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SUPPLEMENTARY INFORMATION

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Simulated resilience of tropical rainforests to CO_2-induced climate change

We present below additional details of our modelling scheme (22 climate models, driving the MOSES-TRIFFID land surface model) including plots to provide extra supporting information beyond those in the main body of the paper. A more extensive discussion of current uncertainty in ecological representation of tropical forests is also given, and a Table listing other studies to date that have investigated climate change impacts for tropical forest is shown at the end. For background details of the model simulations that supplied the extra diagnostics for Figure 4, however, then please refer to the original references (Parameter Perturbation Experiments[1] and DGVM-intercomparison study[2]).

Patterns of climate change, by geographical position and month, are an extension of a smaller number of patterns first used in an earlier study[3]. First a global thermal Energy Balance Model (EBM)[4] is fitted against average global warming predictions and average top of the atmosphere radiative fluxes, and for the full suite of CMIP3 simulations (22 models). In this first set of simulations, atmospheric CO_2 concentration only is prescribed as increasing at 2% per annum cumulative. Then, independently and against a second set of CMIP3 simulations, the levels of global mean warming are extracted directly from the model and now the seasonal and geographical patterns of climate change are calibrated against the climate model diagnostics. This second set of CMIP3 model runs is designed to describe the contemporary period (i.e. pre-industrial to present) followed by the SRES A2 future scenario. By fitting both the EBM and patterns against independent alternative simulations, then the risk of interplay between the parameterisation of each is removed. Changes are calculated in 1.5m temperature and humidity, rainfall, downward shortwave and longwave radiation, windspeed and atmospheric pressure. These are all variables needed to drive the land surface model. The patterns for precipitation are relative, such that the change per unit of global warming derived from each model is then normalised against the CRU climatology. Hence for a climate model that is for instance 25% too dry compared to the CRU climatology, the patterns of rainfall change from that model are enhanced by a factor of (1.0/0.75). The 22 climate models emulated are the full set that contributed to the last UN IPCC report.

In this study, we could have circumnavigated climate pattern-scaling by extracting directly the changes in surface conditions predicted from the CMIP3 family of simulations, and for the SRES A2 scenario. However this could prevent making completely "like-for-like" simulations, especially as there are alternative representations of non-CO_2 greenhouse gas concentrations and associated radiative forcing. There are also large differences in estimates of the amount of cooling due to raised atmospheric aerosol loading, expressed as an altered and this time negative radiative forcing. This latter uncertainty remains very large[5] despite emerging analysis of contemporary measurements to constrain models[6]. For these reasons, we forced in all instances IMOGEN with the CO_2 concentration increase that is known for the contemporary period, followed by one representative for the SRES A2 emission scenario. The future component of the CO_2 pathway is based on calculations linking emissions to concentrations using the Bern-CC climate-carbon cycle model. There is also a common combined estimate of radiative forcing for non-CO_2 GHG and sulphate forcings, thus avoiding the issue above. Prescription of a CO_2 pathway (as opposed to a common emission scenario) also allows consistency when studying particular geographical regions. In simulations from multiple modelling centres that have carbon dioxide fully interactive, then warming levels over the Amazon could also be influenced by, for example, different representation of northern latitude soil carbon stocks feeding back through the atmospheric

concentration of CO_2. This is also true for IMOGEN itself, which can be forced by CO_2 emissions and with the global carbon cycle interactive. It is noted that aerosols can have different time-evolving geographical patterns of change, as they are not generally as well-mixed in the atmosphere as greenhouse gases. Hence raised aerosol concentrations do not map directly (in influence on surface climatology) as simply the opposite features expected for any warming due to raised greenhouse gases – there are small differences. If sulphate-only simulations become available from all climate modelling groups, then some form of separate aerosol-only patterns could be derived and implemented.

The baseline climatology to which our calculated anomalies in surface meteorology are added is constructed from the Climate Research Unit (CRU) dataset. For the technical description of the methods used to derive the CRU dataset, i.e. linking weather station measurements to provide gridded estimates of weather conditions, see Ref[7] and Ref[8]. There are various configurations possible for our simulations regarding use of this dataset. Although we did not investigate formally the implications of different periods of the CRU data to select as our baseline representative of pre-industrial, given the larger number of weather stations available in the recent past, then the averaged period of CRU data 1960-1989 was adopted. This compromise by taking that period will introduce a bias of around 0.3K due to the global warming between pre-industrial periods and period centred on year 1975. However, this difference is very small compared to some of the model biases removed, as shown in Figure S1. In particular, for the Americas region (i.e. Amazonia and Central America rainforest regions), every model under predicts yearly rainfall average amounts.

The IMOGEN system requires spinning-up for the initial climatology taken as representative of pre-industrial, such that the soil and vegetation components move in to equilibrium. We do this, forcing IMOGEN with the "perpetual" CRU climatology averaged 1960-1989, and with atmospheric CO_2 concentration prescribed as appropriate for pre-industrial (approximately 286ppm). Soil temperatures and moistures arrive in equilibrium relatively quickly, requiring typically a model run of order decades. However the timescales implicit in the dynamic vegetation model TRIFFID and especially for its description of broadleaf trees applicable to the tropics, are a period of order centuries. A semi-analytical scheme reduces this period by making a first approximating expected soil and vegetation carbon for prescribed climate drivers. All simulations are made on a common grid of 2.5° in latitude direction and 3.75° in longitude direction. This is the same grid spacing used by the original global carbon cycle simulation with Version 3 of the Hadley Centre GCM, HadCM3[9]. It is this common initial state to which anomalies of climate change are added, forming our transient simulations between years 1860 through to 2100.

