CAPACITY FOR CARBON SEQUESTRATION AND CLIMATE CHANGE MITIGATION IN DIFFERENT ECOLOGICALLY-DISTINCT ZONES OF SRI LANKA

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ABSTRACT

The capacity of vegetation for carbon sequestration and mitigation of long-term climate change was estimated for Sri Lanka using a combination of four dynamic global vegetation models, namely, NCAR-CLM4, LPJ, LPJ-GUESS and TRIFFID. All models simulated the major processes of carbon acquisition (e.g. photosynthesis) and emission (e.g. autotrophic and heterotrophic respiration) by vegetation ecosystems while selectively estimating other sources of carbon emissions (e.g. fire, land use change, riverine export etc.) on latitude x longitude grids of 0.5° x 0.5° (NCAR-CLM4, LPJ and LPJ-GUESS) and 3.75° x 2.5° (TRIFFID) over a 110-year period from 1901 to 2010. Carbon sequestration capacity was estimated as the atmosphere-to-land flux of annual Net Biome Productivity (NBP), defined as the difference between the annual flux of gross primary productivity (GPP) and the combined fluxes of autotrophic (Ra) and heterotrophic respiration (Rh) and the disturbance flux (D). Two separate simulations were run: S1 with varying atmospheric CO_2 at fixed pre-industrial climate and S2 with varying CO_2 and climate. Model outputs for eight 1° x 1° grid cells covering Sri Lanka were used in the present study. Weighted average NBP (S2) for the whole of Sri Lanka did not show a statistically-significant ($p = 0.05$) increasing or decreasing trend over the entire 110-year period. However, it showed substantial inter-annual variation ranging from -197 gC m^{-2} yr^{-1} to 122 gC m^{-2} yr^{-1}. On the other hand, mean NBP (S2) for defined periods showed that on average, Sri Lanka was a net carbon sink for the periods 1901-1969 and 1970-1979 with respective strengths of 5.98 and 10.05 gC m^{-2} yr^{-1}. Notably, Sri Lanka was a net carbon source during the 1980s and 1990s with mean decadal NBP (S2) of -29.61 and -12.87 gC m^{-2} yr^{-1} respectively. Sri Lanka reverted back to a net carbon sink during the 2000-2010 periods with a mean NBP (S2) of 35.81 gC m^{-2} yr^{-1}. The time course of NBP (S1) showed a significant ($p=0.019$) increasing trend (0.204 gC m^{-2} yr^{-1}) indicating a positive CO_2 fertilization effect plus other positive impacts of increasing CO_2 (e.g. increased water use efficiency). On the other hand, the impact of climate change during the 110-year period, as estimated by NBP (S2-S1), showed a decreasing trend (-0.162 gC m^{-2} yr^{-1}), which however, was not significant ($p = 0.402$) primarily because of its substantial inter-annual variation. However, a highly-significant ($p < 0.0001$) positive linear relationship between NBP (S2-S1) and NBP (S2) over the whole 110-year period, with a slope of less than one (i.e. 0.973) indicated an overall negative impact of climate change on the land carbon sink of Sri Lanka. Estimation of NBP of six designated ecologically-distinct zones (EDZs) of Sri Lanka showed significant variation in the strength of the land carbon sink and its temporal trends between different EDZs. Based on our estimates of NBP(S2) and the reported national CO_2 emission data, we estimate that during the 2000-2010 period, the land biosphere of Sri Lanka absorbed 68.4% of its carbon emissions from fossil fuel burning and cement production.

INTRODUCTION

Vegetation has the capacity to mitigate greenhouse gas (GHG)-induced climate change by absorbing and sequestering carbon dioxide, the principal GHG, in plant biomass (Field *et al.*, 1998; Malhi and Grace, 2000). Le Quéré *et al.*, (2009) have estimated that at the global scale, the land biosphere absorbs 29% of the anthropogenic CO_2 emissions. Sri Lanka, an island located in the humid tropical South Asia, has a considerable range of ecologically-distinct zones (EDZs) as a result of the spatial and temporal variation of its climate (Domroes, 1974). These EDZs are characterized by different dominant vegetation types and ecosystems with varying ground cover (Koelmeyer, 1957). Hence, the carbon sequestration capacity which determines the strength of the 'land carbon sink' is likely to vary in the different EDZs. Analysis of long-term climatic data has shown that trends of climate change (e.g. increasing atmospheric temperature and potential evapotranspiration and decreasing precipitation and soil water availability) of the different climatic zones of Sri Lanka reflect the established global trends (Chandrapala, 1996; Domroes, 1996; Malmgren *et al.*, 2003; De Costa, 2008 & 2009). These trends in climate change are likely to modify the carbon sequestration capacity of different EDZs over time. Therefore, the objective of this work is to estimate the carbon sequestration and climate change mitigation capacity of different EDZs of Sri Lanka and its historical variation to determine the possible impacts of climate change.

There have been several recent and on-going efforts to quantify the components of the carbon cycle at (Friedlingstein *et al.*, 2010; Sarmiento *et al.*, 2010; Ballantyne *et al.*, 2012; Piao *et al.*, 2013; Sitch *et al.*, 2013), continental (Janssens *et al.*, 2003; Ciais *et al.*, 2009; Gloor *et al.*, 2012), regional (Piao *et al.*, 2012; Patra *et al.*, 2013) and national (Pacala *et al.*, 2001; Piao *et al.*, 2009) scales. A variety of different approaches have been used including top-down approaches such as inversion of atmospheric CO_2 measurements and bottom-up approaches such as land-based dynamic global vegetation models (DGVMs). Based on an ensemble of nine DGVMs, Sitch *et al.*, (2013) estimated a mean global land carbon sink of 2.0 ± 0.8 Pg C yr^{-1} during the period from 1980 to 2009. The sign convention throughout this paper is based on an atmosphere-to-land surface carbon flux (i.e. a carbon sink) being considered as positive. The estimate of Piao *et al.*, (2013) is very close to the estimated global residual land sink (RLS) of 2.1 ± 1.2 Pg C yr^{-1} by Friedlingstein *et al.*, (2010). Sarmiento *et al.*, (2010) estimated the net land carbon sink (NLS) by subtracting the sum of model estimated oceanic CO_2 uptake and atmospheric CO_2 growth rate from fossil fuel emissions and showed that the NLS increased rather abruptly in strength from a relatively stable level of 0.27 Pg C yr^{-1} during the period from 1960 to 1988 to a new average level of 1.15 Pg C yr^{-1} during the 1989-2003/7 period. Using global-scale atmospheric CO_2 measurements and CO_2 emission inventories, Ballantyne *et al.*, (2012) also showed an increase in the combined land and ocean carbon sink from 2.4 ± 0.8 to 5.0 ± 0.9 Pg C yr^{-1} from 1960 to 2010.

