emissions during immature and mature phases

Fertilizers, disease control measures and weeding constitute the major agronomic practices in the main field both during the immature and mature phases of the plantation. During the immature period (the first seven years during

Table 1. Potential emissions from seed-bed nursery raised for 1 ha planting area

Input	Amount	Area/ planting size	Unit emissions/ kg component	CO_2 equivalents (eq.) kg/1000 seeds
Gunny bags	–	–	0	0 (insignificant)
Charcoal powder	2 kg	1000 seeds	2.56	5.12
Compost	50 kg	200 m^2	0.415	20.75
Herbicide (diuron)	500 g	200 m^2	5.4	2.7
PO_4	7.0 kg	200 m^2	0.56	3.92
Fertilizers				
Urea	5.5 kg	200 m^2	5.15	28.3
Rock PO_4	15.6 kg	200 m^2	0.56	8.74
Potassium	1.7 kg	200 m^2	0.43	0.73
$MgSO_4$	4.7 kg	200 m^2	0.3	1.4
Tillage and irrigation				15.2
Total				86.9 kg CO_2/ha

Emission potential of various inputs and activities is calculated based on IPCC guidelines[13].

Table 2. Potential emission from rubber nursery activities

Activity	Component	Amount/1000 plants	CO_2 eq./1000 plants
Polybags	Plastic	20 kg @2.7/kg	54.00
Root trainer	Reusable (15% of attrition from emission potential)	12.75 kg × 2.7 kg CO_2	34.43*
Spray for powdery mildew	Sulphur	0.2% of sulphur (six sprays) 432 g/1000 plants	0.38
Bordeaux mixture	$CuSO_4$	2.16 kg	1.80
	Lime	2.16 kg	0.246
Fertilizer			
	(N : P : K and $MgSO_4$)	30 kg	92.00
Fuel/transport and spray	Petrol/gasoline	30 litre × 2.31 kg	69.30
Tillage and irrigation			23.00
			240.7 kg

*For the present study, possible emissions from the use of polybag plant were considered. Emission potential of various inputs and activities is calculated based on published guidelines[12,13]. Accounting of CO_2 emission for generating 1000 numbers of planting material is done.

Table 3. Potential emissions from land clearance activities during planting operations

Activity	Component (kg/ha)	Emission CO_2 eq./kg component	CO_2 eq. (kg/ha)
Mechanization (including clearance of old trees)	Land clearance (diesel, etc.), terrace and pitting, and transport	2.79 kg CO_2 × 200 litre	558.0
	Chainsaw operations (petrol)	2.31 kg CO_2 × 50	
		3.19 kg × 2	122.0
Burning debris	175 kg dry wt	1.65 kg × 175	289.0
Planting	Farmyard manure	12 kg/pit (0.416 × 12 kg × 500)	2500.00
	Rock PO_4	200 g/pit (0.56 × 200 g × 500)	56.00
Conservation tillage, etc.	Planting and immature phase		510.00
Total CO_2			4.035 MT CO_2

Emission potential of various inputs and activities is calculated based on IPCC guidelines[13].

which the trees are not under tapping for latex yield), the total emission was about 6.2 MT CO_2, of which fertilizers alone were responsible for 67% of the emissions (Table 4). In the mature phase (when the trees are under tapping for latex yield; 8–27 years in the present analysis), almost 61% of the total emissions were contributed by fertilizers, which was around 9.7 MT CO_2 (Table 5). The estimated emission from latex harvesting activities during the mature phase was about 3.7 MT CO_2 (Table 6).