Figures S2 and S3 present the sensitivity of changes in vegetation carbon between years 1860 and 2100, to the different atmospheric drivers of temperature, precipitation and CO_2 concentration changes, and for the Africa and Asia tropical forest regions respectively. These figures are identical in format to Figure 3 of the main text, presented there for the Americas. As for the Americas, terrestrial biomass C_v, is generally a balance between a more dominant CO_2-fertilisation effect and a decreasing C_v response to raised temperature. Precipitation changes have relatively little influence. Figure S4 presents the sensitivity of time-evolving vegetation carbon for the Americas to all the different forcings required by the MOSES-TRIFFID model. In particular changes in shortwave radiation, relative humidity, longwave radiation, wind and pressure are either small themselves, or ecosystem response of C_v to them is small.

Additional information on modelling uncertainty is as follows. Ref[10] qualify their findings of higher rates of Net Primary Productivity in a CO_2-enriched environment as representative of an accelerated forest development. They observed enhanced soil nutrient cycling and further proposed that nitrogen losses that would otherwise have occurred from the system may have been reduced by the CO_2 enrichment. They noted, however, no increase in nitrogen use efficiency (i.e. more plant biomass per unit of plant nitrogen). Combining these factors, they were unable to state whether CO_2 enrichment would ultimately lead to higher biomass over the long term. Ref[11] also explained maintained productivity over 12 years of CO_2 enrichment by accelerated rates of soil nitrogen mineralisation caused by increased below-ground carbon allocation. The question remains whether this additional nitrogen mineralised from the soil under raised atmospheric CO_2 concentrations can continue at a later stage in the forest's development. If this is not possible, then the nitrogen cycle could provide a restraint on ability of C_v to increase through this Century, compared to the extent depicted in Figure 2.

Ref[12] find that there are substantial species differences in responses to higher carbon dioxide concentrations, although[10] show that different communities of, at least temperate broadleaved trees, do not vary in their response to CO_2. Results might depend on differing ability to acquire nutrients. There may also be variability due to alternative allocation strategies, for instance the amount of carbon diverted to finer roots and stems[13]. This in turn will impact on forests dynamics and terrestrial carbon stores, as a consequence of variability in residence time in roots and stems[14]; this has been highlighted earlier in a model-based analysis[15]. We expand on the potential for tropical forests to access more soil phosphorus in a CO_2-enriched environment. Increases in root mass and redistribution of root mass, as well as increasing root-to-shoot ratios has been shown to be a general feature of experimental CO_2 enrichment[16]. Such changes may provide a mechanism to allow extra previously unavailable phosphorus to be taken up from the soil solution to support increased growth. A key requirement is to develop robust parameterisation of both nitrogen and phosphorus cycles that are valid at the large-scale for the tropical regions. An initial step towards this, for the phosphorus cycle, is a semi-analytical study for the Amazon region[17]. Ref[18] argue that soil fertility rather than soil moisture[19] may provide the strongest delineation of distributions of deciduous forest versus mostly evergreen savannah around the current Amazon forest periphery.

Refining the temperature dependence of plant respiration remains a priority. The declining temperature-sensitivity of respiration as measurement temperatures rise (giving the roughly "bell"-shape) is linked to shifts in the control exerted by maximum enzyme activity at low temperature, substrate limitations at moderate-high temperature, and loss of enzyme function at very high temperatures[20]. Our study highlights that failure to account for the fundamental non-exponential form of the respiration-temperature relationship can lead to respiratory CO_2 release being overestimated (and carbon storage being underestimated). A similar conclusion regarding carbon storage was made when the JULES land surface model (which is tightly related to MOSES-TRIFFID) was recently run testing modelled acclimation in tropical biomes[21]. The magnitude of such acclimation and its response timescale requires accurate definition and eventual routine inclusion in climate change simulations. The temperature responses of features of the photosynthesis components of land surface models are always amenable to improvement. For instance the maximum rate of carboxylation by the enzyme Rubisco ($V_{c,max}$), a key parameter defining leaf temperature influence on photosynthesis (e.g. ref[22]) is also a strong function of possible future variation in leaf nitrogen availability. Figure S5 provides implications for C_v corresponding to uncertainty in plant dark respiration; left hand plots are for a constant Q_{10}=2.0, showing for some climate models significantly less

vegetation carbon towards year 2100, and these can be compared to the right hand plots which repeat the panels of Figure 2 in the main paper.

Tropical field studies are only just starting to test the predictive skill and mechanistic accuracy of ecosystem models in response to any potential drying for tropical forests. Results from throughfall exclusion experiments in Amazonia, where rainfall is prevented from reaching the soil, suggest a strong dependency of tree mortality on changed soil moisture status[23,24]. Increases in mortality can be expected to have an impact on carbon storage. Across the tropical biome the empirical relationship between mortality and rainfall deficit varies strongly, with South Eastern Asian forests seemingly much more sensitive to severe drought events than those in Amazonia[25]. The mechanistic basis of this difference in response is not yet understood, and therefore remains to be represented in terrestrial ecosystem models[26]. Experiments used to deliberately impose higher soil moisture deficits in Amazonia[27] have provided the opportunity to start improving the specification of hydraulic and biochemical constraints in soil and vegetation[28-32] as well as to test the representation of the mortality response to soil moisture deficit[23].