Strength of the terrestrial carbon sink has been estimated for most continents. Janssens *et al.*, (2003), using a combination of atmosphere- and land-based approaches, estimated Europe's terrestrial biosphere to be a net carbon sink of 0.135 – 0.205 Pg C yr^{-1} . Using the land process-based dynamic vegetation model ORCHIDEE, Ciais *et al.*, (2009) estimated the terrestrial carbon balance of the African Continent and found that the net terrestrial carbon balance (i.e. the Net Biome Productivity) increased from -0.14 Pg C yr^{-1} in the 1980s to 0.15 Pg C yr^{-1} in the 1990s. Gloor *et al.*, (2012) estimated the carbon balance of South America by estimating the carbon fluxes from fossil fuel use, deforestation and land use change, riverine, agricultural and wood export and uptake from old-growth forests using a variety of methods and approaches. In contrast to the increasing trends shown at the global scale (Sarmiento *et al.*, 2010; Ballantyne *et al.*, 2012; Sitch *et al.*, 2013), the South American Continent was shown to be a net source of ~ 0.3 – 0.4 Pg C yr^{-1} during the 1980s, a near neutral C balance of ~ 0.1 Pg C yr^{-1} in the 1990s and a net source ~ 0.28 –

0.51 PgC yr^{-1} from 2000 to 2009. (Gloor *et al.,* 2012). Increased emissions from deforestation and land use change and reduced forest carbon sink in the Amazon basin due to drought-induced tree mortality and decay were identified as the major causes of increased strength of the net carbon source from South America.

Several regional estimates of the terrestrial carbon balance have been done recently as part of the RECCAP (Regional Carbon Cycle Assessment Processes) effort. Piao *et al.,* (2012) estimated the carbon balance of East Asia (*i.e.* China, Japan, Korea and Mongolia) by three different approaches (*i.e.* inventory and satellite greenness, DGVMs and atmospheric inversion) which converged on a range of 0.224 – 0.293 Pg C yr^{-1} for the 1990 – 2009 period, thus indicating a net carbon sink in this region. Patra *et al.,* (2013) estimated the carbon budget of South Asia (*i.e.* Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka) using both top-down (*i.e.* atmospheric inversion) and bottom-up methods (*i.e.* field observations, satellite data and an ensemble of ten DGVMs) and found a terrestrial biospheric carbon sink (in terms of NBP) of 0.104 ± 0.15 Pg C yr^{-1} (top-down) to 0.191 ± 0.193 Pg C yr^{-1} (bottom-up) for the 2000-2009 period. However, this was offset by a larger emission component so that the South Asian region was a net carbon source of 0.297 ± 0.244 Pg C yr^{-1}.

There have been only a few national estimates, especially in the tropics, of the strength of the terrestrial carbon sink. Pacala *et al.,* (2001), using both atmosphere- and land-based methods, estimated a net terrestrial carbon sink for the coterminous United States (*i.e.* USA excluding Alaska and Hawaii) of a strength ranging from 0.30 to 0.58 Pg C yr^{-1}. A smaller sink of 0.19 – 0.26 Pg C yr^{-1} was estimated for China by Piao *et al.,* (2009). The present study aims to estimate the terrestrial carbon balance of Sri Lanka, which is a much smaller landmass than either China or USA, using the bottom-up approach of ground-based terrestrial ecosystem models.

METHODOLOGY

Estimation of net biome productivity

The carbon sequestration capacity of the land biosphere was estimated as the Net Biome Productivity (NBP), the balance between the rates of land surface processes that acquire carbon from the atmosphere and those that release carbon from land to atmosphere. Accordingly, the annual flux of NBP from atmosphere to land was defined as,

$$\mathbf{NBP = GPP - Ra - Rh - D} \qquad \text{(eq. 1)}$$

Where, GPP is gross primary productivity, Ra and Rh the autotrophic and heterotrophic respirations and D the carbon emissions from land to the atmosphere due to disturbances such as land use change and fire. A positive value of NBP indicates a land carbon sink whereas a negative value indicates a land carbon source. A bottom-up dynamic simulation modelling approach was used to estimate NBP.

Models and simulations

An ensemble of four dynamic global vegetation models (DGVMs) was used to simulate NBP by estimating the components of eq. 1 during the period from 1901 to 2010. The DGVMs used were NCAR-CLM4 (Lawrence *et al.,* 2011), LPJ (Sitch *et al.,* 2003), LPJ-GUESS (Smith *et al.,* 2001) and TRIFFID (Cox, 2001). NCAR-CLM4, LPJ and LPJ-GUESS ran at a spatial resolution of 0.5° (latitude) x 0.5° (longitude) while TRIFFID ran at the coarser resolution of 3.75° x 2.5°. The four DGVMs have different origins and approaches and are different in the biogeochemical processes that are taken in to account when simulating NBP. For example, NCAR-CLM4 takes in to account the full N-cycle in its simulation while the others do not. Fire simulation is included in all models except TRIFFID. NCAR-CLM4 and TRIFFID includes a land surface model while LPJ and LPJ-GUESS do not. NCAR-CLM4 and TRIFFID ran at a 0.5 hour time step whereas LPJ and LPJ-GUESS ran with a daily time step.

Two simulations of the models, termed S1 and S2, were run globally; S1 was run with varying atmospheric CO_2 with fixed pre-industrial climate whereas S2 was run with varying CO_2 and varying climate. Both simulations were run with fixed present-day land use mask. Climate forcing data from CRU-NCEP monthly data sets at a spatial resolution 0.5° x 0.5° were used for the simulations. The CRU-NCEP data for the eight 1° x 1° grid cells covering Sri Lanka were validated from on-station precipitation and air temperature data obtained from the Department of Meteorology, Sri Lanka for selected locations (Results not shown). Outputs of all models, initially obtained for the respective spatial resolutions of the different models, were adjusted to a spatial resolution of 1° x 1°.

Classification of ecologically-distinct zones of Sri Lanka

The eight 1° x 1° grid cells of Sri Lanka were classified in to six ecologically-distinct zones (EDZs) as shown in Fig. 1. The South-West covers the south-western plains of the wet zone and the western slopes of the central highlands up to ca. 400 m above mean sea level (a.s.l.). The EDZ designated as the 'Central Highlands' comprises the major part of the central highlands including its eastern slopes and part of the south-eastern plains.Both the South-West and Central Highlands, with the exception of its eastern slopes and south-eastern plains, have a precipitation regime which is well-distributed throughout the year. Although the annual precipitation levels of the two zones are on par (ca. 2500 mm yr^{-1}), the Central Highlands have a much lower temperature regime than the South-West (ca. 15 – 20°C as compared to 27 – 29°C). Because of the well-distributed precipitation regime, both zones support dense perennial vegetation such as tropical, montane and sub-montane forests, forest plantations (mainly Pinus and Eucalyptus), agricultural plantations such as tea, rubber and coconut and multi-layered homegardens. In addition, the coastal and inland plains and valleys support rice, a crop which has the highest water requirement among the cereals. The two grid cells covering the south-eastern end of Sri Lanka are designated as one EDZ termed the 'Eastern Coastal Plain (ECP)'. The northern half of Sri Lanka was classified in to three EDZs as the 'North-West', the 'North-East' and the 'North'. All four of the above EDZs are located outside the humid tropical zone (locally termed the 'Wet Zone') of Sri Lanka and therefore experience a lower annual precipitation regime ranging from 900 – 1400 mm yr^{-1}. Moreover, they experience a bi-modal precipitation regime with a major peak in the November-December period from the North-East Monsoonal rains and a minor peak in May-June from the South-West Monsoon. Consequently, all four zones experience a prolonged dry period of 4 – 5 months from July to September/October. Furthermore, all four zones experience a higher temperature regime of ca. 28 – 36°C. Rice paddies in the coastal and inland plains, annual upland agricultural crops (*e.g.* maize, pulses and a variety of vegetable crops), coconut plantations (especially in the North-West), sub-humid evergreen and deciduous forests and savannahs are the characteristic vegetation types. Highly weathered and leached Ultisols are the major soil order in the South-West and the Central Highlands. In contrast, relatively less-weathered and less-leached Alfisols are the major soil order of the rest of the EDZs (Panabokke, 1996).

