

Developed-developing world partnerships for sustainable development (3): reducing carbon sequestration uncertainties in south Indian tropical dry evergreen forest

Dr Mark Everard, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol BS16 1QY, UK. (Corresponding author: mark.everard@uwe.ac.uk, +44-(0)-7747-120019.)

Professor James Longhurst, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol BS16 1QY, UK.

Dr John Pontin, The Converging World, c/o Everoze, 5th Floor, 30 Queen Charlotte Street, Bristol BS1 4HJ, UK.

Dr Wendy Stephenson, The Converging World, c/o Everoze, 5th Floor, 30 Queen Charlotte Street, Bristol BS1 4HJ, UK.

Joss Brooks, Pitchandikulam Bio Resource Centre (PBRC), Pitchandikulam Forest, Auroville 605101, Tamil Nadu, India.

Molly Byrne, The Converging World, c/o Everoze, 5th Floor, 30 Queen Charlotte Street, Bristol BS1 4HJ, UK.

Abstract

Climate regulation services provided by tropical dry evergreen forest (TDEF), a threatened habitat of India's Coromandel Coast, appear significant due to high carbon assimilation rates. International markets for climate regulation represent an 'anchor service' potentially promoting TDEF restoration, co-beneficially generating multiple linked ecosystem services. Understanding the forest type and carbon sequestration rate is essential to underpin these markets. Literature suggests that TDEF is a broad categorisation of forest types shaped by environmental conditions and human pressures, a plastic biome rather than a definitive vegetation type, though regionally representative if now highly fragmented. Previous estimates of carbon sequestration potential in restored TDEF were found to be flawed, calculated from incorrectly stated units in a source paper. Structured literature review confirms the sparsity of relevant literature, though the distinctive nature of TDEF makes data transfer from other forest types unreliable. From the limited literature, carbon sequestration potential from restoration of TDEF is of the order of 292 tC ha⁻¹ (1,071 tCO₂e ha⁻¹), subject to multiple stated assumptions and significant uncertainty that is unquantifiable based on limited data. Further research is required to quantify TDEF carbon sequestration and additional ecosystem services, expanding potential market-based restoration and informing optimal land use policies and practices.

Keywords

Tropical dry evergreen forest; carbon sequestration; The Converging World; Tamil Nadu; Coromandel Coast; payments for ecosystem services

Research highlights

Tropical dry evergreen forest is a biome shaped by environmental and human pressures

High forest biomass and soil carbon assimilation contribute to climate regulation

Climate regulation by this forest type is one of many linked co-beneficial services

The climate regulation 'anchor service' can attract investment in forest restoration

Prior calculations based on data wrongly stated in source literature are corrected

1. Introduction

Consensual international studies (e.g. IPCC, 2001 and 2007) provide compelling evidence linking climate change to human-induced increases in atmospheric concentrations of greenhouse gases, particularly carbon dioxide. The Kyoto Protocol explicitly accounts for sequestration of carbon through reforestation and afforestation (IPCC, 2007). Carbon assimilation, defined as the overall rate of fixation of carbon through the process of photosynthesis, has become central to climate change research (Kaul *et al.*, 2009 and 2010). Tropical dry forests are of particular significance, accounting for approximately 42% of the landmass of the tropics (Miles *et al.*, 2006). Field *et al.* (1998) estimated that annual net carbon sequestration by tropical forests and savanna cumulatively account for 60% of global terrestrial photosynthesis, and tropical forests are of particular importance as stored carbon is portioned more or less equally between vegetation and soil (Ramachandran *et al.*, 2007; Ravindranath *et al.*, 1997; Malhi *et al.*, 1999) though a study by Kaul *et al.* (2010) found that soil carbon can be almost double that in the biomass. Climate regulation services by tropical dry evergreen forest (TDEF) may be particularly significant, as Kaul *et al.* (2010) found that evergreen forests in India assimilate carbon at a higher rate than other forest and grassland types. This may exceed the world's highest total biomass carbon density (living plus dead) reported by Keith *et al.* (2009) as 1,867 tC ha⁻¹ from Australian Central Highlands temperate moist *Eucalyptus regnans* forests found amongst published global site biomass data (the source reference is Van Pelt *et al.* (2004) for living plus dead total biomass in >100 year-old *E. regnans* forest), a value that excludes soil carbon.

Forest loss or degradation has an adverse effect on controlling atmospheric carbon concentrations. During the 1990s, tropical deforestation released approximately 1-2 billion tonnes of carbon per year, equating to 15-25% of annual global greenhouse gas emissions which exceeded transportation sector emissions over the same period (Gibbs *et al.*, 2007; Madeira, 2008). Conversely, IPCC (2000) estimated a total global potential carbon sequestration through afforestation and reforestation activities for the period 1995–2050 of between 1.1 and 1.6 Pg C yr⁻¹ (1.1 and 1.6 x 10⁹ Mg or tonnes C yr⁻¹), of which 70% could occur in the tropics. Consequently, carbon sequestration and biodiversity protection received increases in priority in

scientific, governmental and civil-society agendas as a means to mitigate climate change (Díaz *et al.*, 2009). Under the international REDD+ programme, investment for carbon offsetting from developed nations funds protection and regeneration of developing world forests, providing developing nations with a source of revenue for the service of climate regulation (United Nations, 2008 and 2014). This type of market-based instrument has promoted forest protection and plantation programmes in developing countries, yielding a range of benefits including carbon credits and the generation of significant income (Niles *et al.*, 2002). Forest regeneration can also produce a range of linked ecosystem service co-benefits in addition to the marketed service (Everard *et al.*, 2017).

Quantifying the potential rate by which climate regulation can be influenced by forest conservation and restoration is necessary to underpin global markets for this ecosystem service. However, despite a broad literature on carbon stocks, publications specifically addressing sequestration rates for different tropical forest types are sparse. In India, Mani and Parthasarathy (2007) used different methods to estimate that above-ground biomass in TDEF varied from 39.69 to 173.10 Mg C ha⁻¹ (tC ha⁻¹). For India's dry tropical forest resource as a whole, Singh and Singh (1991) estimated an average standing crop of 66.98 t ha⁻¹. Chhabra *et al.* (2003) estimated that the total soil organic carbon (SOC) pool in Indian forests ranges from 4.13 Pg C (4.13 x 10⁹ Mg or tonnes C) for the top 50cm soil depth to 6.18 Pg C (6.18 x 10⁹ Mg or tonnes C) for the top 1 m soil depth. Based on different forest types in India, the national average of soil organic carbon per ha in forest soil was estimated as 183 Mg C ha⁻¹ (Jha *et al.*, 2003).

Across India, approximately 36 million ha of degraded and non-forest lands were afforested between 1951 and 2002 (FSI, 2003; Forestry and Wildlife Statistics of India, 2004). Ravindranath *et al.* (1997) and Kaul *et al.* (2009) respectively calculated marginal net sequestration rates of 5 Tg C (5 x 10⁶ Mg or tonnes C) for the reference year 1986 and of 1.09 Tg C (1.09 x 10⁶ Mg or tonnes C) for 2002 for India as a whole. Lal and Singh (2000) estimated that, at then currently reported rates of biomass productivity of natural forest cover (1.1 Mg ha⁻¹ yr⁻¹) and plantations (3.2 Mg ha⁻¹ yr⁻¹), forest carbon sequestration potential was in the range of 1.1 and 2.7 Pg C (1.1 and 207 x 10⁹ Mg or tonnes C), respectively, by the years 2020 and 2045. However, substantial variation was observed between forest types found in India, with total long-term average carbon stocks in biomass and wood products calculated at 156 Mg C ha⁻¹ for slow growing long rotation forests and in the range of 101-134 Mg C ha⁻¹ for fast growing short rotation forests. These optimistic estimates of potential sequestration are however undermined by reports of rapid loss and degradation of forests across India. Based on satellite data, Jayakumar *et al.* (2009) found alarming decreases in the extent of all of India's major forest types (evergreen, deciduous, southern thorn and southern thorn scrub), all the more concerning as these rapid declines had occurred after India's Conservation Act was passed in 1980 and the launch of a National Forest Policy in 1988, amongst other conservation initiatives intended to limit deforestation and conserve biodiversity.