Finally, to place this study in context, Table S1 provides a summary of existing studies associated with future climate change and tropical forest response.

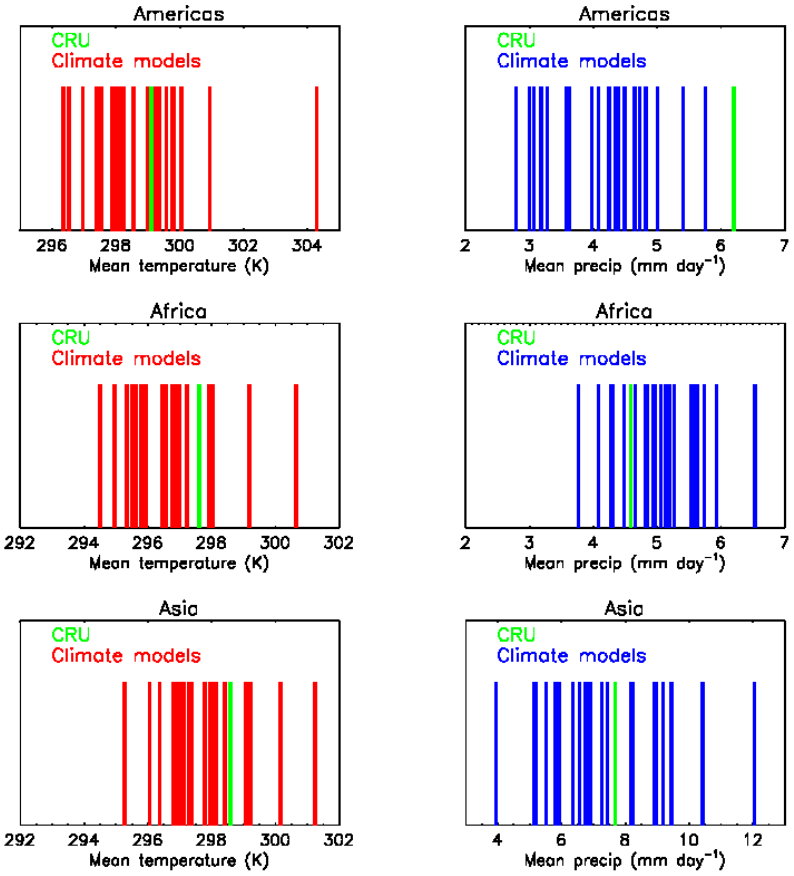

Figure SI-1: Model biases. A plot of predictions by the 22 GCMs emulated in this study of initial yearly-mean temperature (left plots, red vertical bars) and precipitation amounts (right plots, blue vertical bars), and for the three regions of interest. Also plotted in all are the Climate Research Unit (CRU) estimates in green, centred on period years 1960-1989.