Analysis of model output

An annual average NBP for each of the six EDZs was calculated separately by taking the arithmetic mean of annual estimates of the four selected DGVMs. Weighted average net biome productivity (NBP) for Sri Lanka was calculated by averaging the respective NBPs of the six EDZs weighted by the number of grid cells covered by each EDZ. Overall trend over the entire 110-year period from 1901 to 2010 was determined by simple linear regression of the mean annual NBP. Analysis of NBP estimates under scenarios S1 and S2 were carried out separately. To determine the impact of climate change during the 110-year period from 1901 to 2010, the difference in NBP under S2 and S1 scenarios (S2-S1) was also analyzed. Hence, a positive value for NBP (S2-S1) represented a positive impact of climate change and *vice versa*.

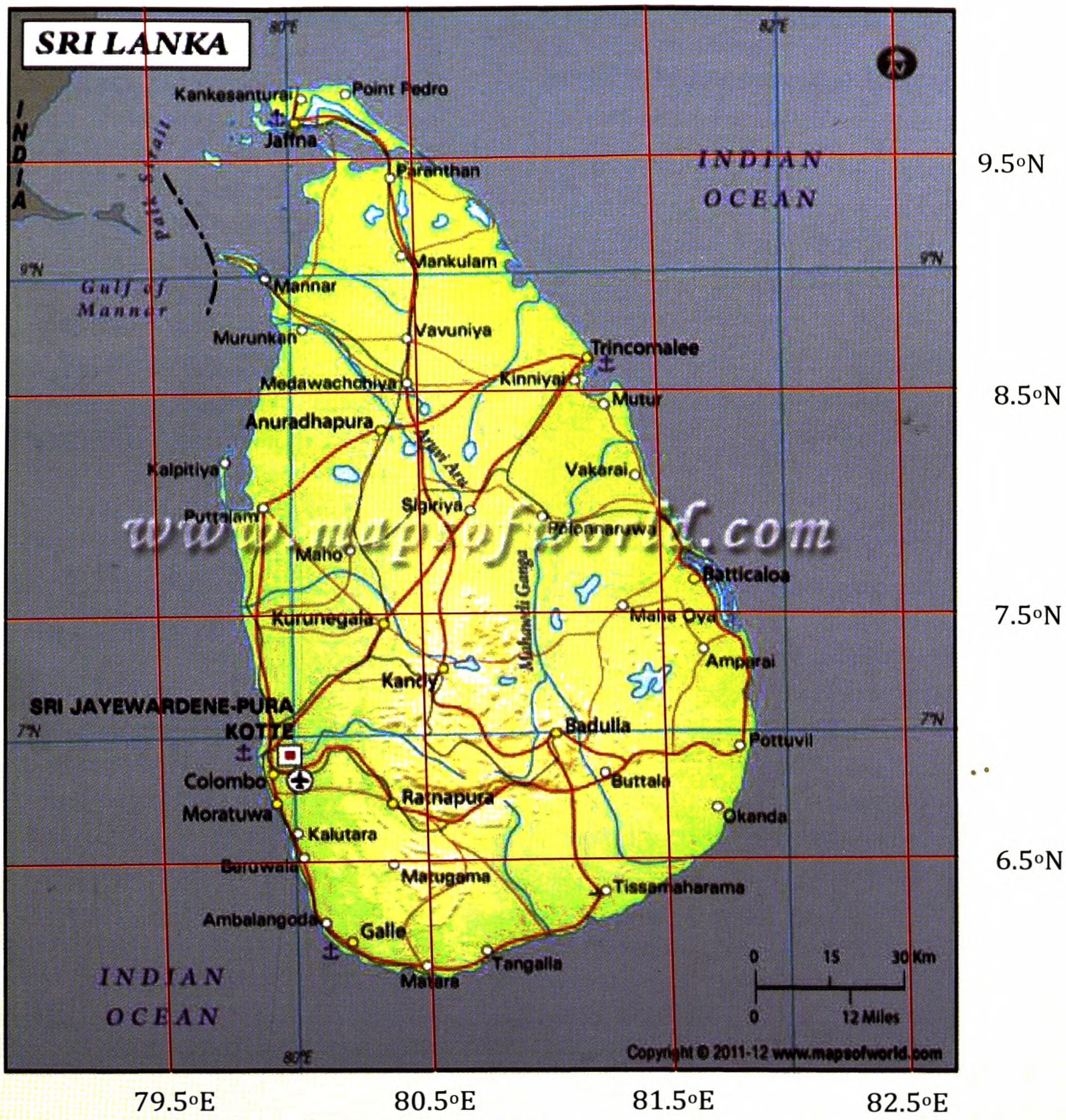

Fig. 1. **Selected land area of Sri Lanka with 1° x 1° grid cells and designated ecologically-distinct zones (EDZs): SW – South-West; CH – Central Highlands; ECP – Eastern Coastal Plain; NW – North-West; NE – North-East; N – North.**

In addition to trends over the entire 110-year period, mean NBP was calculated for the following defined periods: (a) 1901-1969 - a period of relatively slow rise of atmospheric CO$_2$ and temperature; (b) 1970-1979 – a period characterized by the the onset of accelerated CO$_2$ and temperature rise and some strong *La Niña* s (*e.g.* 1971 and 1975) (http://www.esrl.noaa.gov/psd/enso/mei/); (c) 1980-1989 – a period of strong *El Niño* s (e.g. 1982, 1983 and 1987) with warm temperatures and rising CO$_2$; (d) 1990-1999 – a period which included the Pinutobo volcanic eruption followed by increased atmospheric aerosols leading to increased diffuse radiation and associated cooling but also recording strong *El Niño* s in 1992, 1993 and 1997; (e) 2000-2010 – a period of slower rate of warming without strong *El Niño* s or *La Niña* s but continuously rising CO$_2$.

RESULTS

Variation of weighted averaged NBP for Sri Lanka

The weighted averaged NBP (S2) for Sri Lanka did not show a significant trend over the 110-year period (Fig. 2). However, there was substantial inter-annual variation ranging from -197 g C m^{-2} yr^{-1} in 1983 to 122 g C m^{-2} yr^{-1} in 1984. There was substantial variation in mean NBP (S2) between defined periods over the 110-year period (Fig. 3). Mean NBP (S2) was positive in both 1901-1969 and 1970-1979 periods (*i.e.* 5.98 and 10.05g C m^{-2} yr^{-1}) with a slight increase from 1901-1969 to 1970-1979. This implied an overall C sinks which had increased slightly. The 1980-1989 decade showed a substantial reduction in NBP (S2) with the decadal mean being -29.61 g C m^{-2} yr^{-1}, indicating a net C source during this decade. It is also notable that NBP (S2) showed the widest inter-annual variation during the 1980s. During the two decades that followed mean decadal NBP (S2) showed a continuous increase. However, during the 1990s, mean NBP (S2) remained negative at -12.87 g C m^{-2} yr^{-1}, which meant that Sri Lanka continued to be a net C source during this decade. Notably, during the first decade of the new millennium, NBP(S2) showed a substantial increase up to 35.81 g C m^{-2} yr^{-1}, which meant that the land biosphere of Sri Lanka became a net C sink once again.