Everard *et al.* (2017) describe how developing-developed world partnerships potentially present win-win opportunities for addressing climate-active gas emissions at lower cost, recognising the geographical independence of where carbon is

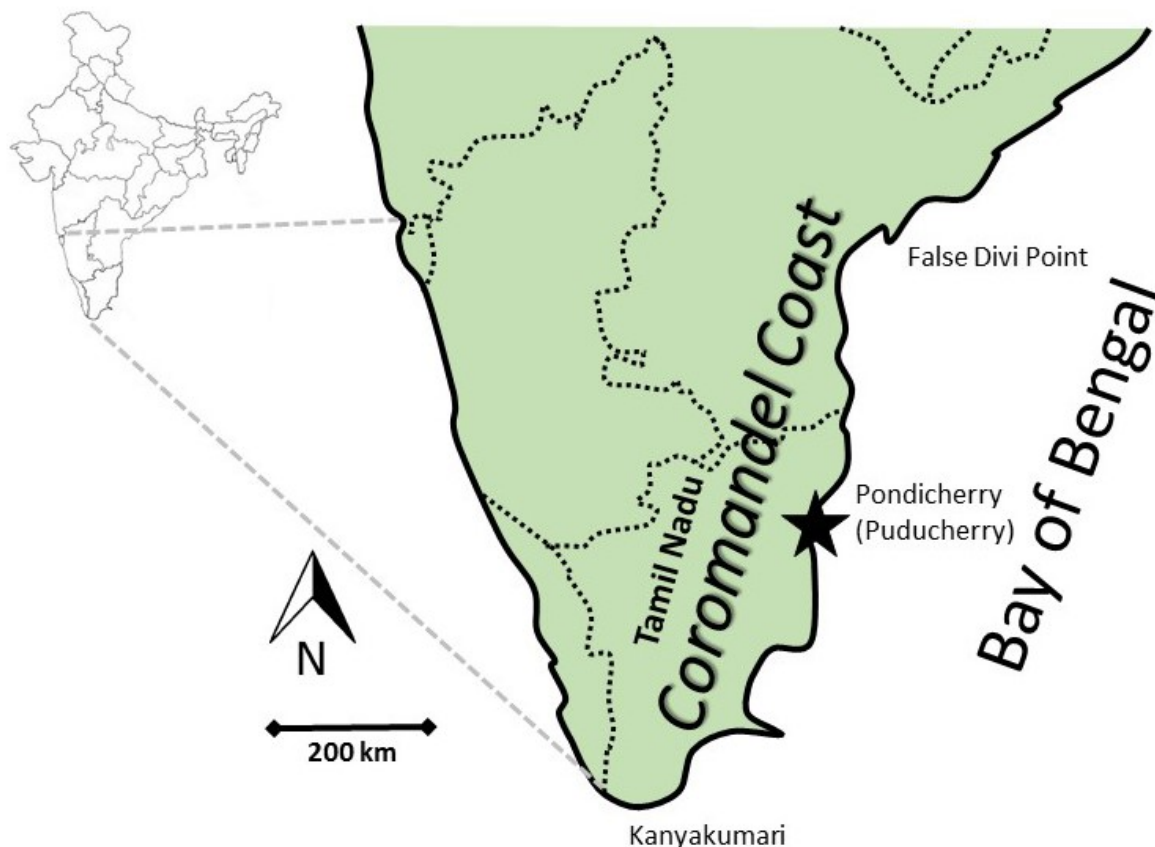
emitted, stored and sequestered. This is broadly consistent with measures under the REDD+ programme. Principles of how REDD+ would operate in India are discussed by Sharma and Chaudhry (2013). The particular case explored by Everard *et al.* (2017) – a partnership between south-west England and Tamil Nadu state, India, under The Converging World (TCW) model – was described in terms of an expanded PES (payment for ecosystem services) framework, initially founded on globally beneficial services generated by the function of carbon sequestration in the biomass and soil of restored tropical dry evergreen forest (TDEF). However, a far wider, societally beneficial set of services (water regulation, storm buffering, harvested food and medicinal products, soil formation, etc.) provided by regenerating TDEF was also recognised. If subsequently characterised and quantified, these additional services could provide additional bases for PES markets. The process of carbon sequestration in TDEF is the basis for the ‘anchor service’ (*sensu* Everard, 2014) of climate regulation, constituting the driving interest around which systemic consideration and design can optimise co-delivery of a range of linked ecosystem service benefits referred to variously as ‘environmental services’ (*sensu* Schomers and Matzdorf, 2013) or ‘bundles’ (Balvanera *et al.*, 2016: p.48) of greater potential cumulative societal benefit. Everard *et al.* (2017) recognised that initial quantification of this anchor service was limited by sparse published data on sequestration rates in restored TDEF. Considerable disparity was noted between published generic rates in temperate systems and the very few data available for a representative tropical evergreen forest type, citing Ramachandran *et al.* (2007) as the only directly comparable case study. Everard *et al.* (2017) acknowledged substantial uncertainties in values extrapolated from such a sparse evidence base, though methods used to translate a value published by Ramachandran *et al.* (2007) into market values were conservative, precautionary and framed as being highly uncertain.

Quantification and monitoring of ecosystem service production and, if necessary, sanctioning mechanisms are necessary to underpin the development and operation of effective PES schemes (Meijerink, 2008; Sommerville *et al.*, 2011; Potschin and Haines-Young, 2016). For robust climate regulations and linked markets to be established for TDEF restoration, it is necessary to be clear about both the characteristics of this forest type and its associated carbon sequestration rate.

A review by Everard (2018) addresses the characteristics, representativeness, function and conservation importance of TDEF on India’s Coromandel Coast, comprising the south-eastern coastal region of peninsular India seaward of the Eastern Ghats and bordering the Bay of Bengal, between False Divi Point in the north and Kanyakumari at India’s southern tip (Figure 1). This review found that TDEF is a product of natural forces (tectonic movement and biogeography, climate, soil type) as well as anthropogenic factors relating to forest use, conversion and protection throughout the long history of human activity on the Coromandel Coast (Begley, 1993; Begley *et al.*, 1996; Chandra, 2011). The population of Tamil Nadu state has boomed post-Independence from just over 30 million in 1951 to in excess of 79 million in 2017 (Indiaonlinepages.com, undated), intensifying these pressures, which have resulted in regionally characteristic though now fragmented forest with a 9-12 m canopy comprising climax vegetation that is commonly evergreen. The simple leaves often with waxy upper surfaces characteristic of this forest type limits evapotranspiration, seeds are often contained in small fruits appearing between April

and September, and trees exhibit slow growth with dense, hard wood and a general lack of thorns though with some exceptions, all apparently adaptations to infrequent, intermittent and unpredictable rains. However, the broad literature reviewed by Everard (2018) reveals a high degree of heterogeneity of even closely adjacent extant forest stands, leading to the conclusion that, though there are some characteristic tree species, the categorisation of TDEF is representative of a larger, plastic biome (as for example 'tropical rainforest' or 'coral reef') distinctive to the Coromandel Coast and some other global regions with a similar biogeography rather than a specific vegetation type. However, whether biome or distinctive forest type, the functions that TDEF performs and the breadth of ecosystem services that it provides are considered significant (Everard *et al.*, 2017) and in particular through carbon sequestration functions that appear to be particularly significant given observed high soil organic carbon in TDEF.

Figure 1: Location of the Coromandel Coast, southern India



This paper undertakes a structured review of available literature concerning the rate at which restored TDEF can sequester carbon, as a basis for subsequent development of ecosystem service market instruments (and PES in particular). This may potentially provide a mechanism for quantification of the contribution of restored ecosystems to the meeting of human needs (Everard and Longhurst, 2018). Improved knowledge can also better inform recommendations for enhancing the sustainability and net benefits of formal and informal strategies, policy instruments and practical land use management.