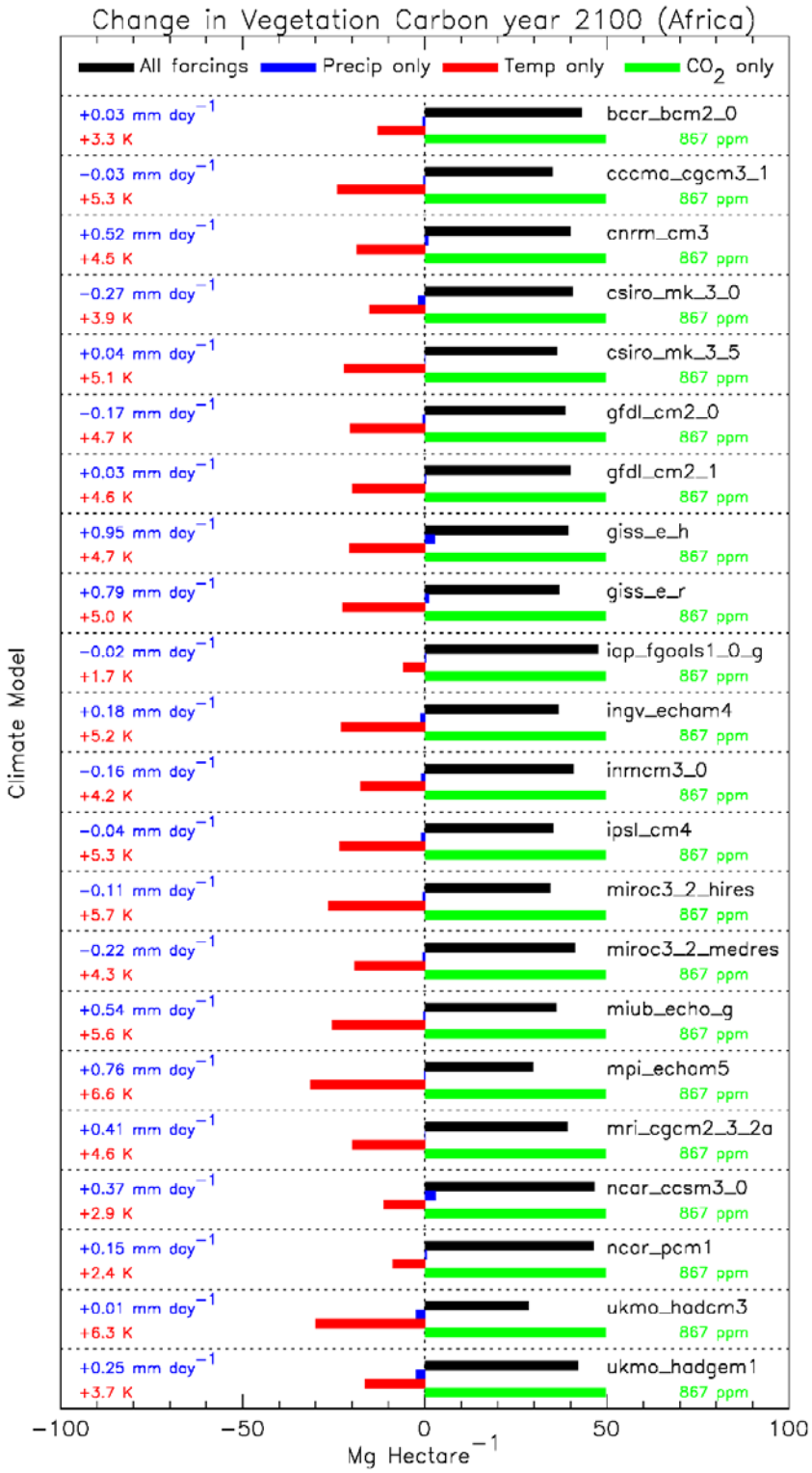

Figure SI-2: Sensitivity of changes in biomass of Africa to different climate model drivers. Plot of changes to C_v for year 2100 minus 1860, and is in identical format to Figure 3 of the main paper, but here presented for Africa.

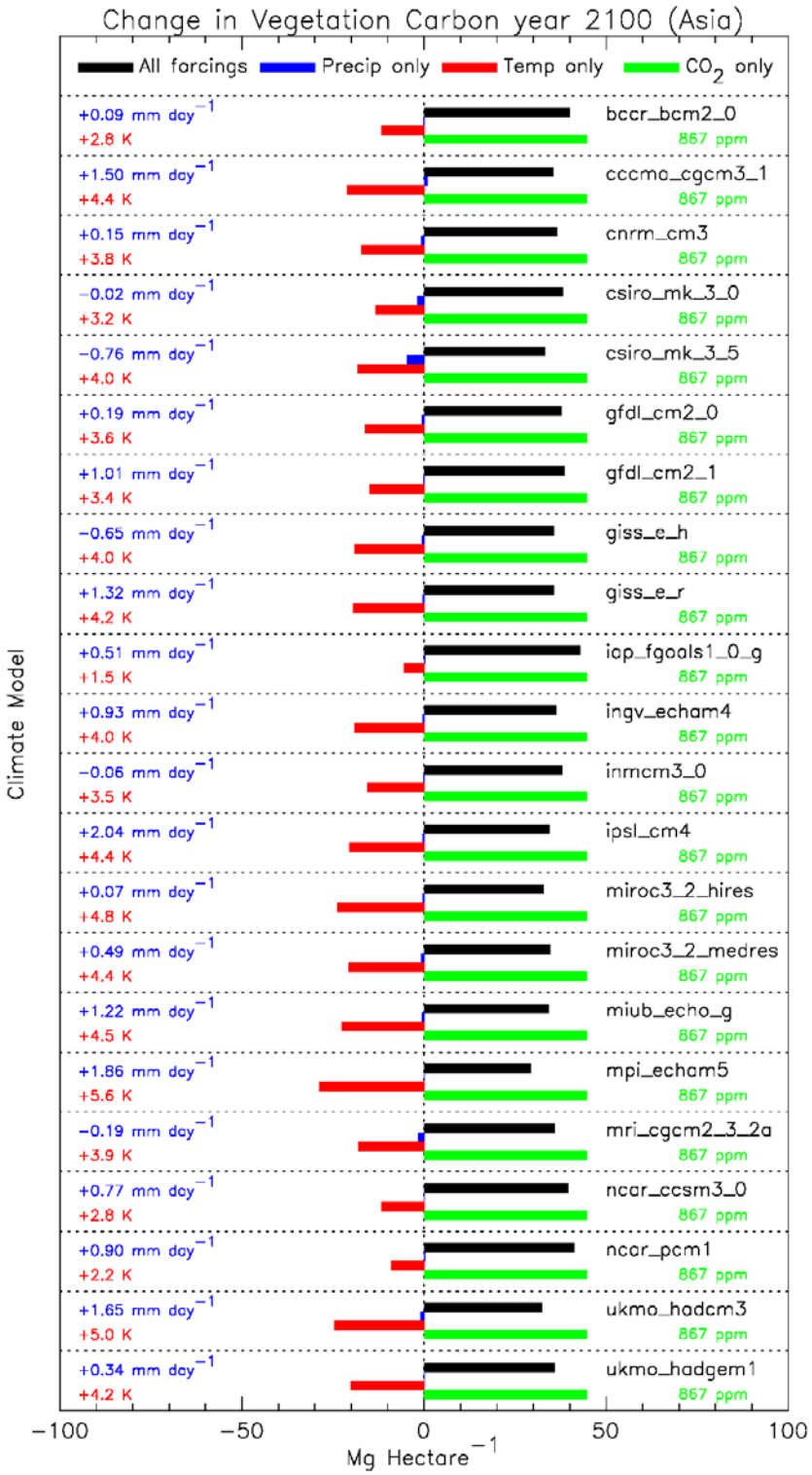

Figure SI-3. Sensitivity of changes in biomass of Asia to different climate model drivers. Plot of changes to C_v for year 2100 minus 1860, and is in identical format to Figure 3 of the main paper, but here presented for Asia.