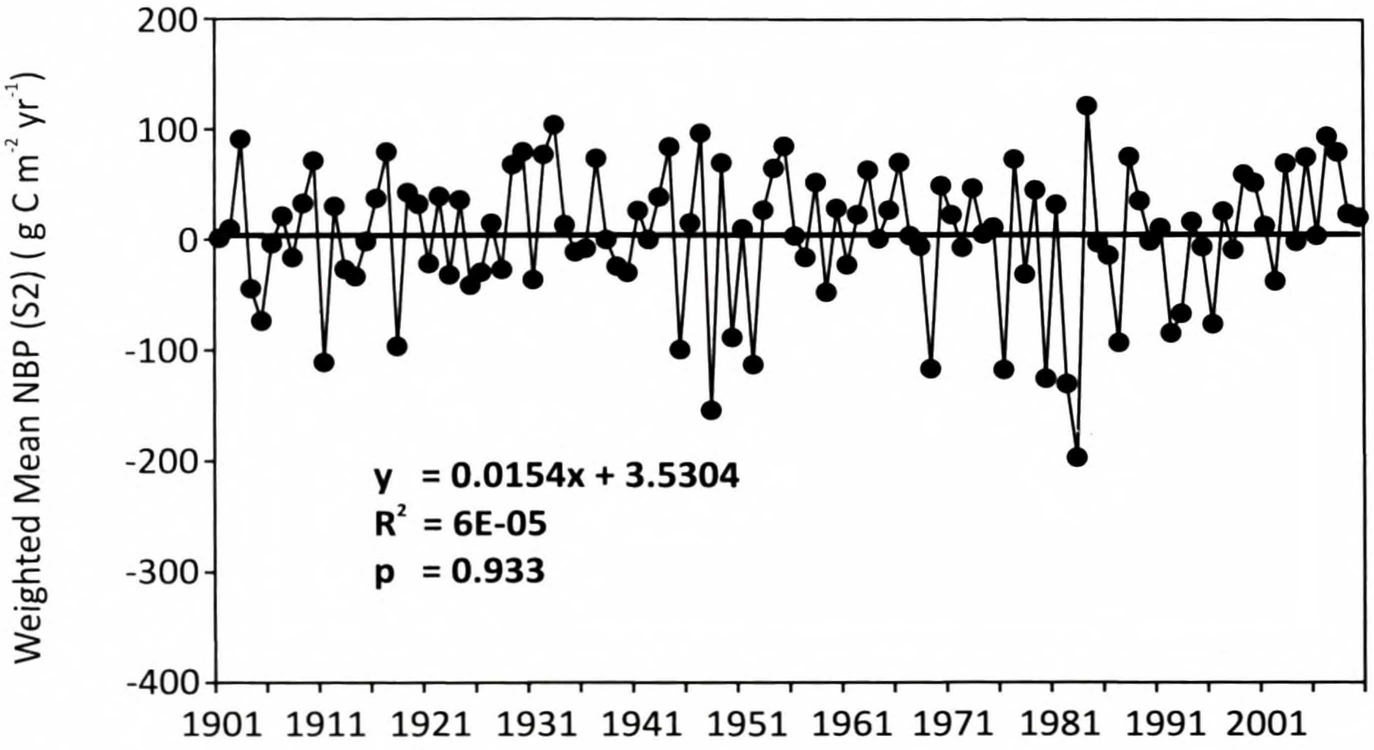

Fig. 2. Time course of weighted averaged NBP (S2) for Sri Lanka during the 110-year period from 1901 to 2010. Each data point is a weighted average of mean NBP of six ecologically-distinct zones of Sri Lanka. Mean NBP (S2) was calculated as the arithmetic average of NBP (S2) estimated from four DGVMs (*i.e.* CLM, LPJ, LPJ-GUESS and TRIFFID).

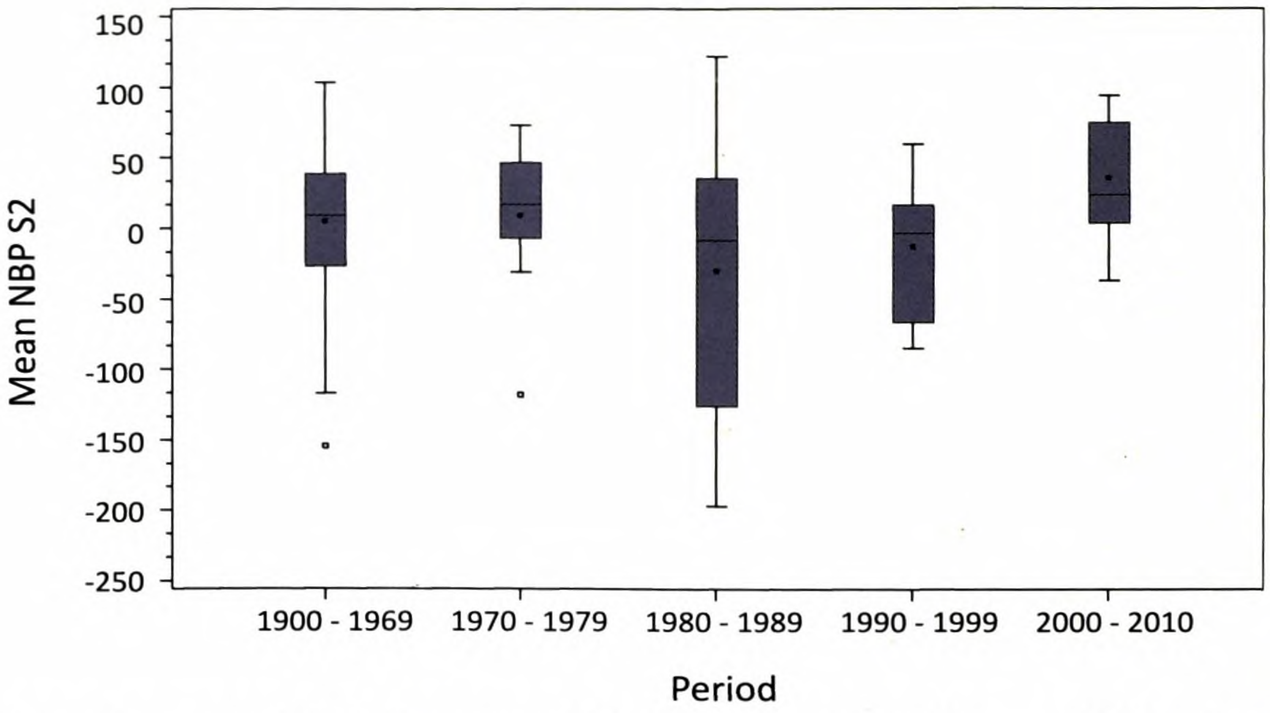

Fig. 3. Box plots of mean weighted averaged NBP(S2) for Sri Lanka over defined periods.