2. Methods

Identification of suitable literature from which to assess carbon stocks and sequestration in TDEF was founded on a systematic approach. This entailed using the ‘advanced’ library search facilities available through the University of the West of England (UWE Bristol), accessing and interrogating a range of internal and external scientific databases. Search terms and library items explored are listed in Table 1, which also notes three levels of filtering. Initial search results returned a total of 39,420 potentially relevant items. Filter #01 was then applied to limit the search to the 22 most relevant disciplines, reducing the number of potentially relevant items to 20,786. Filter #02 restricted the search to the eight most relevant subject disciplines, still returning over 20,000 items. At this point, a further strategic level of manual filtering was adopted, only accepting items that specifically address key habitat type, geography and the topic of carbon. Despite this further level of sophistication, we found that there was still a low degree of relevance in most papers. Beyond the first 250 returns from the search, relevance dropped off substantially with single search terms (such as ‘forest’) dominating the remainder.

Table 1: Extended review of literature pertaining to carbon sequestration in TDEF

Search instrument	Online ‘advanced’ search facilities of the University of the West of England (UWE) Library
Terms searched	tropical AND dry AND evergreen AND forest AND India AND carbon
Items explored	Book/e-book, Journal article, Book chapter, Thesis, Government document, Journal/e-journal, Technical report
Initial search	No disciplinary filter
Filter #01	Disciplines limited to (22): Agriculture, Applied sciences, Biology, Botany, Business, Chemistry, Ecology, Economics, Environmental sciences, Forestry, Geography, Geology, Government, Law, Meteorology and climatology, Physics, Political sciences, Public health, Sciences, Social sciences, Statistics
Filter #02	Disciplines limited to (8): Biology, Botany, Ecology, Economics, Environmental sciences, Forestry, Geography, Meteorology and climatology
Manual filter of ‘top 250’	Manually filtered out topics not focused on carbon: <ul style="list-style-type: none"> • Non-TDEF (e.g. wet forests, deciduous forests) • Non-trees (e.g. lianas) • Non-India (e.g. Vietnam, South America, Ethiopia) • Studies just on soil, water, biodiversity, etc.

3. Results

The sparse literature on forest of a relevant type and locality highlighted by Everard *et al.* (2017) is confirmed by the extended, structured review described in the Methods section, though these searches have located several more references. However, in common with Everard *et al.* (2017), we find that a great deal of the literature addresses biomass rather than carbon, also often only addressing a limited component such as above-ground biomass. The few sources addressing carbon tend to focus on stock, with even fewer directly assessing sequestration rate and those that do so largely by comparison of stock in different states. In order to make use of the available data, three assumptions outlined in Table 2 are applied.

Table 2: Assumptions applied to convert data from literature sources

1. Where biomass data is provided, almost invariably there no distinction as to whether this relates to wet or dry mass. It is assumed that data relate to dry mass.
2. Carbon content of (dry) biomass is assumed to be 49.1%, following Ramachandran *et al.* (2007).
3. Mass of CO₂ is calculated by multiplying C mass by 3.667 (molecular weight of CO₂ divided by atomic weight of carbon).

Information from relevant publications identified by a structured search routine is recorded in Table 3, including pertinent data and its transformation into terms relevant to sequestration assessment.

Table 3: Relevant publications with data as presented and, as bullet points, commentary on transformation into terms relevant to sequestration assessment

<p>Ramachandran <i>et al.</i> (2007, p.327) state that “Vegetation biomass carbon density of 0.60 Tg ha⁻¹ in semi-evergreen forests”, also presenting a range of summary data in a set of Tables.</p> <ul style="list-style-type: none"> • The 0.60 Tg ha⁻¹ figure quoted above was used by Everard <i>et al.</i> (2017) to calculate a CO₂ equivalent sequestration rate making a number of transparent and conservative assumptions, and noting a low degree of confidence in this value though finding no other contradictory evidence in the literature. However, unfortunately, it subsequently came to light that the unit as presented by Ramachandran <i>et al.</i> (2007) was incorrect. Also, the term ‘TOC’ is not defined by Ramachandran <i>et al.</i> (2007), leading to some assumptions. Subsequent review of the data in Tables within the source paper reveals that this figure should be 0.60 Tg in a total of 3,962.23 ha of semi-evergreen forest, rather than per hectare. Though other calculations by Everard <i>et al.</i> (2017) are found to be robust on review, the incorrect presentation of data by Ramachandran <i>et al.</i> (2007) means that CO₂ equivalent sequestration rate calculated by Everard <i>et al.</i> (2017) was substantially overestimated. • Note that the biomass value of 1,867 tC ha⁻¹ in Australian temperate moist <i>Eucalyptus</i> forests reported as the world’s highest by Keith <i>et al.</i> (2009), derived from values published by Van Pelt <i>et al.</i> (2004) for living plus dead total biomass in >100 year-old <i>E. regnans</i> forest, approaches the order of magnitude of the value misreported by Ramachandran <i>et al.</i> (2007) when soil carbon is also taken into account making this value appear more plausible if high.
<p>Chaturvedi <i>et al.</i> (2011) report from study of a tropical dry forest (not specifically evergreen) in Uttar Pradesh state, India, that “Annually, the forest accumulated 5.3 t-C ha⁻¹ yr⁻¹ on the most productive, wettest Hathinala site to 0.05 t-C ha⁻¹ yr⁻¹ on the least productive, driest Kotwa site. This study indicated a marked patchy distribution of carbon density (151 t-C ha⁻¹ on the Hathinala site to 15.6 t-C ha⁻¹ on the Kotwa site); the maximum value was more than nine times the minimum value”.</p> <ul style="list-style-type: none"> • Extrapolation of annual CO₂ equivalent sequestration rate from these figures could be based on an assumed time scale of progression to climax community, and conversion from C to CO₂, though this has not been calculated as evergreen forest is not specified.
<p>Lal and Singh (2000) address the carbon sequestration potential of Indian forests and plantations, deriving a value of at least 0.125 Gt CO₂ in 1995 from 64 Mha of forest cover.</p> <ul style="list-style-type: none"> • This value covers all forest types and is a generalisation, so is of limited value specifically to address the potential of TDEF. However, division of 0.125 Gt CO₂ by 64 Mha yields a sequestration rate of approximately 2 tCO₂ ha⁻¹ yr⁻¹. This low value compared to those of tropical evergreen forest, appears to result from addressing a wide mix of forest types.
<p>Joshi and Singh (2003) produced a conference paper addressing carbon sequestration by rehabilitating degraded forests in India. The paper reports that 1,008.49 Tg C is sequestered over 75 years.</p>