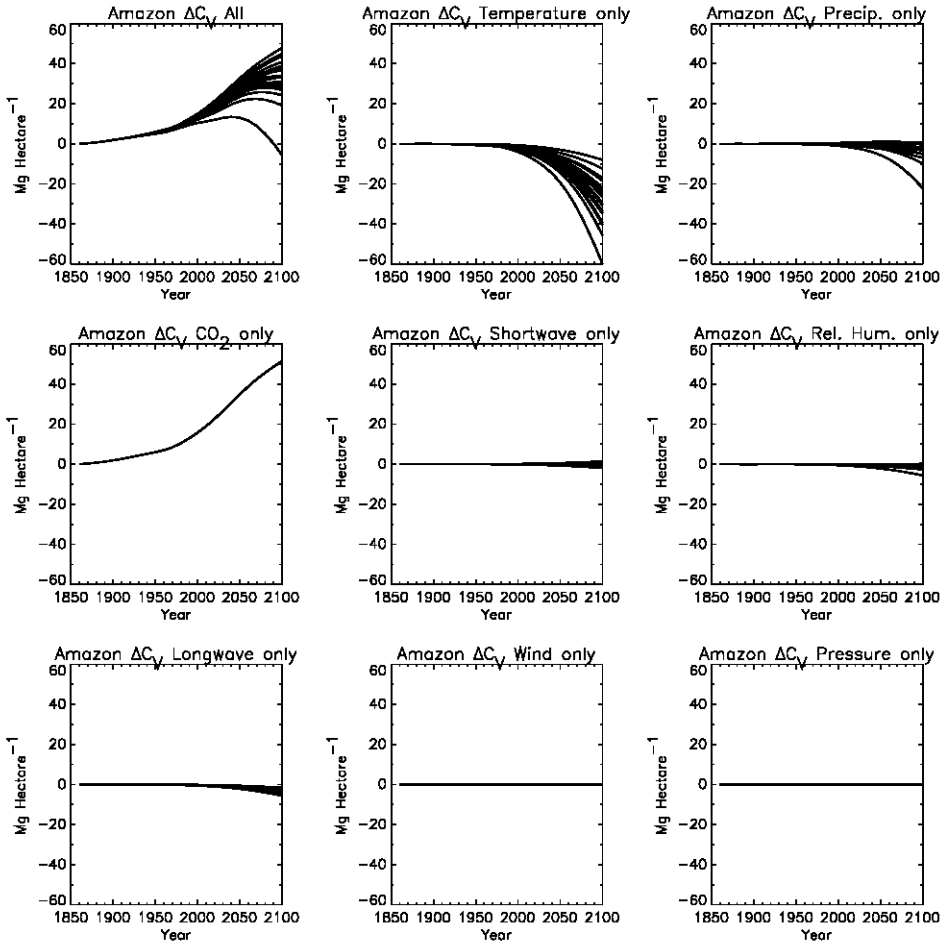

Figure SI-4: Sensitivity of changes in biomass of Americas for all climate model drivers. Changes in terrestrial carbon content, C_v, for all forcings applied simultaneously (top left hand panel) and then for each of the individual forcings only, as described in the panel titles. Each plot has 22 curves, corresponding to the calculated change in vegetation carbon associated with each climate model emulated (the exception is just one common curve for CO_2-only response). Top left-hand panel displays same curves to those in Figure 2a. Year 2100 minus 1860 values, for the panels corresponding to temperature, precipitation and CO_2 only, give the sensitivities presented in Figure 3.