The total lifecycle emissions from seedbed preparation till the end of the economic lifecycle of the plantation (total 27 years) added up to 26.5 MT CO_2/ha, or roughly 1 MT CO_2/ha/yr. The long 20-year mature phase of the plantation contributed almost 46% of the lifecycle emissions, followed by seven years of the immature phase (23%), planting activities in the main field (15%) and latex harvesting (14%). On an annual basis, the emissions were higher during the immature phase (0.89 MT CO_2/ha/yr) than during the mature

Table 4. Potential emissions from immature plantations (seven years immaturity phase is accounted for)

Activity	Name of the chemicals used (kg/ha)	Total amount of chemicals used (kg or litre/ha)	Emission CO_2 eq. kg/kg component	CO_2 eq. (kg/ha) in seven years
Fertilizers				
	Urea	609	5.15	3136.4
	Rock PO_4	1525	0.56	854.0
	Potash	307.9	0.43	132.4
	$MgSO_4$	150	0.3	45.0
Transport	Diesel	140 litre	2.79	391.0
Disease control spraying	Sulphur	25.2 kg	0.88	22.2
Powdery mildew	Bordeaux mixture	25.2 kg	1.04	28.1
Shoot rot	Bordeaux mixture	27 kg	1.04	12.5
Pink disease	Bordeaux mixture	12 kg bordeaux 480 g thride + 60 kg rubber cote	1.04 3.9 4.02	255.4
Corynespora	Mancozeb	39 kg	3.9	151.3
Colletotrichum	Bavistin/indofil	27 kg	3.9	105.3
Weedicides	Paraquat/glyphosate	24 kg	6.3	151.2
Total spraying activities	Sprayer (petrol) and	250	2.31	577.5
	transport (diesel)	120	2.79	335.0
			Total CO_2	6.2 MT CO_2

Emission potential of various inputs and activities is calculated based on IPCC guidelines[12,16].

Table 5. Potential emissions from mature rubber plantation activities (20 years), except the tapping process

Activity	Component (kg or litre/ha)	Emission CO_2 eq./kg or litre component	CO_2 eq. (kg/ha)
Fertilizers			
Urea	1209.6	5.15	6229.4
Rock PO_4	3024.0	0.56	1881.6
Potash	972.0	0.43	464.4
Transport: diesel	400 litre	2.79	1116.0
Disease control			
Powdery mildew	Sulphur 648 kg	0.88	570.0
ALF/shoot rot	COC 121 kg	3.9	470.0
Corynespora	COC 121 kg	3.9	470.0
Spraying activities, transport, etc.	Petrol 300 litre	2.31	693.0
	Diesel 100 litre	2.79	279.0
Weeding	Paraquat and 2,4D/3 kg	6.3	19.0
		Total CO_2	12.2 MT CO_2

Emission potential of various inputs and activities is calculated based on IPCC[12,13]. CO_2 equivalents of all the greenhouse gases from industrial production and application of components in the field are accounted together.

phase (0.61 MT CO_2/ha/yr), this is because of the more intensive agronomic practices followed during the immature phase when the plants are actively growing.

Among the various components of emission during the immature and mature phases of the plantation, chemical fertilizers contributed the single largest lifecycle emissions (12.9 MT CO_2 or 49%), and tillage contributed only 2% (0.55 MT CO_2). This is because once the plants are planted in the main field, few tillage operations are needed in the NR plantations. It may be noted that the chemical fertilizer requirement for NR farming is rather small compared to many other crops, and the soil requires less cultivation. In the case of field crops which require more intense tilling compared to rubber, it is estimated that around 18–26 kg CO_2/ha/yr is emitted (or 0.49–0.70 MT CO_2 in 27 years) due to tillage operations. This can vary substantially depending on the cropping pattern, soil type and organic matter content of the soil, local climate, etc.[19].

Emissions from the primary processing of latex

In the present analysis, we considered a mean NR productivity of 1.5 MT/ha/yr from a period of 20 years or a lifecycle yield of 30 MT and the estimated emissions during its processing into either RSS, TSR or cenenx.

Ribbed smoked sheet rubber: Using fuel and energy consumption data from NR processing factories, we estimated the amount of CO_2 released during the processing of RSS, TSR and cenex.

Depending upon ambient weather conditions and the efficiency of the smokehouses to dry, 1 tonne of RSS, about

Table 6. Potential emissions from crop harvesting activities for 20 years yielding period

Activity	Component (kg/ha)	CO_2 eq./kg component	CO_2 eq. (kg/ha)
Ethephon 10% stock	12 litre	1.24	14.9
Palm oil	30 kg	2.93	88.0
Rain guard (polythene shade)	16 kg × 20 years = 320 kg	2.06	659.0
	Polythene ribbon-0.3 kg	2.06	62.0
	Bituminous compound-40 kg	0.22	8.8
Collection and transport of latex	Diesel-1020 litre	2.79	2846.0
		Total	3.68 MT CO_2

Emission potential of various inputs and activities is calculated on the basis of IPCC[12,13].