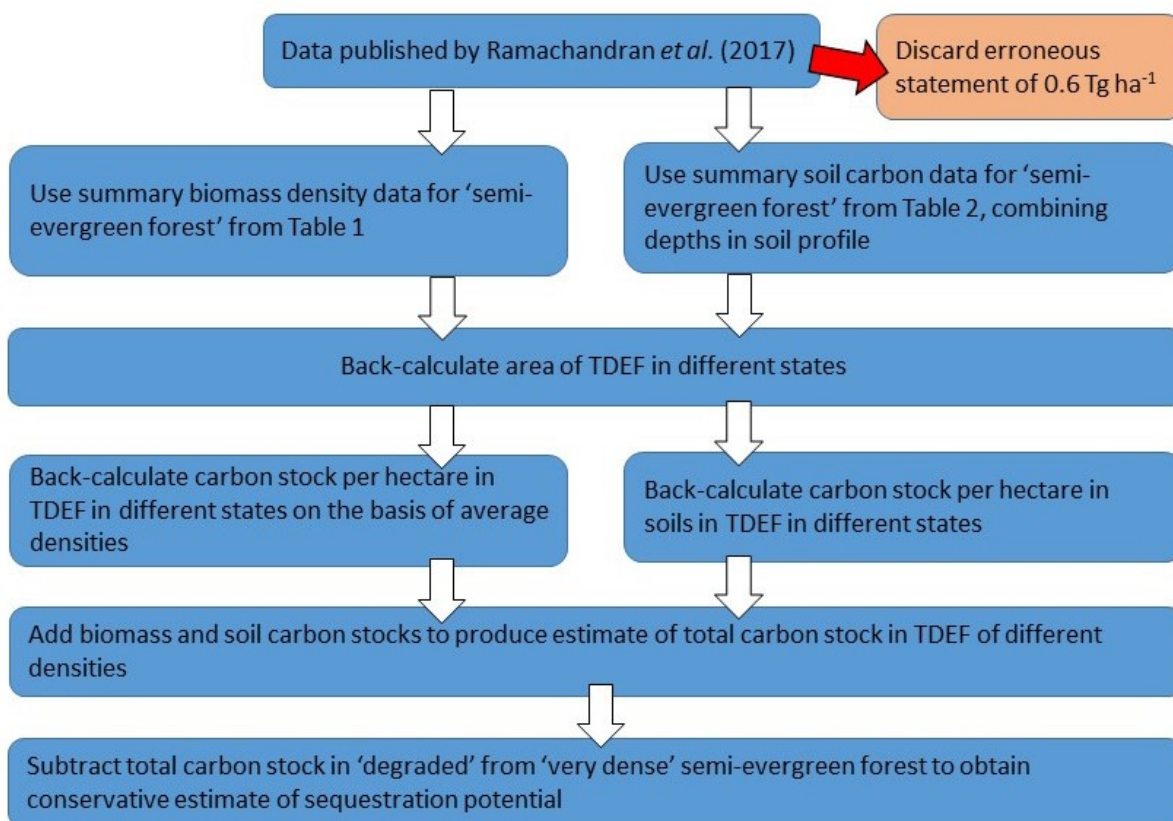
<ul style="list-style-type: none"> Simple calculation of these data yields a figure of 13.45 Tg C yr⁻¹ but the lack of supporting data in the paper on hectarage as well as coverage of total forest means that no meaningful extrapolation can be made to TDEF sequestration rate.
<p>Kishwan <i>et al.</i> (2012) address emission removal capability of India's forest and tree cover, estimating that 37.7 Mt C yr⁻¹ were removed from 1995 to 2005 by a forest area 76.87 M ha of forest and tree cover</p> <ul style="list-style-type: none"> Calculations based on these published figures suggest a removal (carbon capture) rate of 0.049 tC ha⁻¹ yr⁻¹. However, multiple Indian forest types are considered. This may explain why figures are low compared to those of TDEF.
<p>Mani and Parthasarathy (2007) calculate above-ground biomass (AGB) estimates in ten TDEF sites of peninsular India, use of two methods calculating AGB values ranging from 39.69-173.10 Mg ha⁻¹.</p> <ul style="list-style-type: none"> Whilst this study does address TDEF sites of peninsular India, there are uncertainties created by: (1) no clarity as to whether this is dry or wet weight; (2) exclusion of roots and soil; and (3) that this is stock rather than flow (e.g. rate of sequestration). Very crudely assuming that dry mass is presented, multiplying it by 2 as a conservative allowance of root and soil carbon, and multiplying again by 0.491 to give an approximation of carbon mass, this yields a total stock range of 39.0-170.0 Mg C ha⁻¹ (= tC ha⁻¹)
<p>Gibbs <i>et al.</i> (2007) published a paper on monitoring and estimating tropical forest carbon stocks to support REDD+ implementation, citing a biomass carbon stock estimate for TDEF of 72 t C ha⁻¹ from IPCC (2007). This estimate includes below ground forest biomass, based on a number of stated assumptions, but not soil organic carbon.</p> <ul style="list-style-type: none"> Assuming that soil organic carbon is equivalent to that in biomass (observed by other authors for TDEF) this would yield a total TDEF stock estimate of 144 t C ha⁻¹ (or 528 t CO₂ ha⁻¹) If this stock value is considered robust, a sequestration value could be calculated from an assumed baseline condition pre-restoration, averaged over growth to climax community
<p>Kaul (2010) published a PhD thesis <i>Carbon budgets and carbon sequestration potential of Indian forests</i>, found that between 1992 and 2002 about 0.79 Mha of forests were lost and 4.64 Mha were reforested giving a net increase in the total forest cover of 3.87 Mha, with carbon stocks in Indian forests increasing from 2849 Tg C to 2890 Tg C (an annual increment of 4 Tg of carbon and an average density of 43 Mg C ha⁻¹) over the same period.</p> <ul style="list-style-type: none"> These figures indicate not only stock, but also that the forest resource is dynamic with reforestation and plantations and deforestation occurring simultaneously.
<p>Ravindranath and Somashekhar (1995) highlighted the need to understand carbon sequestration potential of forestry and its financial implications, estimating that then current Indian C emissions from deforestation were nearly offset by C sequestration in forests under succession and tree plantations, highlighting the need for investment as the cost per tonne of C sequestered through forestry options was lower than that for energy generation options.</p> <ul style="list-style-type: none"> This paper sheds interesting economic light on forest management for carbon without providing any new insight into actual carbon sequestration rates, and certainly not for any specific forest type.
<p>Mohapatra (2008) assessed a forestry-based carbon sequestration option for India, estimating that tropical forest in India holds on average 150-250 Mg C in live biomass which, if productivity were increased by fertilisation at a rate of 0.1% per year, would result in a net biomass C sink of 2.5 Mg C yr⁻¹.</p> <ul style="list-style-type: none"> It is not clear from the paper if this refers to a per hectare figure but, if it does and assuming that soil carbon accretes at the same rate, enhanced forest productivity could then represent a net sink of 5 tC ha⁻¹ yr⁻¹.
<p>Various Indian Forest Service reports provide estimates of gross carbon stocks in India, none of which are amenable to braking down into forest type and locality, and hence meaningfully locally relevant sequestration rates.</p>

<p>Jayakumar <i>et al.</i> (2009) observed changing perception amongst forest managers from utilization to conservation during the 1980s, following enactment of the Forest Conservation Act in 1980, but that remote sensing revealed a considerable amount of change in forest types between 1990 and 2003.</p> <ul style="list-style-type: none"> • This paper highlights the volatility of forests under different patterns of use and conservation, and so emphasises the complexity of carbon assessment whilst not providing detail on carbon dynamics.
<p>Sahu <i>et al.</i> (2016) address forest structure, composition and above ground biomass of tree communities in tropical dry forests of the Eastern Ghats.</p> <ul style="list-style-type: none"> • The focus of this promising-sounding paper is deciduous forest, so data presented are not comparable.
<p>Ravindranath and Sukumar (1998) published on climate change and tropical forests in India.</p> <ul style="list-style-type: none"> • The paper addresses the implications of climate change for forests, rather than the influence of forests on climate change and regulation processes.
<p>Visalakshi (1993) assesses the standing crop of litter and their nutrients in two TDEF stands in India, finding production of 4.3-6.1 Mg ha⁻¹ and 10.1-12.1 Mg ha⁻¹ respectively, though not extrapolating this to sequestration rate.</p>
<p>Silver <i>et al.</i> (2000) explore the potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands, reviewing literature that shows aboveground biomass increases at a rate of 6.2 Mg ha⁻¹ yr⁻¹ during the first 20 years of succession and at a rate of 2.9 Mg ha⁻¹ yr⁻¹ over the first 80 years of regrowth.</p> <ul style="list-style-type: none"> • As generic data, the study is interesting, setting a broad potential but not addressing the unique situation of TDEF on the Coromandel Coast.
<p>Véga <i>et al.</i> (2015) assessed above-ground biomass in a complex tropical Indian forest using lidar.</p> <ul style="list-style-type: none"> • This paper is of interest in terms of testing a remote sensing technological approach, but provides no useful data to address the focal problem of this paper.
<p>Nair <i>et al.</i> (2009) explored agroforestry in India as a strategy for carbon sequestration.</p> <ul style="list-style-type: none"> • This paper is conceptually interesting but contains no data relevant to the problem addressed in this paper.
<p>Manhas <i>et al.</i> (2006) undertook a temporal assessment of growing stock, biomass and carbon in Indian forests.</p> <ul style="list-style-type: none"> • This paper addresses grossed-up values of biomass and carbon in forests, considering fluxes under exploitation and regrowth, but not broken down into a form from which useful data for this study can be derived.
<p>Mishra <i>et al.</i> (2013) estimated standing carbon stock in different tree species grown in dry tropical forests of vindhyan highland, Mirzapur, India.</p> <ul style="list-style-type: none"> • Though the study seemed promising, the stand of forest was in a campus near the River Ganga in Uttar Pradesh, so very similar to TDEF on the Coromandel Coast but with no transferrable data into this study.
<p>Moghiseh <i>et al.</i> (2013) describe how soil organic carbon (SOC) storage and CO₂ flux into the atmosphere can be influenced by land use change, especially re/deforestation.</p> <ul style="list-style-type: none"> • These issues are discussed at broad scale with no transferrable data into this study.
<p>Parthasarathy <i>et al.</i> (2008) discuss the ecology and conservation significance of tropical dry evergreen forests of peninsular India.</p> <ul style="list-style-type: none"> • The studies are informative about general ecology and provision of some ecosystem services, but not specifically about carbon fluxes.