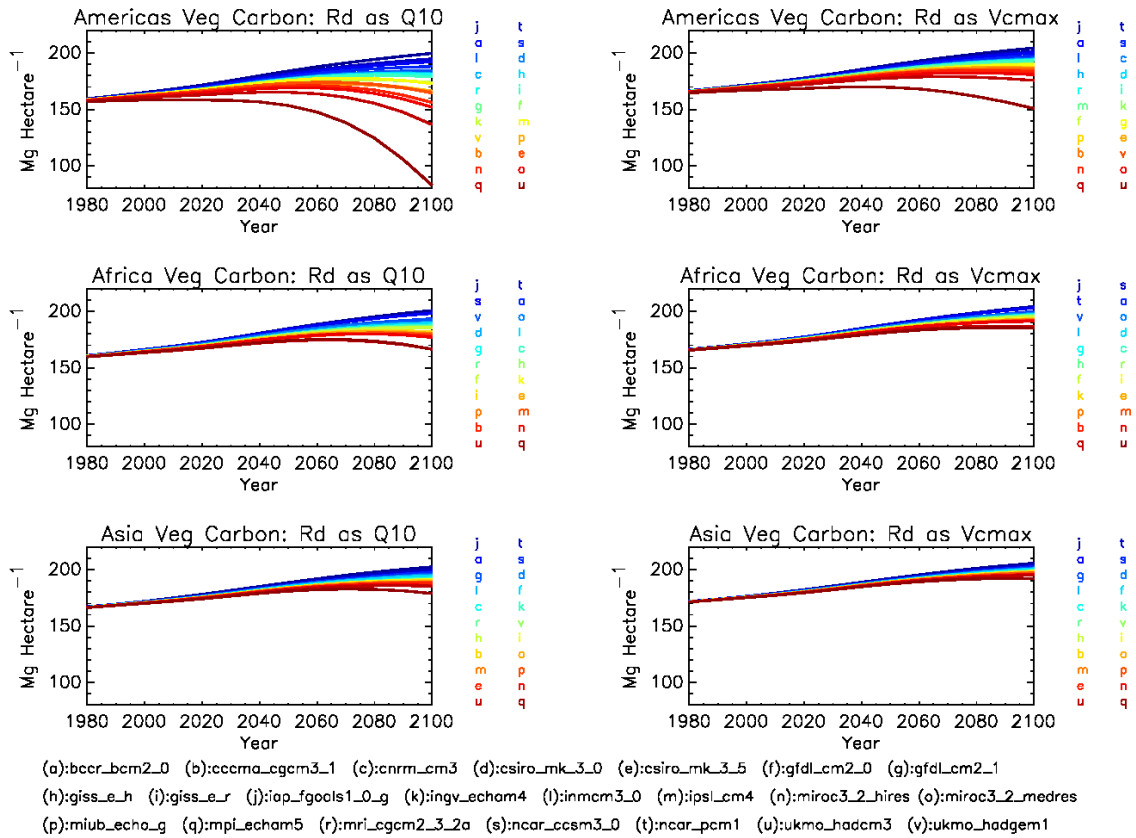

Figure SI-5: Implications of maintenance respiration as a fixed Q_{10} formulation. Panels are similar to those of Figure 2 in the main body of the paper. Here shown in the left-hand column are simulations of vegetation carbon C_v, but with dark respiration given as a constant Q_{10}=2 function. Then for completeness, the right-hand column panels are identical to those in Figure 2 (there panels are displayed horizonally between regions). Here the axes are identical between the two columns to catch the full range of solutions (notably the major loss of C_v for HadCM3 and with Q_{10}=2), and to allow direct comparison. For each panel, the colour-coded letters for each GCM are for highest values of C_v in year 2100 (top left) to lowest values (bottom right).

1 **Table SI-1: Summary of existing studies on the impacts of future climate change on the Amazon rainforest.**

Reference	*Focus Region*	*Online/Offline*	*SRES*	*Climate Data*	*Vegetation Model*	*Study Details/Findings*
White *et al.* 1999[33]	Global	Offline	IS92A	HadCM2/HadCM3	Hybrid	Large losses of Amazon rainforest, especially when forced with HadCM3
Cox *et al*. 2000[9]	Global	Online	IS92A	HadCM3LC	MOSES-TRIFFID	Large losses of forest carbon in fully coupled simulation; this contributed to the amplification of atmospheric CO_2 concentrations
Cramer *et al*. 2001[34]	Global	Offline	IS92A	HadCM2	Hybrid, SDGVM, IBIS, MOSES-TRIFFID, LPJ, VECODE	Climatic sensitivity of Amazon rainforest varies widely across DGVMs (not really addressed in the paper, but this point is expanded more by Cox *et al*. 2004, who plotted data from Cramer *et al*. 2001)
Betts *et al*. 2004[35]	Amazonia	Online	IS92A	HadCM3LC	MOSES-TRIFFID	Investigates forcings and feedbacks involved in simulated reductions in Amazonian precipitation by HadCM3LC.
Cox *et al*. 2004[36]	Amazonia	Online	IS92A	HadCM3LC	MOSES-TRIFFID	Describes mechanics of Amazon 'dieback' in HadCM3LC.
Huntingford *et al*. 2004[37]	Amazonia	Offline	IS92A	HadCM3/IMOGEN	MOSES-TRIFFID	Explores the sensitivity of Amazon 'dieback' to baseline climatology and land surface model parameterization.
Levy *et al*. 2004[38]	Global	Offline	A1FI, A2, B1, B2	HadCM3	Hyland	Explore the contributions of climate, CO2 and land use to future changes in the terrestrial carbon sink, including Amazonia.
Cowling *et al*. 2006[39]	Amazonia	Offline	N/A	Prescribed changes in temperature and precipitation	LPJ	Amazonian carbon stocks quite resilient to changes in precipitation and temperature
Schaphoff *et al*. 2006[40]	Global	Offline	IS92A	5 GCMs (CCSR, CGCM1, CSIRO, ECHAM4, HadCM3)	LPJ	Resulted in dieback under HadCM3 but not in other climate models.
Scholze *et al*. 2006[41]	Global	Offline	A1B,A2,B1	Ensemble of 16 GCMs	LPJ	High risk of forest loss in some scenarios
Salazar *et al*. 2007[42]	Amazonia	Offline	A2,B1	Ensemble of 15 GCMs	CPTEC-PVM	Found that GCMs were a more important source of uncertainty than SRES scenarios in predicted