Variation of NBP of different ecologically-distinct zones of Sri Lanka over the entire period from 1901 to 2010

Annual NBP estimates of all four models and the mean NBP (*i.e.* the mean of estimates from the four DGVMs) showed substantial inter-annual variation in all EDZs (data not shown). Over the entire 110-year period, mean NBP showed a negative linear trend in the South-West, Central Highlands and North-East zones (Table 1). On the other hand, a positive linear trend was shown in the Eastern Coastal Plain, North-West and North zones. The R^2 values of all regressions were very low (*i.e.* < 0.02) because of the high inter-annual variation of mean NBP and some extreme outliers of NBP estimates of LPJ-GUESS and TRIFFID.

Variation of mean NBP of EDZs for defined periods

There was substantial variation in mean NBP over the defined periods in all EDZs (Table 2). During the initial 70-year period from 1901 to 1969, the mean NBP was positive in all zones except the North. The highest NBP was in the Central Highlands. During the 1970s, all EDZs except the Central Highlands had a positive mean NBP, with the South-West having the highest. South-West, Eastern Coastal Plain and the North showed increased mean NBP during the 1970s in comparison to their respective mean NBP during the initial 70-year period. In contrast, mean NBP of the Central Highlands, North-West and the North-East showed decreases during the 1970s in comparison to the preceding 70 years. Notably, the mean NBP of the Central Highlands had decreased from 15.05 g C m^{-2} yr^{-1} during 1901-1969, to -23.21 g C m^{-2} yr^{-1} during 1970-79. The mean NBP of all EDZs of the 1980s were negative with substantial reductions from their respective values in the 1970s. The mean NBP of the 1980s ranged from -49.89 g C m^{-2} yr^{-1} in the North to -5.78 g C m^{-2} yr^{-1} in the South-West. All EDZs except the Eastern Coastal Plain showed increases in mean NBP during the 1990s relative to their respective values in the 1980s. However, with the exception of the North-West and the North, the mean NBPs of all other EDZs were still negative during the 1990s. The respective mean NBPs in the 1990s ranged from -48.24 g C m^{-2} yr^{-1} in the South-West to 12.11 g C m^{-2} yr^{-1} in the North. During the period from 2000 to 2010, all EDZs showed substantial increases in their mean NBP relative to their respective values in the 1990s. The highest increase was shown in the South-West and the lowest in the North. Accordingly, the mean NBP of all EDZs were positive during the first decade of the 21st century, ranging from 16.32 g C m^{-2} yr^{-1} in the Eastern Coastal Plain to 43.12 g C m^{-2} yr^{-1} in the South-West.

Table 1. Linear trends in mean NBP under S2, S1 and S2-S1 scenarios in ecologically-distinct zones of Sri Lanka during the time period from 1901 to 2100

	Linear trend of NBP (gC m^{-2} yr^{-2})†					
	Trend (S2)	**p‡**	**Trend (S1)**	**p**	**Trend (S2-S1)**	**p**
Sri Lanka	0.015	0.933	0.204	0.019	-0.162	0.402
South-West	-0.157	0.455	0.025	0.607	-0.182	0.381
Central Highlands	-0.133	0.477	0.161	<0.0001	-0.294	0.117
Eastern Coast. Pl.	0.015	0.870	0.050	0.317	-0.035	0.746
North-West	0.020	0.918	0.214	0.051	-0.193	0.395
North-East	-0.154	0.391	0.168	0.097	-0.322	0.117
North	0.2426	0.169	0.199	0.021	0.0434	0.815

†Slope of the linear regression against time

‡Probability of the slope being equal to zero

Separation of the impact of climate change (S2-S1) from the contribution from CO_2 fertilization (S1) to the annual variation of NBP Whole of Sri Lanka

In contrast to NBP (S2), the weighted averaged NBP (S1) for Sri Lanka showed a significant (p=0.0193) positive trend over the 110-year period from 1901 to 2010 (Fig. 4). The mean NBP (S1) for the defined periods showed a slight upward trend with small reductions during the 1980-1989 and 2000-2010 periods (data not shown). The impact of climate change on NBP, as indicated by the difference between NBP (S2-S1), for Sri Lanka did not show a significant trend over the 110-year period (Fig. 4). The variation of mean NBP (S2-S1) for the defined periods (data not shown) followed a pattern which was similar to that of NBP (S2) (Fig. 3). Accordingly, there was a significant positive relationship between weighted means of NBP (S2-S1) and NBP (S2) (Fig. 5), with a slope of less than one, indicating an overall negative impact of climate change on NBP.

Ecologically-distinct zones of Sri Lanka

As indicated by the positive trends in the time courses of NBP-S1, there was a positive CO_2 fertilization effect on NBP (*i.e.* NBP-S1) in all EDZs (Table 1). However, there was significant inter-annual variation of NBP-S1 so that all R^2 values in the regressions were below 0.10. The magnitude of the CO_2 fertilization effect, as indicated by the regression slope, was highest in North-West (0.214 g C m^{-2} yr^{-2}) and lowest in South-West (0.025 g C m^{-2} yr^{-2}). Among the rest of the EDZs, North, Central Highlands and the North-East had higher CO_2 fertilization effects (0.161 – 0.199 g C m^{-2} yr^{-2}) than that of the Eastern Coastal Plain (0.050 g C m^{-2} yr^{-2}).

The impact of climate change (*i.e.* NBP (S2-S1)) was negative during the majority of defined periods of all EDZs (Table 3). The negative impacts of climate change on NBP were highest during the two decades between 1980 and 1999 in all EDZs. It is also notable that the impact of climate change on NBP has been positive in all the EDZs except the North-East during the 2000-2010 periods. Similar to that observed for the weighted average

Table 2. Variation of mean NBP of ecologically-distinct zones of Sri Lanka for defined periods as estimated from four dynamic global vegetation models

Periods	Mean* NBP-S2 (g C m^{-2} yr^{-1})									
	South-West		Central Highlands		Eastern Coastal Plain		North-West		North-East		North	
	Mean	se†	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se
1900-1969	5.372	7.959	15.050	6.022	3.092	3.763	10.026	6.817	1.994	6.718	-1.374	6.941
1970-1979	26.857	14.727	-23.211	23.576	7.657	7.899	4.796	23.412	1.431	13.445	17.543	14.323
1980-1989	-49.894	20.780	-33.665	36.909	-8.980	13.181	-31.173	37.210	-33.374	32.346	-5.782	29.312
1990-1999	-48.241	27.477	-4.677	13.926	-17.596	8.972	5.452	14.582	-18.780	16.714	12.108	12.832
2000-2010	43.122	15.548	42.875	10.257	16.322	5.889	31.413	17.695	17.376	14.254	23.707	15.893
p‡	0.003	0.123	0.064	0.312	0.285		0.642					