Many of the more generic references revealed from the structured search relating to extent and carbon stocks in Indian forest were already known, and have informed the Introduction of this paper. This paucity of relevant literature echoes the conclusions of Everard *et al.* (2017), the structured review yielding no substantially new analyses of carbon sequestration rate in TDEF and also confirming its distinctively high level of soil organic carbon accumulation. Of all of the publications reviewed, data in the Ramachandran *et al.* (2007) paper, ignoring the incorrect units reported on page 327 (see Table 3), provides the most defensible values from which to recalculate total potential carbon sequestration from restoration of TDEF.

Ignoring the incorrect statement of units relating to vegetation biomass carbon density of semi-evergreen forests, and receiving no response from attempts to contact the authors to access raw data, we have recalculated data provided in Tables published by Ramachandran *et al.* (2007). The flow of calculations is illustrated in Figure 2. Our recalculations and their associated generalisations and assumptions, as well as the sampling density on which the source values are based, are outlined in Appendix 1. On the basis of these methods, we determine that total TDEF carbon sequestration potential arising from restoration of TDEF from 'degraded' to 'very dense' semi-evergreen forest is 292 tC ha^{-1} , equating to a TDEF carbon dioxide equivalent sequestration potential of $1,071 \text{ tCO}_2\text{e ha}^{-1}$, with a high degree of uncertainty that is not readily quantified on the basis of available published data. The small sample size ($N=1$) of relevant forest type from which this value is derived clearly creates substantial uncertainty compounded, as observed in assessing climate-active gas emissions and sequestration in wetlands, by the sensitivity of results to methods adopted (Lloyd *et al.*, 2013). It is also acknowledged that sequestration rate in restored TDEF will be variable during succession to climax community due both to variable carbon sequestration rates and timber production throughout tropical forest life (for example Quintero-Méndez and Jerez-Rico, 2017) as well as climate change that, in Tamil Nadu, is projected to raise maximum temperature by 2.2 and 3.1°C and decrease rainfall by $1\text{--}4$ and $4\text{--}9\%$ for the periods 2035–2065 and 2065–2095 against a baseline period of 1970–2000 (Bal *et al.*, 2014). However, seeking to calculate changing sequestration rate over time against these predictions based on what is acknowledged to be a carbon sequestration rate subject to high uncertainty would generate only spurious precision. For simplicity, a linear rate of sequestration over a century to climax community is assumed, generating an illustrative annual sequestration rate of $2.9 \text{ tC ha}^{-1} \text{ yr}^{-1}$, or $10.7 \text{ tCO}_2\text{e ha}^{-1} \text{ yr}^{-1}$, with a high degree of uncertainty that is not readily quantified on the basis of available published data.

Figure 2: Flow of calculations used to transform data from Ramachandran et al. (2007) into potential carbon sequestration in restored TDEF



The distinctive character of TDEF, particularly its propensity to accumulate substantial soil organic carbon but also storage in perennial vegetative parts, means that simple application of generic carbon sequestration values such as those published by German Bundestag (1990) are unlikely to be reliable. Comparison with temperate systems, for example as provided in the Forestry Commission report *Understanding the carbon and greenhouse gas balance of forests in Britain* (Morison *et al.*, 2012), highlights the extents to which these systems are incomparable in carbon intensity and seasonal variance. Many other international studies were also excluded from our search, for example one on the Neblina Reserve rain forest in Northwest Ecuador in which it was calculated that 366 ha of forest would be protected from deforestation saving emissions of approximately 253,873 tonnes of carbon dioxide into the atmosphere over a 30 year period (Rainforest Concern, undated), from which one can calculate an average saving of 23.1 tC ha⁻¹ yr⁻¹ (or 84.8 tCO₂ ha⁻¹ yr⁻¹). However, rainforests are fundamentally different systems to dry tropical forests, with different accretion and breakdown rates in soil and biomass. Due to the distinctive nature of TDEF, comparison or data transfer from these fundamentally different systems is unsafe.

4. Discussion

TDEF appears to be at best a coarse classification of a regionally representative forest type, plastic in local form significantly influenced by local variability in both natural and human factors, as well as edge effects. As such, it is best considered as a biome with imprecise boundaries, as much reflective of 'cultural landscapes' shaped by long-term formative, destructive and potentially protective human

interventions as it is a product of natural forces. The term 'Coromandel Coast forest' may be less contentious, and therefore more helpful, if it evades some of the criticism levelled at TDEF as a strict botanical rather than a more generalised descriptor. However, recognition of TDEF as a biome exhibiting considerable plasticity in no way undermines the functional value of the classification. It may not be possible to be definitive about which tree communities constitute a 'natural' land cover, if indeed a meaningful baseline can be identified with confidence given continuing tectonic, climatic and human fluxes over extended time scales. Nevertheless, restoration of this broad forest type/biome is important to rebuild the ecology and 'carrying capacity' of ecosystem services across the degraded Coromandel Coast ecoregion, helpful in combatting climate change, hydrological perturbations including pressing coastal saline groundwater intrusion problems (Bhattacharya *et al.*, 2005; Kumar *et al.*, 2014), erosion of soil quality and quantity, and pollination of crops in a predominantly agricultural region underpinning food security concerns (Everard, 2018). Negative trends currently observed in all of these factors inhibit livelihood security and progress towards the UN Sustainable Development Goals (United Nations, 2015).

Based on the structured literature search, we suggest that functional enhancement of carbon sequestration potential likely to arise from TDEF restoration is in the order of 292 tC ha^{-1} (or $1,071 \text{ tCO}_2\text{e ha}^{-1}$). However, given the limited sample size, albeit that data presented were averaged across multiple sampling locations, this gives rise to a high degree of uncertainty that is not readily quantified, or currently quantifiable. Whilst subject to uncertainty, these calculated values provide an illustrative baseline upon which to establish an ecosystem service market for TDEF restoration. Though substantial, this value is only 16% of the value reported by Keith *et al.* (2009) as the world's highest biomass carbon density, drawing values from Van Pelt *et al.* (2004) for an Australian Central Highlands *Eucalyptus regnans* forest, which does not include stored soil carbon in TDEF which is known to be high. Our conservative approach may mean that the value recalculated for TDEF may be an underestimate. The markets being developed under the TCW developing-developed world partnership model are informed by these values, which may also prove illustrative for additional national and international markets for the service of climate regulation from TDEF. The back-calculation method used in Appendix 1 represents a novel and replicable approach for deriving illustrative sequestration estimates from formerly published summary data on forest carbon storage where empirical data is lacking, supporting further research and indicative policy directions. Further work is required to test this method in a range of forest and, potentially, other habitat types.

Climate regulation is just one of a linked set of ecosystem services provided by restored TDEF, for example with educational, traditional medicinal, handicraft and business-supporting services at Nadukuppam and Pitchandikulam amongst a broader range of beneficially co-produced ecosystem services (Everard *et al.*, 2017). Optimisation of all potential services in management policy and practice is necessary to address a linked set of human needs, as articulated by the UN Sustainable Development Goals (Everard and Longhurst, 2018). Recognition of this diversity of potentially co-generated values should advise caution on TDEF management approaches such that maximisation of a narrow, focal service does not preclude or compromise a wider range of ecosystem service benefits (Millennium Ecosystem Assessment, 2005). Furthermore, in agreement with Everard *et al.* (2017), there

remains a need to quantify the potentially substantial multiple and multi-scalar benefits achieved through co-production of additional ecosystem services arising from restoration of TDEF and other currently degraded regional habitats, contributing to cumulative societal security and value, and also potentially bolstering international PES markets.

5. Conclusions

Further consensus is required on appropriateness of terminology to describe the regionally representative natural or semi-natural forest type on the Coromandel Coast. The term 'Coromandel Coast forest' may be less contentious, and therefore more helpful, if it evades criticism of the term 'tropical dry evergreen forest' (TDEF).