Table 7. Energy consumption for the processing one kg of rubber

Forms of processed rubber	Firewood (MT)	Diesel (litre)	Electricity (kWh)	kg CO_2 emitted per kg processed rubber/cenex
Sheet rubber	1–1.5	–	10–15	0.926–1.388
TSR	0.26–0.32	0–29	240–309	0.442–0.764
Cenex	–	–	150–218	0.089–0.131

Table 8. Carbon footprint of various forms of processed rubber

Forms of processed rubber	Carbon footprint of natural rubber (kg CO_2 per kg dry rubber/cenex)
Sheet rubber	–14.4 to –14.9
TSR	–15.0 to –15.4
Cenex	–15.4 to –15.6

1–1.5 tonnes of firewood was required, as evidenced by a survey among several small growers who make mostly RSS (Table 7). Assuming a water content of 50% in firewood, about 0.917–1.375 MT of CO_2 was emitted when 1 tonne of RSS was dried in the smokehouse. Additionally, in large RSS-processing centres, electricity is required to operate sheeting batteries, which is approximately 10–15 kWh per MT of RSS produced. Taking an emission factor of 0.85 kg CO_2/kWh of electricity[20], this amounts to an additional emission of 8.5–12.75 kg CO_2 per tonne of RSS processed. Thus, the maximum amount of emissions when 1 MT of RSS was fully processed was in the range of 0.926–1.388 MT CO_2. In other words, for the lifecycle yield of 30 MT of RSS, the total emission 27.78 to 41.74 MT CO_2. According to Jawjit *et al.*[21], about 0.64 MT CO_2 was emitted for every tonne of RSS produced in Thailand, where the scale of RSS production is higher compared to India.

Technically specified rubber: TSR-making, which is more systematic and large-scale, is more energy-efficient and less emitting than RSS-making. During TSR processing, CO_2 emission was in the range of 0.442–0.764 MT per MT TSR made (Table 7), which is considerably less than the amount of CO_2 emitted during sheet-making. This works out to 13.26–22.92 MT CO_2 emitted for the total lifecycle yield 30 MT of NR. Considerable variation in the amount of CO_2 emitted per MT of TSR results from differences in the efficiency of processing, which is largely determined by the age/condition of the TSR factory, scale of processing and efficiency of the drying system.

Centrifuged latex: The cleanest type of latex processing was cenex production, where the amount of CO_2 emitted was the smallest (0.089–0.131 kg CO_2 per kg of cenex) compared to the other forms of processed NR (Table 7). This is because latex is still in a liquid form, and there is no fuel or energy spent on drying. Lifecycle emission for processing 30 MT of cenex was 2.67–3.93 MT CO_2.

Carbon footprint of natural rubber: The present analysis shows that for a lifecycle yield of 30 MT dry rubber (productivity @1.5 MT/ha/yr for 20 years), the total emission from farming operations and primary processing of latex was 27.8–41.7, 13.3–22.9 and 2.67–3.93 MT CO_2 for making RSS, TSR and cenex respectively. From earlier studies using eddy covariance analysis[18], we have shown that rubber plantations in Kerala, on average fix, about 25 MT CO_2/ha/yr, which amounts to 500 MT CO_2 during the 20-year mature phase of the plantation (tapping period). Since much more CO_2 is removed from the atmosphere than what is released into it when NR is produced, the carbon footprint of NR is highly negative. Although lifecycle emissions were markedly different for processing RSS, TSR or cenex (Table 7), the total amount of CO_2 sequestered during the entire lifecycle of the plantation was substantially higher than these emissions and therefore, there were only marginal differences in the carbon footprints of the different forms of processed rubber (Table 8). Thus, based on the lifecycle estimates of emissions and carbon sequestration, it can be observed that the carbon footprints of RSS, TSR and cenex are similar: –14.4 to 14.9, –15.0 to –15.4 and –15.4 to –15.6 respectively (Table 8). To summarize, irrespective of the forms of processed rubber, the carbon footprint of NR is around –15 MT (Table 8). In other words, about 15 MT of net CO_2 is sequestered for every tonne of RSS, TSR or cenex produced. Notably, this assessment is based on the assumption that all agronomic practices are fully adopted for cultivating NR plantations, which is not generally the case, as most growers tend to skip fertilizers, plant protection practices, etc. for economic reasons. While this will reduce emissions from farm operations and potentially reduce the carbon footprint of NR, the reduction will be only marginal given the extremely high amounts of CO_2 sequestration by the plantation compared to the emission.