*Mean of four dynamic global vegetation models across the defined periods

†Standard error of mean

‡Probability of significance

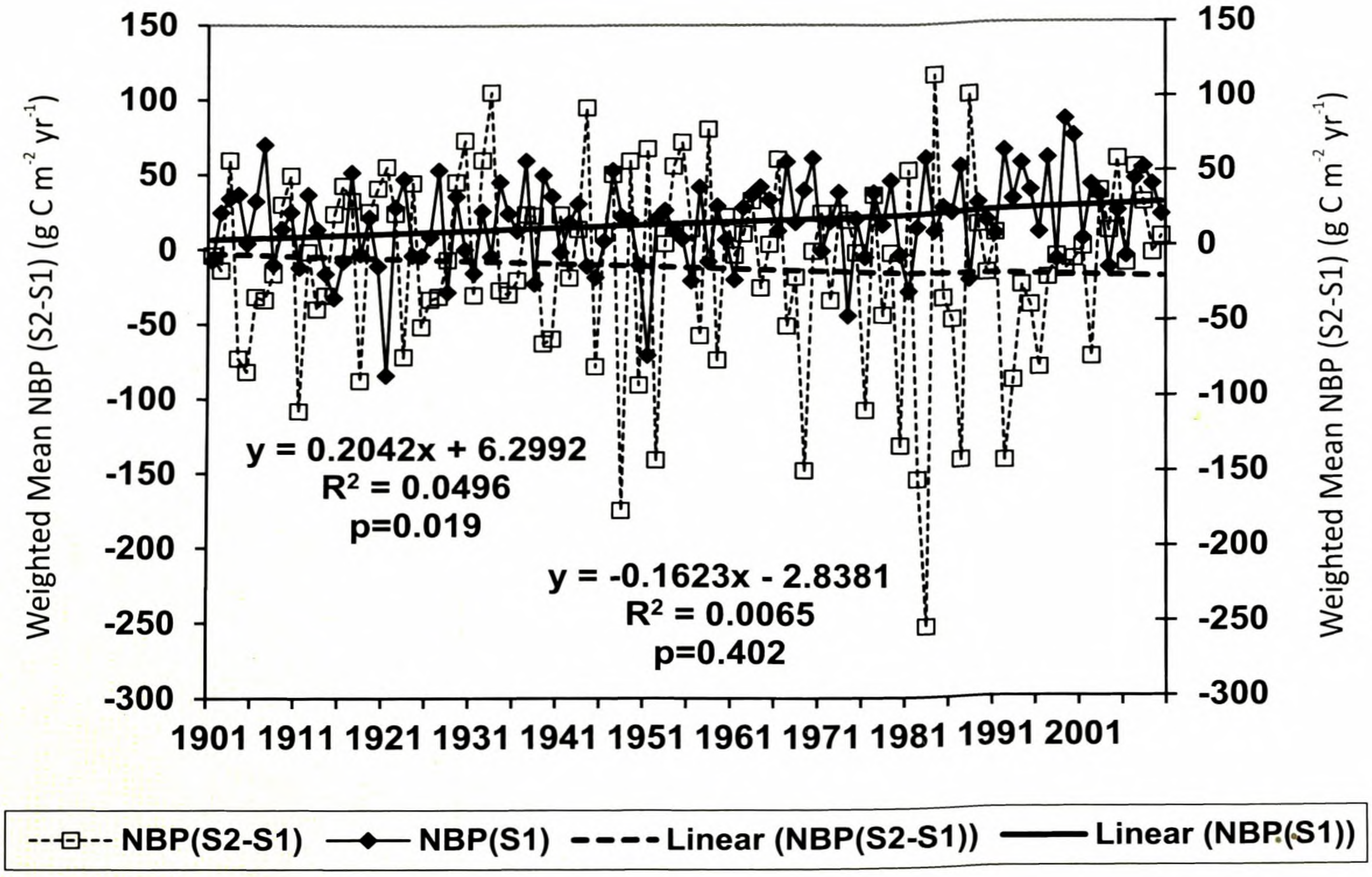

Fig. 4. Time course of weighted averaged NBP (S1) and the impact of climate change (*i.e.* NBP (S2-S1) for Sri Lanka during the 110-year period from 1901 to 2010.

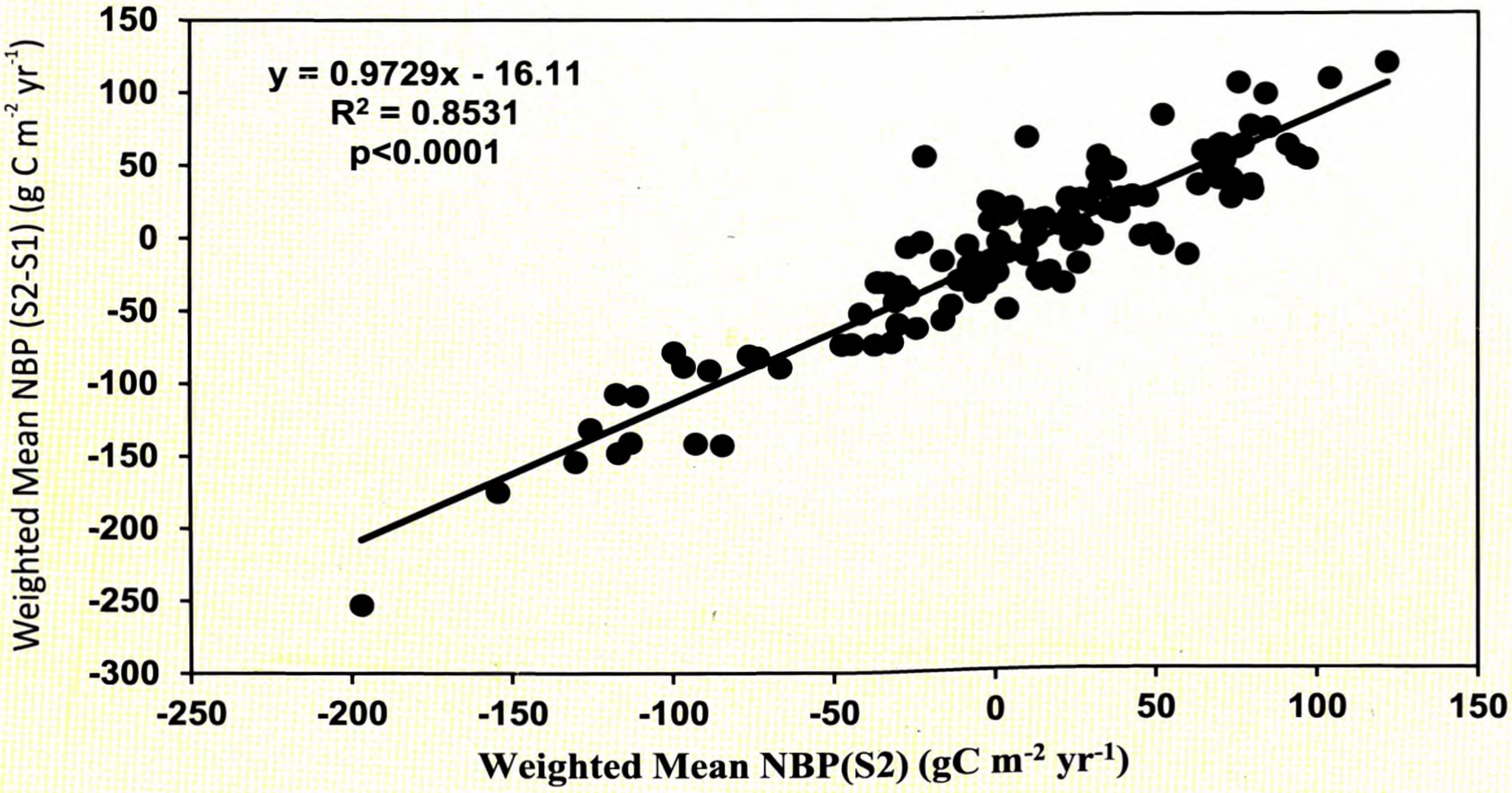

Fig. 5. Relationship between weighted averaged NBP (S2) and the impact of climate change (*i.e.* NBP (S2-S1) for Sri Lanka during the 110-year period from 1901 to 2010.