Literature directly addressing, or amenable to confident extrapolation of, carbon sequestration potential in TDEF is very sparse. Though methods and stated assumptions used by Everard *et al.* (2017) have been tested and found to be robust, input data on carbon stocks in TDEF were discovered to be calculated from incorrectly stated units published by Ramachandran *et al.* (2007), leading to overestimation of carbon sequestration potential. Nevertheless, summary data published by Ramachandran *et al.* (2007) are still the most appropriate available source from which to calculate potential sequestration rates from TDEF restoration. We have recalculated new values in this study on the basis of data presented in Tables within the Ramachandran *et al.* (2007) paper, using a range of stated assumptions and statistical techniques that are acknowledged as introducing further uncertainty.

Following detailed literature review and recalculation, our best estimate based on a limited dataset of the sequestration potential of TDEF restored from 'degraded' to 'very dense' semi-evergreen forest on the Coromandel Coast is 292 tC ha^{-1} . This equates to a carbon dioxide equivalent sequestration potential of $1,071 \text{ tCO}_2\text{e ha}^{-1}$. There is clearly a high degree of uncertainty that is not readily quantified. In deriving these values, we have avoided spurious certainty by assuming no change in the forest system in terms of climate and environmental management, although the wider literature suggests that India's forest extent and condition remains volatile and that the local climate is likely to change. Consequently, we recommend that further research is undertaken to explore the implications of current and planned land uses on the ecosystem services provided by TDEF, with a view to informing more sustainable management policies and practices to enhance the provision of beneficial services.

In addition to suggesting carbon sequestration potential, we also highlight a substantial knowledge gap introducing significant uncertainties and ambiguities. There is therefore a need for further targeted research on actual rates of carbon sequestration, taking into account both above-ground and below-ground carbon in TDEF and other localised forest types to support more robust policies, PES markets and other restoration initiatives.

There is an additional need to quantify the multiple and multi-scalar benefits likely to be achieved through co-production of a linked set of ecosystem services,

contributing to overall societal benefits arising from restoration of TDEF/‘Coromandel Coast forest’ and other regionally appropriate habitats. Forest restoration and management policies and practices should be cognisant of these wider societal benefits, ensuring that they are not compromised by a narrow focus on carbon sequestration. Further work is required to quantify these broader potential benefits, informing future land use strategies in order to better meet a diversity of human needs.

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6. References

- Bal, P.K., Ramachandran, A., Geetha, R., Bhaskaran, B., Thirumurugan, P., Indumathi, J. and N Jayanthi, N. (2014). Climate change projections for Tamil Nadu, India: deriving high-resolution climate data by a downscaling approach using PRECIS. *Theoretical and Applied Climatology*, 123(3-4), pp.523–535.
- Balvanera, P., Quijas, S., Martín-López, B, *et al.* (2016, p.48). The links between biodiversity and ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R. and Turner, R.K. (eds). *Routledge Handbook of Ecosystem Services*. Routledge: London. pp.45-61.
- Begley, V. (1993). New investigations at the port of Arikamedu. *Journal of Roman Archaeology*, 6, pp.93-108.
- Begley, V., Francis, P.J., Mahadevan, I., Raman, K.V., Sidebotham, S.E., Slane, K.W. and Will, E.L. (1996). *The Ancient Port of Arikamedu*. École Française d’Extrême-Orient, Paris.
- Bhattacharya, A.K., Basak, S., Maity, P., Paira, L.K., Sarkar, S. and Maji, S.C. (2005). Hydrogeology of the Bay of Bengal Coast of India with Special Emphasis on Saline Water Intrusion. *Electronic Journal of Geotechnical Engineering*, 0477. [online]. (<http://www.ejge.com/2004/Ppr0477/Ppr0477.htm>, accessed 04th November 2017.)
- Chandra, M. (2011). *Trade and trade routes in ancient India*. Abhinav Publications, Buldana, Maharashtra. 274pp.
- Chaturvedi, R.K., Raghubanshi, A.S. and Singh, J.S. (2011). Carbon density and accumulation in woody species of tropical dry forest in India. *Forest Ecology and Management*, 262(8), pp.1576-1588.

Chhabra, A., Palriab, S. and Dadhwal, V.K. (2003). Soil organic carbon pool in Indian forests. *Forest Ecology and Management*, 173(1-3), pp.187-199.

Diáz, S., Hector, A., and Wardle, D.A. (2009). Biodiversity in forest carbon sequestration initiatives: not just a side effect. *Current Opinion in Environmental Sustainability*, 1, pp.55-60.

Everard, M. (2014). Nature's marketplace. *The Environmentalist*, March 2014, pp.21-23.

Everard, M. (2018). The characteristics, representativeness, function and conservation importance of tropical dry evergreen forest (TDEF) on India's Coromandel Coast. *Journal of Threatened Taxa*, 10(6), pp.11760-11769.

Everard, M. and Longhurst, J.W.S. (2018). Reasserting the primacy of human needs to reclaim the 'lost half' of sustainable development. *Science of the Total Environment*, 621, pp.1243-1254.

Everard, M., Longhurst, J.W.S., Pontin, J., Stephenson, W. and Brooks, J. (2017). Developed-developing world partnerships for sustainable development (1): an ecosystem services perspective. *Ecosystem Services*, 24, pp.241-252.

Field, C.B., Behrenfeld, M.J., Randerson, J.T., and Falkowski, P. (1998). Primary production of the biosphere: integrating terrestrial and oceanic components. *Science*, 281, pp.237-240.

FSI (2003). *State of the Forest Report 2003*. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

Forestry and Wildlife Statistics of India. (2004). National Afforestation and Eco-Development Board, Ministry of Environment and Forest, Govt. of India.

German Bundestag. (1990). *Protecting the Tropical Forests: A High Priority International Task*. Bonner Universitäts-Buchdruckerei, Bonn.

Gibbs, H.K., Brown, S., Niles, J.O. and Foley, J.A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters*, 2, 045023.

Indiaonline. (Undated). *Population of Tamil Nadu*. Indiaonline. (<http://www.indiaonlinepages.com/population/tamil-nadu-population.html>, accessed 25th April 2018.)

IPCC. (2000). Chapter 3: Afforestation, reforestation and deforestation activities. In: Watson, R., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. and Dokken, D.J. (Eds.). *Land use, land use change, and forestry: a special report of the Intergovernmental Panel for Climatic Change (IPCC)*. Cambridge University Press, Cambridge, p 377.

IPCC. (2001). *Climate change 2001: the scientific basis*. IPCC third assessment report, Working group I, Technical Summary. Cambridge University Press, Cambridge

IPCC. (2007). *Climate Change 2007: The Scientific Basis*. IPCC fourth assessment report, Working Group I. Available online at <http://www.ipcc.ch>.

Jayakumar, S., Ramachandran, A., Bhaskaran, G. and Heo, J. (2009). Forest Dynamics in the Eastern Ghats of Tamil Nadu, India. *Environmental Management*, 43(2), pp.326–345.

Jha, M.N., Gupta, M.K., Alok, S. and Rajesh, K. (2003). Soil organic carbon store in different forests in India. *Indian Forester*, 129(6), pp.714–724.

Joshi, M. and Singh, P.P. (2003). *Carbon sequestration by rehabilitating degraded forests in India*. XII World Forestry Congress, Quebec City, Canada. (Available at <http://www.fao.org/docrep/ARTICLE/WFC/XII/0405-B2.HTM>, accessed 04th November 2017.)

Kaul, M. (2010). *Carbon budgets and carbon sequestration potential of Indian forests*. PhD thesis, Wageningen University, Wageningen, the Netherlands

Kaul, M., Dadhwal, V.K. and Mohren, G.M.J. (2009). Land use change and net C flux in Indian forests. *Forest Ecology and Management*, 258, pp.100–108.

Kaul, M, Mohren, G.M.J. and Dadhwal, V.K. (2010). Carbon storage and sequestration potential of selected tree species in India. *Mitigation and Adaptation Strategies for Global Change*, 15, pp.489-510.

Keith, H., Mackey, B.G. and Lindenmayer, D.B. (2009). Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *PNAS*, 106(28), pp.11635-11640.

Kishwan, J., Pandey, R. and Dadhwal, V.K. (2012). Emission Removal Capability of India's Forest and Tree Cover. *Small-scale Forestry*, 11(1), pp.61–72.