						change in Amazonian forest cover
Golding & Betts 2008[43]	Amazonia	N/A	N/A	HadCM3 ensemble	N/A	Investigated impacts of climate change and deforestation on fire risk in Amazonia
Sitch *et al*. 2008[2]	Global	Offline/Online*	A1FI,A2,B1,B2	HadCM3/IMOGEN	Hyland, LPJ, ORCHIDEE, SDGVM, MOSES-TRIFFID	Loss of forest carbon occurs to some extent across all DGVMs in the A1FI scenario but is most pronounced in Hyland, LPJ and TRIFFID
Huntingford *et al*. 2008[44]	Amazonia	Offline	A1B	Perturbed physics ensemble of HadCM3/IMOGEN	MOSES-TRIFFID, MOSES-ED	Amazon die-back is robust to different parameterisations of HadCM3 and occurs with ED as well as TRIFFID
Jones *et al*. 2009[45]	Amazonia	Online	A2	HadCM3LC	MOSES-TRIFFID	Examined 'committed' changes in Amazonian forest cover due to climate change
Lapola *et al*. 2009[46]	Amazonia	Offline	A2,B1	Ensemble of 14 GCMs	CPTEC-PVM2	CO_2 fertilisation effects avoid biome shift in most climate scenarios.
Malhi *et al*. 2009[19]	Amazonia	N/A	A2	Ensemble of 19 GCMs	N/A	Explored the likelihood of shifts in the climatic envelope that would support tropical forests in Amazonia
Poulter *et al*. 2010[47]	Amazonia	Offline	A2, B1	Ensemble of 8 GCMs	LPJ (Monte Carlo Analysis with perturbed parameter sets)	GCMs a bigger source of uncertainty than parameter uncertainty in LPJ.
Galbraith *et al*. 2010[48]	Amazonia	Offline	A1FI,A2,B1,B2	HadCM3/IMOGEN	MOSES-TRIFFID,LPJ,Hyland	Temperature is a more important driver of Amazonian biomass losses across 3 DGVMs than precipitation. Processes leading to biomass losses vary considerably across models.
Doherty *et al.* 2010[49]	East Africa	Offline	A2	Ensemble of 9 GCMs	LPJ	Gains in biomass in East Africa predicted in all future climate scenarios.
Zelazowski *et al*. 2011[3]	All tropics	N/A	Global temperature increases of 2 and 4 °C	Ensemble of 17 GCMs	N/A	Some risk of forest contraction in the 2 °C increase scenario but much more in a 4 °C scenario, especially in the Neotropics.
Good *et al*. (2011)[50]	All tropics	Online	A2	HadCM3LC	MOSES-TRIFFID	Supplies simultaneous boundaries in temperature and precipitation to maintain tropical forest, concluding a one degree warming is roughly equivalent to a two-week increase in dry season length.

Gumpenberger *et al.* 2011[51]	All tropics	Offline	A2	ECHAM5,ECHO-G,HadCM3,GFDL-CM2.1,NCAR/CCSM 3.0	LPJ	Climate-change driven losses of biomass in the neotropics occurred with HadCM3 and to a lesser extent with ECHAM5. African and Asian forests generally gained biomass in all model simulations.

1. Booth, B.B.B. et al. High sensitivity of future global warming to land carbon cycle processes. *Environmental Research Letters* **7**, 024002 (2012).
2. Sitch, S. et al. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology* **14**, 25 (2008).
3. Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S. & Fisher, J.B. Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **369**, 137-160 (2011).
4. Huntingford, C. & Cox, P.M. An analogue model to derive additional climate change scenarios from existing GCM simulations. *Climate Dynamics* **16**, 575-586 (2000).
5. Andreae, M.O., Jones, C.D. & Cox, P.M. Strong present-day aerosol cooling implies a hot future. *Nature* **435**, 1187-1190 (2005).
6. Stott, P.A., Huntingford, C., Jones, C.D. & Kettleborough, J.A. Observed climate change constrains the likelihood of extreme future global warming. *Tellus Series B-Chemical and Physical Meteorology* **60**, 76-81 (2008).
7. New, M., Hulme, M. & Jones, P. Representing twentieth-century space-time climate variability. Part I: Development of a 1961-90 mean monthly terrestrial climatology. *Journal of Climate* **12**, 829-856 (1999).
8. Mitchell, T.D. & Jones, P.D. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* **25**, 693-712 (2005).
9. Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. & Totterdell, I.J. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**, 184-187 (2000).
10. Zak, D.R., Pregitzer, K.S., Kubiske, M.E. & Burton, A.J. Forest productivity under elevated CO2 and O3: positive feedbacks to soil N cycling sustain decade-long net primary productivity enhancement by CO2. *Ecology Letters* **14**, 1220-1226 (2011).
11. Drake, J.E. et al. Increases in the flux of carbon belowground stimulate nitrogen uptake and sustain the long-term enhancement of forest productivity under elevated CO(2). *Ecology Letters* **14**, 349-357 (2011).
12. Korner, C. et al. Carbon flux and growth in mature deciduous forest trees exposed to elevated CO2. *Science* **309**, 1360-1362 (2005).
13. Norby, R.J. et al. Net primary productivity of a CO2-enriched deciduous forest and the implications for carbon storage. *Ecological Applications* **12**, 1261-1266 (2002).
14. Korner, C. Through enhanced tree dynamics carbon dioxide enrichment may cause tropical forests to lose carbon. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **359**, 493-498 (2004).
15. Dufresne, J.L. et al. On the magnitude of positive feedback between future climate change and the carbon cycle. *Geophysical Research Letters* **29**(2002).
16. Iversen, C.M. Digging deeper: fine-root responses to rising atmospheric CO(2) concentration in forested ecosystems. *New Phytologist* **186**, 346-357 (2010).
17. Mercado, L.M. et al. Variations in Amazon forest productivity correlated with foliar nutrients and modelled rates of photosynthetic carbon supply. *Philosophical Transactions of the Royal Society B-Biological Sciences* **366**, 3316-3329 (2011).
18. Lloyd, J. et al. Ecophysiology of Forest and Savanna Vegetation. in *Amazonia and Global Change*, Vol. 186 (ed. Keller, M.B.M.G.J.D.P.S.) 463-484 (2009).
19. Malhi, Y. et al. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 20610-20615 (2009).
20. Atkin, O.K. & Tjoelker, M.G. Thermal acclimation and the dynamic response of plant respiration to temperature. *Trends in Plant Science* **8**, 343-351 (2003).