NBP for the whole of Sri Lanka (Fig. 5), there was a highly significant ($p<0.0001$) positive (slope = 0.942) linear relationship (R2 = 0.816) between NBP(S2-S1) and NBP(S2) across all EDZs as well.

The regression slopes of time courses of NBP (S2-S1) indicate the direction and magnitude of change of the climate impact on NBP. All EDZs except the North showed increasing negative impacts of climate change (Table 1) ranging from -0.035 g C m^{-2} yr^{-2} in the Eastern Coastal Plain to -0.322 gC m-2 yr-2 in the North-East. The only exception was the North in which the negative impact of climate change on NBP decreased at a rate of 0.043 g C m^{-2} yr^{-2}.

DISCUSSION

Comparison of the estimated magnitudes and trends of NBP (S2) for Sri Lanka with other regional estimates

The absence of a significant long-term (*i.e.* 1901-2010) trend in the strength of the land carbon sink, estimated as the slope of the time course of annual NBP (S2), of Sri Lanka is consistent with the finding of Patra *et al.,* (2013) for the South Asian region, where ensemble mean annual NBP (S2) of ten DGVMs did not show a significant trend from 1980 to 2009. Similar to the present study, Patra *et al.,* (2013) also observed a large inter-annual variation in the terrestrial carbon sink of South Asia. However, the absence of a significant trend for Sri Lanka contrasts with the significant increasing trends for the land carbon sink in the tropical land (Sitch *et al.,* 2013) and specifically for Tropical Asia (Sitch *et al.,* 2013). This is understandable as Sri Lanka represents only a very small fraction of these regional land masses.

There are only a few estimates of per unit land area carbon balance with which to compare our estimates. Piao *et al.,* (2009) has computed the per unit area values for the terrestrial carbon sinks of China (20 – 27 g C m^{-2} yr^{-1}), Europe (16 – 24 g C m^{-2} yr^{-1} based on Janssens *et al.,* 2003) and the USA (33 – 63 g C m^{-2} yr^{-1} based on Pacala *et al.,* 2001) for the 1980s and 1990s. Our estimates of weighted averaged NBP (S2) for Sri Lanka for the corresponding periods are -29.61 and -12.87 g C m^{-2} yr^{-1} which indicate a net C source while China, Europe and USA were showing a net C sink. When Sri Lanka became a net C sink again during 2000-2010, we estimate its strength to be 35.81 g C m^{-2} yr^{-1}, which is within the range of per unit land area values reported by Piao *et al.,* (2009). Based on Patra *et al.,* (2013)'s estimates, we calculate per unit land area values of 23.01g C m^{-2} yr^{-1} (for top-down estimates during 2007-2008) and 42.26 g C m^{-2} yr^{-1} (for bottom-up estimates during 2000-2009) for the land carbon sink of South Asia. Our estimate of 35.81 g C m^{-2} yr^{-1} falls within the range specified by the top-down and bottom-up estimates of Patra *et al.,* (2013)

The estimated magnitudes of the mean NBP (S2) of Sri Lanka (Fig. 3) for the 1980-2010 period showed Sri Lanka to have been a net C source in the 1980s and 1990s before becoming a net C sink during 2000-2010. This contrasts with the finding of Patra *et al.,* (2013) that South Asia was net C sink during 1980-2009. Patra *et al.,* (2013) show that CO_2 emissions from fossil fuel use and land use change of the South Asian region is largely dominated by those in India which accounts for 72% of the land area of South Asia. This could be the reason for the divergence of findings on whether the land has been a source or a sink for Sri Lanka in the 1980s and 1990s. However, it can be noted that mean NBP(S2) of Sri Lanka over the last three decades has shown an increasing trend (Fig. 3), which is in agreement with the increasing trend for the annual NBP(S2) of tropical land and Tropical Asia during 1990-2009 (Sitch *et al.,* 2013).

The significant increasing trend of NBP (S1) (Fig. 4) indicated a strengthening of the CO_2 fertilization effect. However, the non-significant decreasing trend of NBP (S2-S1) and the non-significant increasing trend of NBP (S2) show that the strengthened CO_2 fertilization effect has been off-set by the climate change effects. The negative impact of climate change on the land carbon sink of Sri Lanka is evident from Fig. 5 as well, where the slope of the linear relationship between NBP

Table 3. Mean climate change impact on NBP of ecologically-distinct zones of Sri Lanka for defined periods as estimated from four dynamic global vegetation models

Periods	Mean* NBP (S2-S1) ($g\ C\ m^{-2}\ yr^{-1}$)											
	South-West		Central Highlands		Eastern Coastal Plain		North-West		North-East		North	
	Mean	se†	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se
1900-1969	-11.328	9.158	4.553	6.269	-0.770	3.960	-1.767	7.794	-7.768	8.027	-8.789	7.388
1970-1979	-5.394	18.995	-52.059	25.457	6.889	7.620	-19.232	23.257	-13.843	8.673	12.390	10.767
1980-1989	-73.372	27.825	-64.949	42.363	-13.719	18.086	-35.403	47.127	-54.661	35.791	-14.169	34.244
1990-1999	-61.544	32.107	-16.548	12.876	-32.613	9.724	-38.379	15.513	-40.227	19.299	-17.347	14.181
2000-2010	20.273	19.681	8.285	15.922	9.912	8.442	10.980	18.397	-11.590	15.260	1.285	11.008
p‡	0.037		0.233		0.037		0.629		0.423		0.680	

*Mean of four dynamic global vegetation models across the defined periods

†Standard error of mean

‡Probability of significance

(S2-S1) and NBP (S2) is less than one. These findings for Sri Lanka are in agreement with the finding of Patra *et al.,* (2013) for South Asia that the fertilization effect of rising CO_2 accounted for 89-110% of the carbon sink as estimated by NBP (S2). This contrasts with the finding of Ciais *et al.,* (2009) for the African continent that the CO_2 fertilization effect contributed only 25% to the observed NBP trend during 1980-2002 while the variation of precipitation was contributing 74%.