Kumar, S.K., Bharani, R., Magesh, N.S., Godson, P.S. and Chandrasekar, N. (2014). Hydrogeochemistry and groundwater quality appraisal of part of south Chennai coastal aquifers, Tamil Nadu, India using WQI and fuzzy logic method. *Applied Water Science*, 4(4), pp.341–350.

Lal, M. and Singh, R. (2000). Carbon sequestration potential of Indian forests. *Environ Monit Assess*, 60, pp.315–327.

Lloyd, C.R., Rebelo, L-M. and Finlayson, C.M. (2013). Providing low-budget estimations of carbon sequestration and greenhouse gas emissions in agricultural wetlands. *Environmental Research Letters*, 8, 015010 (13pp) doi:10.1088/1748-9326/8/1/015010.

Madeira, E.C.M. (2008). Forests and carbon cycle. In: Foerster, A. and Atwater, S. (Eds.), *Policies to reduce emissions from deforestation and degradation (REDD) in developing countries: an examination of the issues facing the incorporation of REDD into market-based climate policies*. Resource for the Future Press, Washington DC. pp.18-30.

Malhi, Y., Baldocchi, D.D. and Jarvis, P.G. (1999). The carbon balance of tropical, temperate and boreal forests. *Plant, Cell and Environment*, 22, pp.715-740.

Manhas, R.K., Negi, J.D.S., Kumar, R. and Chauhan, P.S. (2006). Temporal Assessment of Growing Stock, Biomass and Carbon Stock of Indian Forests. *Climatic Change*, 74(1-3), pp.191–221.

Mani, S. and Parthasarathy, N. (2007). Above-ground biomass estimation in ten tropical dry evergreen forest sites of peninsular India. *Biomass and Bioenergy*, 31, pp.284-290.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V. and Gordon, J.E. (2006). A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, 33, pp.491-505.

Millennium Ecosystem Assessment. (2005). *Ecosystems & Human Well-being: Water and Wetlands Synthesis*. World Resources Institute: Washington DC.

Mishra, A.K., Singh, J., Kumar, V., Srivastava, R. and Srivastava, S. (2013). Standing carbon stock estimation in different tree species grown in dry tropical forests of vindhyan highland, Mirzapur, India. *Ecology, Environment and Conservation*, 19(2), pp.401-407.

Meijerink, G.W. (2008). The Role of Measurement Problems and Monitoring in PES Schemes. In: Dellink, R.B. and Ruijs, A. (eds) *In Economics of Poverty, Environment and Natural-Resource Use*. Wageningen: Wageningen UR Library, 61-85.

Moghiseh, E., Heidari, A. and Ghannadi, M. (2013). Impacts of deforestation and reforestation on soil organic carbon storage and CO₂ emission. *Soil and Environment*, 32(1), pp.1-13.

Mohapatra, A.K. (2008). Forestry based carbon sequestration option for India. *Indian Journal of Forestry*, 31(4), pp.483-490.

Morison, J., Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012). *Understanding the carbon and greenhouse gas balance of forests in Britain*. Forestry Commission Research Report. Forestry Commission, Edinburgh. i–vi + 1–149 pp.
([https://www.forestry.gov.uk/pdf/fcrp018.pdf/\\$file/fcrp018.pdf](https://www.forestry.gov.uk/pdf/fcrp018.pdf/$file/fcrp018.pdf), accessed 04th November 2017.)

Nair, P.K.R., Kumar, B.M. and Nair, V.D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*, 172(1), pp.10–23.

Niles, J.O., Brown, S., Pretty, J., Ball, A.S. and Fay, J. (2002). Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. *Philosophical Transactions of Mathematical, Physical and Engineering Sciences*, 360, pp.1621-1639.

Parthasarathy, N., Selwyn, M.A. and Udayakumar, M. (2008). Tropical dry evergreen forests of peninsular India: ecology and conservation significance. *Tropical Conservation Science*, 1(2), pp.89-110.

Potschin, M. and Haines-Young, M. (2016). Defining and measuring ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R. and Turner, R.K. (eds). *Routledge Handbook of Ecosystem Services*. Routledge: London. pp.25-44.

Quintero-Méndez, M.A. and Jerez-Rico, M. (2017). Heuristic forest planning model for optimizing timber production and carbon sequestration in teak plantations. *iForest*, 10, pp.430-439.

Rainforest Concern. (Undated). *Projects: Neblina Reserve, Northwest Ecuador*. Forest Credits by Rainforest concern.
(http://www.forestcredits.org.uk/projects?qclid=CjwKCAjw6ZLOBRALEiwAxzyCW38e6l1gS4_K_dTo1cq3zljPp_xasBAAbC5AKSOuF7pegLB8_ZLpL_BoCv7AQAvD_BwE, accessed 25th April 2018.)

Ramachandran, A.S., Jayakumar, R.M., Haroon, A.B. and Arockiasamy, D.I. (2007). Carbon Sequestration: estimation of carbon stock in natural forests using geospatial technology in the Eastern Ghats of Tamil Nadu, India. *Current Science*, 92(3), pp.323-331.

Ravindranath, N.H. and Somashekhar, B.S. (1995). Potential and economics of forestry options for carbon sequestration. *India Biomass and Bioenergy*, 8(5), pp.323-336.

Ravindranath, N.H. and Sukuma, R. (1998). Climate change and tropical forests in India. *Climate Change*, 39, pp.563-581.

Ravindranath, N.H., Somasekhar, B.S. and Gadgil, M. (1997). Carbon flows in Indian forest. *Climatic Change*, 35(3), pp.297–320.

Sahu, S.C., Suresh, H.S. and Ravindranath, N.H. (2016). Forest Structure, Composition and Above Ground Biomass of Tree Community in Tropical Dry Forests of Eastern Ghats, India. *Notulae Scientia Biologicae*, 8(1), pp.125–133.

Schomers, S. and Matzdorf, B. (2013). Payments for ecosystem services: a review and comparison of developing and industrialized countries. *Ecosystem Services*, 6, 16-30.

Sharma, V. and Chaudhry, S. (2013). An Overview of Indian Forestry Sector with REDD+ Approach. *ISRN Forestry*, 2013, article ID 298735 (10 pages, <http://dx.doi.org/10.1155/2013/298735>).

Silver, W.L., Ostertag, R. and Lugo, A.E. (2000). The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. *Restoration Ecology*, 8(4), pp.394–407.

Singh, L. and Singh, J.S. (1991). Species structure, dry matter dynamics and carbon flux of a dry tropical forest in India. *Annals of Botany*, 68(3), pp.263-273.

Sommerville, M.M., Milner-Gulland, E.J. and Jones, J.P.G. (2011). The challenge of monitoring biodiversity in payment for environmental service interventions. *Biological Conservation*, 144(12), 2832-2841.

United Nations. (2008). *UNFCCC Report on the Conference of the Parties on its Thirteenth Session, Held in Bali from 3 to 15 December 2007*. Part Two: Action Taken by the Conference of the Parties at its Thirteenth Session 8-10 (United Nations, 2008).

United Nations. (2014). *FORESTS New York Declaration on Forests: Action Statements and Action Plans*. United Nations, New York.
(<http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forest-%E2%80%93Action-Statement-and-Action-Plan.pdf>, accessed 04th November 2017.)

United Nations. (2015). Resolution adopted by the General Assembly on 25 September 2015: 70/1. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations General assembly, New York.
(http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E, accessed 04th November 2017.)

Van Pelt, R., Sillett, S.C., Nadkarni, N.M. (2004). Quantifying and visualizing canopy structure in tall forests: Methods and a case study. In: Lowman, M.D. and Rinker, H.B. (eds) *Forest Canopies*. Elsevier Academic, San Diego. pp 49–72.

Véga, C., Vepakomma, U., Morel, J., Bader, J-L., Rajashekar, G., Jha, C.S., Ferêt, J., Proisy, C., Péliissier, R. and Dadhwal, V.K. (2015). Aboveground-Biomass Estimation of a Complex Tropical Forest in India Using Lidar. *Remote Sensing*, 7(8), pp.10607-10625.