The negative carbon footprint of NR is in stark contrast with the high carbon footprint of SR, which is about 10–15 tonnes of CO_2 per tonne SR[22]. This should make NR a unique and preferred raw material over SR, which is increasingly being used in the Indian rubber products manufacturing industry due to the deficit in the production of NR in the country.

It is quite likely that depending on the growth rate of the rubber trees, the productivity of the plantation and the agro-management practices followed, there can be some variations in the total emissions and sequestration of CO_2 by NR plantations in different countries and agro-climatic regions. Yet, the total amount of CO_2 sequestered by the plantations is always high. Studies from various countries have shown that the net CO_2 sequestration rate of NR plantations varies between 20 and 43 MT CO_2/ha/yr (refs 7, 18, 23, 24) after accounting for emissions from litter decomposition and soil respiration, which is 27 MT CO_2/ha/yr (refs 25, 26).

Conclusion

Unlike SR, which is produced in factories most often associated with large oil refineries, NR is produced by several million small and marginal growers from some of the most populous, poor and developing countries. In India alone, there are nearly 1.2 million small and marginal NR-growers, including some of the most socially and economically marginalized indigenous people in the North East, even as SR is manufactured by a couple of large industry houses in the country. The highly favourable environmental and social credentials of NR over SR should make the former a more preferred raw material for the global rubber industry. The glaring contrast in the carbon footprints of NR and SR makes a compelling argument in favour of charging a Pigouvian carbon tax on SR. The proceeds from such a tax on SR could support small NR-growers and help the rubber products manufacturing industry offset its emissions by promoting more NR consumption, thus creating a circular rubber economy with reduced carbon intensity.

Conflict of interest: None.