Variation of NBP in Ecologically-Distinct Zones

Long-term variation of NBP (S2), NBP (S1) and NBP (S2-S1) among the six EDZs revealed interesting insights in to the drivers and controlling factors of the land carbon balance of different EDZs of Sri Lanka. The CO_2 fertilization effect, as estimated by the slope of the time course of NBP (S1), was stronger in the EDZs covering the sub-humid dry zone of Sri Lanka (*i.e.* North, North-East and North-West) where a prolonged drought is experienced during the June – September/October period (Table 1). Increasing atmospheric CO_2 increases water use efficiency (Drake *et al.,* 1997; De Costa, 2011) and this positive effect would have been most evident in the EDZs which experience drought. The Central Highlands, which experiences a much lower temperature regime (*i.e.* 15° – 20°C) than the rest of the EDZs (27° – 36°C) also, showed a highly-significant strong positive trend in NBP (S1). Analysis of long-term climate data has shown the Central Highlands to be the zone which has experienced the highest rate of increase in air temperature and the highest rate of decrease of precipitation (De Costa, 2008). Increasing temperature in this low-temperature zone would have had a positive impact on photosynthesis, thus enabling better utilization of increased atmospheric CO_2 (Drake *et al.,* 1997), and thereby enhancing the CO_2 fertilization effect. Moreover, CO_2- induced increases in water use efficiency would have been more effective in a zone of decreasing precipitation, thereby contributing to a stronger CO_2 fertilization effect.

The climate change effect, as estimated by NBP (S2-S1) was negative in all EDZs during most periods (Table 3). Negative trends for the time courses of NBP (S2-S1) in all EDZs except the North (Table 1) indicated that the negative climate change effect was enhanced during the 110-year period of this study. This enhancement was greatest (*i.e.* the negative trend was greatest) in the North-East and the Central Highlands, probably due to different reasons. North-East is a zone where the current temperatures are higher with a lower precipitation regime. De Costa (2008) has shown that lower precipitation zones in Sri Lanka have experienced greater year-to-year variability in precipitation. Further increases in temperature due to climate change and increased variability in precipitation could have enhanced the negative climate change impact in the North-East. It can be noted that the North-East is the only zone which showed a negative climate change impact during 2000-2010 (Table 2). In the Central Highlands, where increased temperatures probably had a positive impact, decreased precipitation due to climate change probably made a dominant contribution to the enhancement of the negative climate change impact, especially on the relatively drier eastern slopes and the south eastern plains.

The two zones which showed the lowest enhancement of the negative climate change effect were the North and the Eastern Coastal Plain (ECP) (Table 1). Both these are zones of higher temperature and lower precipitation with sparse vegetation cover. Moreover, the ECP covers only a small land fraction in the two 1° x 1° grid cells which form its boundaries. Therefore, it is possible that the carbon balances of these zones are less sensitive to climate change. This is confirmed by the observation that the carbon balance (*i.e.* NBP (S2)) of both these zones had relatively lower fluctuations over the defined time periods (Table 2) with smaller positive values as well as smaller negative values.

The South-West and North-West also showed substantial negative trends in their long-term time courses of NBP (S2-S1) indicating substantial enhancement of the negative impact of climate change during the 1901-2010 periods (Table 1). The South-West is located in the humid Wet Zone of Sri Lanka having very high precipitation (*i.e.* 2500 – 5000 mm yr^{-1}) which is well-distributed throughout the year (Domroes, 1974). It is also the zone which has shown the least long-term reduction of precipitation (De Costa, 2008). Therefore, increased temperatures are most likely to have contributed to the substantial enhancement of the negative climate change impact in this high precipitation, high temperature (*i.e.* 27° – 32°C) zone. On the other hand, both increased temperatures and decreased precipitation probably contributed to the enhancement of the negative climate change impact in the North-West which is a high temperature (*i.e.* 28° – 36°C), intermediate precipitation (1000 – 1200 mm yr^{-1}) zone. Both these are zones of high vegetation cover. Hence, their carbon balances could be expected to be more sensitive to climate change as compared to those of sparsely-vegetated zones. This is confirmed by the wide fluctuations of both NBP (S2) (Table 2) and NBP (S2-S1) (Table 3) in these two zones.

Inter-annual variability of the land carbon sink

A major feature of the time courses of the overall land carbon sink for Sri Lanka and those of the EDZs is the substantial inter-annual variability. Such large inter-annual variability has been observed in the global (Sarmiento *et al.,* 2010) and continental (Ciais *et al.,* 2009) land carbon sinks as well. Much of this variability has been attributed to the El Niño Southern Oscillation (ENSO), with the land carbon sink decreasing during the warmer *El Niño* phase and increasing during the cooler *La Niña* phase. Large-scale volcanic eruptions (*e.g.* Pinatubo in 1991) have also led to cooler climates with an enhanced land carbon sink (Jones and Cox, 2001). Relationships of the estimated NBP (S2) for Sri Lanka and its EDZs with environmental drivers including ENSO will be examined in a separate paper.

Capacities of the land carbon sink of Sri Lanka for offsetting carbon emissions

The per capita CO_2 emission rate of Sri Lanka has risen steadily from 0.53 Mg yr^{-1} in 2000 to 0.619

Mg yr^{-1} in 2010 (the latest available estimate) (World Bank Data at http://data.worldbank.org/ topic/climate-change), which is lower than the corresponding mean value of 1.4 Mg yr^{-1} for South Asia. The above estimate for Sri Lanka comprises of the CO_2 emissions from burning of fossil fuel and cement production. The reported population of Sri Lanka in 2010 is 20.33 million (World Bank Data at http://data.worldbank.org/ country/sri-lanka) which has resulted in a total CO_2 emission rate of 12.58×10^6 Mg CO_2 yr^{-1} and a total carbon emission rate of 3.432 Tg C yr^{-1} in 2010. This is comparable to the average estimate of 3.107 Tg C yr^{-1} for the 2000-2009 periods by Patra *et al.,* (2013). Based on Sri Lanka's total land area of 65,610 km 2 (http://www.statistics. -gov.lk) and our mean NBP(S2) estimate of 35.81 g C m-2 yr^{-1} for the 2000-2010 period (Fig. 3), we estimate the total terrestrial C sink of Sri Lanka to be 2.349 Tg C yr^{-1}. Accordingly, we estimate that during the first decade of the 21st Century, the land biosphere of Sri Lanka absorbed 68.4% of the carbon emissions from burning of fossil fuel and cement production. This compares favourably with reported carbon offsets of 28-37% in China (Piao *et al.,* 2009), 12% in Europe (Janssens *et al.,* 2003) and 20-40% in USA (Field and Fung, 1999) by the terrestrial carbon sinks.

However, we also note the following caveats: (a) While we have estimated a significant land carbon sink for Sri Lanka during the first decade of the 21st Century, the land biosphere of Sri Lanka was estimated to be a net carbon source in the preceding two decades, both of which contained strong *El Niño* episodes (*e.g.* 1982, 1983, 1987, 1992, 1993 and 1997) (http://www.esrl.noaa. gov/psd /enso/mei/). In contrast, no strong *El Niños* were experienced during the 2000-2010 period, which probably contributed to its substantially positive land carbon balance; (b) The World Bank estimates of per capita CO_2 emissions reportedly do not include emissions from land use change, deforestation and biomass burning. Therefore, our estimate of carbon offset by the terrestrial carbon sink of Sri Lanka may be an overestimation, when the above emission sources are also taken in to account. However, our offset estimate is based on the CO_2 emission data of 2010, which is the highest during the decade, with the preceding years of the decade having relatively lower emissions. Hence, the decadal average of the CO_2 emission rate of Sri Lanka would be lower than the value of 2010.This may have partly compensated the overestimation of the carbon offset due to the non-accounting of CO_2 emissions due to land use change, deforestation and biomass burning.

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