Visalakshi, N. (1993). Litterfall, standing crop of litter and their nutrients in two tropical dry evergreen forests in India. *International Journal of Ecology and Environmental Sciences*, 19(3), pp.163-180.

Appendix 1: Extrapolating from data in Tables published by Ramachandran *et al.* (2007)

This Appendix contains calculations on forest and carbon figures published in a series of Tables in Ramachandran *et al.* (2007) to generate an approximate value of CO₂ equivalent (CO₂e) sequestration potential in TDEF.

Calculations by Ramachandran *et al.* (2007):

- Use an above-ground timber volume assessment method, then apply another method to extrapolate roots and stumps;
- Carbon content is then derived from total biomass using “...the minimum value of 49.1...” as a 1 conversion factor (we assume 0.491 of total biomass); and on this basis recalculating from information presented in tables rather than as presented with the wrong units in text of page 327;
- Total carbon content is of 0.6 Tg in a total of 3,962.23 ha area of semi-evergreen forest, equivalent to 151 tC ha⁻¹.

A problem arises in using these recalculated values to determine sequestration potential as the 0.6 Tg is a gross figure for the total stock of ‘semi-evergreen forest’ (3,962.23 ha in area), inclusive of all four categories of ‘very dense’, ‘dense’, ‘open’ and ‘degraded’ forest. The 0.6 Tg figure therefore represents an average, and can not be used to reflect progression from one state of semi-evergreen forest to another. The grossed up 0.6 Tg value is therefore not a safe basis for calculating potential sequestration.

In the absence of raw data, and after unsuccessful attempts to find current addresses for authors of the source paper, we have drawn information from Tables presented by Ramachandran *et al.* (2007) as a basis for recalculation as described below.

Biomass density in different forest states

Ramachandran *et al.* (2007, p.325), in the section *Estimation of biomass carbon*, report that twenty-five 20x20m samples were taken for each of five forest types (including evergreen forest).

Ramachandran *et al.* (2007, p.326) state that: “The total area under the semi-evergreen forest type is about 3962 ha that comprises 15% of the total forest area (Table 1). This forest type has been classified further into four subclasses based on the crown density, viz. very dense (> 70%), dense (40–70%), open (10–40%) and degraded (< 10%). The very dense semi-evergreen forest occupies 1984 ha which is 50% of the total semi-evergreen forest. About 25 and 21% of the semi-evergreen forests are under dense and open respectively. Only 4% is under degraded semi-evergreen”

Extrapolating these percentages, with admittedly a high degree of simplification:

- ‘Very dense’ = >7 times the density of ‘Degraded’ semi-evergreen forest;

- 'Very dense semi-evergreen forest' occupies 1,984 ha of total area 3,962.23 ha = 50.0% (at minimum 70% crown density);
- 'Dense' and 'Open' forest net up to 46% area, which I calculate = 1,822.63 ha (mean 40% crown density); and
- 'Degraded' area <4%, which assuming 4% = 158.49 ha (maximum 10% crown density).

On the basis of the figures above, acknowledging errors inherent in simplifying available figures but taking the conservative measure of '>70%' = 70 and '10%' = 10:

- $0.6 \text{ Tg} = (70\% \text{ density at } 50\% \text{ area}) + (40\% \text{ density at } 46\% \text{ area}) + (10\% \text{ density at } 4\% \text{ area})$
- Therefore, overall, $1 \text{ unit} \times 4(\%) + 4 \text{ units} \times 46(\%) + 7 \text{ units} \times 50(\%) = 538 \text{ units}$ (comprising total 0.6 Tg)
- Implies that one unit = 1,115,241,636 g, so therefore...
 - 'Very dense semi-evergreen forest':
 - Total C = 350 (7x50) units @ 1,115,241,636 g = 0.390 Tg
 - $0.390 \text{ Tg} / 1,984 \text{ ha} = 197 \text{ tC ha}^{-1}$
 - 'Dense semi-evergreen forest' and 'Open ever-green forest' combined:
 - Total C = 184 (4x46) units @ 1,115,241,636 g = 0.205 Tg
 - $0.205 \text{ Tg} / 1,822.63 \text{ ha} = 113 \text{ tC ha}^{-1}$
 - 'Degraded semi-evergreen forest'
 - Total C = 4 (1x4) units @ 1,115,241,636 g = 0.004 Tg
 - $0.004 \text{ Tg} / 158.49 \text{ ha} = 25 (25.423) \text{ tC ha}^{-1}$
 - Implying that biomass carbon sequestration potential moving from 'Degraded semi-evergreen forest' to 'Very dense semi-evergreen forest' is $197 - 25 = 172 \text{ tC ha}^{-1}$

Soil carbon in different forest states

In Table 2 (page 327), Ramachandran *et al.* (2007) present mean values for SOC at top (0 to 30 cm), middle (30 to 60 cm) and bottom (60 to 90 cm) soil depth.

Ramachandran *et al.* (2007, p.325), in the section *Estimation of SOC*, report that soil samples were collected at 145 locations. Across the five forest types assessed, this averages 29 soil samples per forest type.

- "Very dense evergreen" mean values (we assume as this is not stated) for layers are 3.70, 2.21 and 1.82%C
 - Acknowledging uncertainties created by calculation a new mean from three different means, and also that soil profiles beneath the top 90cm are not significant carbon repositories, this yields a value of 2.58% C in the surface 0 90cm of soil
- "Degraded evergreen" mean values (I assume as not stated) for layers are 2.40, 1.10 and 0.91%C

- Acknowledging uncertainties created by calculation a new mean from three different means, and also that soil profiles beneath the top 90cm are not significant carbon repositories, this yields a value of 1.47% C in the surface 0 90cm of soil

So, if we know what the soil weighs (assume dry weight?) we can calculate SOC for the first 90cm:

- 1 ha = 10^4 m², so 0.9m profile = 9,000 m³
- If “One cubic meter of soil weighs between 1.2 and 1.7 metric tonnes” (source: <https://www.reference.com/science/much-cubic-meter-soil-weigh-e48660fa83d913ab>) then it follows that mean % C x hectare weight yields:
 - “Very dense evergreen” = mean 2.58%C of 9,000 m³ x 1.2 tonnes = 278.64 tC per hectare
 - “Degraded evergreen” = mean 1.47%C of 9,000 m³ x 1.2 tonnes = 158.76 tC per hectare
 - Implies SOC sequestration potential = 119.88 tC per hectare (e.g. 278.64 ‘very dense’ minus 158.76 ‘degraded’ tC per hectare)
 - Note that this is a conservative basis for calculation, as we are mainly dealing with TDEF restoration on degraded and generally highly laterised farmed land, likely to have a far lower carbon content than degraded forest
 - There is nevertheless a level of assurance that the values of SOC are broadly in the same range as those for biomass, according with literature observations on proportions found in TDEF and similar forests (Ravindranath *et al.*, 1997; Malhi *et al.*, 1999; Ramachandran *et al.*, 2007; Kaul *et al.*, 2010)

Adding biomass and soil carbon together in different forest states

Adding the biomass carbon and SOC together we have:

- Biomass carbon sequestration potential = 172 tC ha⁻¹ restoring from ‘degraded’ to ‘very dense’ semi-evergreen forest
- Soil carbon (SOC) sequestration potential = 119.88 tC per hectare restoring from ‘degraded’ to ‘very dense’ semi-evergreen forest
- THEREFORE, **total carbon sequestration potential = 292 tC ha⁻¹** (194 + 120 [119.88]) restoration from ‘degraded’ to ‘very dense’ semi-evergreen forest
- By calculation using the assumptions in Table 2, this produces a **total carbon dioxide equivalent sequestration potential = 1,071 tCO₂e ha⁻¹**

Confidence limits

These figures are highly uncertain, and so should always be interpreted and applied with caution. The sparse data from which they are calculated does not allow for confident calculation of error. However, Ravindranath *et al.* (2007) present data (Table 3, page 328) of a mean soil organic carbon

(SOC) of 184.00 tC ha⁻¹ with a standard deviation of 123.13 in 'Total evergreen' forest. We recognise a high degree of uncertainty, but that this is not readily quantified on the basis of available published summary data. Further primary data and methodological refinement is necessary to better quantify uncertainty.

All of these values are subject to the assumptions, generalisations and uncertainties noted above.

End of Appendix 1