1. Bilanovic, D., Carbon footprint – an environmental sustainability indicator of large scale CO_2 sequestration. In *Environmental Indicators* (eds Arnon, R. H. and Hamninen, O.), Springer, Dordrecht, 2014, pp. 51–66.
2. Wiedmann, T. and Minx, J., A definition of carbon footprint. In *Ecological Economics Research Trends* (ed. Pertsova, C. C.), Nova Science Publishers, USA, 2008, vol. 2, pp. 55–65.
3. Jose, I., Furtado, T. D. R., Belt, T. and Ramachandra. J., Economic development and environmental sustainability. World Bank Institute Resources, 2013; https://doi.org/10.1596/0-8213 4573-7.
4. Joseph, J. and Jacob, J., Over-dependence of Indian rubber industry on imported natural rubber: the question of long-term sustainability. *Rubber Sci.*, 2018, **31**(1), 1–9.
5. https://www.rubberstudy.org (accessed on 24 April 2023).
6. Sivakumaran, S., Kheong, Y. F., Hassan, J. and Rahman, W. A., Carbon sequestration in rubber: implication and economic models to fund continued cultivation. In Proceedings of Indonesian Rubber Conference and IRRDB Symposium, Indonesian Rubber Research Institute, Bogor, 12–14 September 2000, Times Mirror Publishers, pp. 79–102.
7. Yang, J. C., Huang, J. H., Tang, J. W., Pan, Q. and Han, X. G., Carbon sequestration in rubber tree plantations established on former arable lands in Xishuangbanna, SW China. *Chin. J. Plant Ecol.*, 2005, **29**(2), 296–303.
8. Wauters, J. B., Coudert, S., Grallien, E., Jonard, M. and Ponette, Q., Carbon stock in rubber tree plantations in western Ghana and Mato Grosso (Brazil). *For. Ecol. Manage.*, 2008, **255**(7), 2347–2361.
9. Ambily, K. K., Meenkumari, T., Jessy, M. D., Ulaganathan, A. and Nair, N. U., Carbon sequestration potential of RRII 400 series clones of *Hevea brasiliensis*. *Rubber Sci.*, 2012, **25**(2), 233–240.
10. Maggiotto, S. R., Oliveria de, D., Marur, C. J., Stivari, S. M. S., Leclerc, M. and Wagner-Riddle, C., Potential carbon sequestration in rubber tree plantations in the northwestern region of the Parana state. *Brazil. Acta Sci. Agron.*, 2014, **36**(2), 239–245; https://doi.org/10.4025/actasciagron.v36i2.17404
11. Annamalainathan, K. and Jacob, J., Biomass and yield partitioning in *Hevea brasiliensis*: the concept of harvest index redefined. *Rubber Sci.*, 2019, **32**(1), 17–25.
12. IPCC, *IPCC Guidelines for National Greenhouse Gas Inventories, prepared by the National Greenhouse Gas Inventories Programme* (eds Eggleston, H. S. *et al.*), Institute for Global Environmental Strategies, Kanagawa, Japan, 2006, pp. 6–20.
13. IPCC, *Climate Change: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon, S. *et al.*), Cambridge University Press, Cambridge, UK, 2007, pp. 235–1325.
14. Pandey, D., Agrawal, M. and Pandey, J. S., Carbon footprints: current methods of estimation. *Environ. Monit. Assess.*, 2011, **178**, 135–160.
15. Gunathilaka, L. F. D. Z. and Gunawardana, K. D., Carbon footprint calculation from cradle to grave: a case study of rubber manufacturing process in Sri Lanka. *Int. J. Bus. Soc. Sci.*, 2015, **6**(10), 82–94.
16. IPCC, *Climate Change: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2013, pp. 750–1535.
17. *Rubber Growers' Guide*, Rubber Board, Kottayam, 2023, pp. 5–23.

18. Annamalainathan, K., Jayasooryan, K. K., Sathesh, P. R. and James Jacob, Long term monitoring of net ecosystem flux rates of CO_2 and water vapour in a natural rubber plantation using the eddy covariance technique. *Rubber Sci.*, 2021, **34**(2), 111–122.
19. Lal, R., Carbon emission from farm operations. *Environ. Int.*, 2004, **30**, 981–990.
20. CEA, *CO_2 Baseline Database for the Indian Power Sector, User Guide, Version 16*, Central Electricity Authority, Ministry of Power, Government of India, March 2021, pp. 2–30.
21. Jawjit, W., Kroeze, C. and Rattanapan, S., Greenhouse gas emissions from rubber industry in Thailand. *J. Clean. Prod.*, 2010, **18**(5), 403–411.
22. George, B., Varkey, J. K., Thomas, K. T., Jacob, J. and Mathew, N. M., Carbon dioxide estimation reduction through substituting synthetic elastomers with natural rubber. In *Kyoto Protocol and the Rubber Industry* (eds Jacob, J. and Mathew, N. M.), Rubber Research Institute of India, Kottayam, 2006, pp. 135–146.
23. Satakhun, D. *et al.*, Carbon sequestration potential of rubber-tree plantation in Thailand. *IOP Conf. Ser.: Mater. Sci. Eng.*, 2019, **526**, 012036.
24. Ambily, K. K. and Ulaganathan, A., Biomass production, carbon storage capacity and nutrient export in natural rubber. *Rubber Board Bull.*, 2015, **33**(4), 4–10.
25. Abraham, J. and Philip, A., Impact of natural rubber cultivation on nutrient status in tropical soils: a case study in Kerala, India. *Rubber Sci.*, 2017, **30**(2), 160–168.
26. Goldberg, S. D. *et al.*, Soil respiration in sloping rubber plantations and tropical natural forests in Xishuangbanna, China. *Agric. Ecosyst. Environ.*, 2017, **249**, 237–246.

Received 12 April 2023; revised accepted 17 November 2023

doi: 10.18520/cs/v126/i3/374-380