21. Atkin, O.K. et al. Using temperature-dependent changes in leaf scaling relationships to quantitatively account for thermal acclimation of respiration in a coupled global climate-vegetation model. *Global Change Biology* **14**, 2709-2726 (2008).
22. Bonan, G.B. & Levis, S. Quantifying carbon-nitrogen feedbacks in the Community Land Model (CLM4). *Geophysical Research Letters* **37**(2010).
23. da Costa, A.C.L. et al. Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytologist* **187**, 579-591 (2010).
24. Nepstad, D.C., Tohver, I.M., Ray, D., Moutinho, P. & Cardinot, G. Mortality of large trees and lianas following experimental drought in an amazon forest. *Ecology* **88**, 2259-2269 (2007).
25. Phillips, O.L. et al. Drought-mortality relationships for tropical forests. *New Phytologist* **187**, 631-646 (2010).
26. Fisher, R. et al. Assessing uncertainties in a second-generation dynamic vegetation model caused by ecological scale limitations. *New Phytologist* **187**, 666-681 (2010).
27. Meir, P. et al. The Effects of Drought on Amazonian Rain Forests. in *Amazonia and Global Change*, Vol. 186 (ed. Keller, M.B.M.G.J.D.P.S.) 429-449 (2009).
28. Brando, P.M. et al. Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Philosophical Transactions of the Royal Society B-Biological Sciences* **363**, 1839-1848 (2008).
29. Fisher, R.A., Williams, M., Ruivo, M.D., de Costa, A.L. & Meira, P. Evaluating climatic and soil water controls on evapotranspiration at two Amazonian rainforest sites. *Agricultural and Forest Meteorology* **148**, 850-861 (2008).
30. Meir, P., Metcalfe, D.B., Costa, A.C.L. & Fisher, R.A. The fate of assimilated carbon during drought: impacts on respiration in Amazon rainforests. *Philosophical Transactions of the Royal Society B-Biological Sciences* **363**, 1849-1855 (2008).
31. Metcalfe, D.B. et al. Shifts in plant respiration and carbon use efficiency at a large-scale drought experiment in the eastern Amazon. *New Phytologist* **187**, 608-621 (2010).
32. Markewitz, D., Devine, S., Davidson, E.A., Brando, P. & Nepstad, D.C. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. *New Phytologist* **187**, 592-607 (2010).
33. White, A., Cannell, M.G.R. & Friend, A.D. Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment. *Global Environmental Change-Human and Policy Dimensions* **9**, S21-S30 (1999).
34. Cramer, W. et al. Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models. *Global Change Biology* **7**, 357-373 (2001).
35. Betts, R.A. et al. The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and Applied Climatology* **78**, 157-175 (2004).
36. Cox, P.M. et al. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology* **78**, 137-156 (2004).
37. Huntingford, C. et al. Using a GCM analogue model to investigate the potential for Amazonian forest dieback. *Theoretical and Applied Climatology* **78**, 177-185 (2004).
38. Levy, P.E., Cannell, M.G.R. & Friend, A.D. Modelling the impact of future changes in climate, CO2 concentration and land use on natural ecosystems and the terrestrial carbon sink. *Global Environmental Change-Human and Policy Dimensions* **14**, 21-30 (2004).
39. Cowling, S.A. & Shin, Y. Simulated ecosystem threshold responses to co-varying temperature, precipitation and atmospheric CO2 within a region of Amazonia. *Global Ecology and Biogeography* **15**, 553-566 (2006).
40. Schaphoff, S. et al. Terrestrial biosphere carbon storage under alternative climate projections. *Climatic Change* **74**, 97-122 (2006).

41. Scholze, M., Knorr, W., Arnell, N.W. & Prentice, I.C. A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 13116-13120 (2006).
42. Salazar, L.F., Nobre, C.A. & Oyama, M.D. Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters* **34**(2007).
43. Golding, N. & Betts, R. Fire risk in Amazonia due to climate change in the HadCM3 climate model: Potential interactions with deforestation. *Global Biogeochemical Cycles* **22**, - (2008).
44. Huntingford, C. et al. Towards quantifying uncertainty in predictions of Amazon 'dieback'. *Philosophical Transactions of the Royal Society B-Biological Sciences* **363**, 1857-1864 (2008).
45. Jones, C., Lowe, J., Liddicoat, S. & Betts, R. Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience* **2**, 484-487 (2009).
46. Lapola, D.M., Oyama, M.D. & Nobre, C.A. Exploring the range of climate biome projections for tropical South America: The role of CO2 fertilization and seasonality. *Global Biogeochemical Cycles* **23**(2009).
47. Poulter, B. et al. Robust dynamics of Amazon dieback to climate change with perturbed ecosystem model parameters. *Global Change Biology* **16**, 2476-2495 (2010).
48. Galbraith, D. et al. Multiple mechanisms of Amazonian forest biomass losses in three dynamic global vegetation models under climate change. *New Phytologist* **187**, 647-665 (2010).
49. Doherty, R.M., Sitch, S., Smith, B., Lewis, S.L. & Thornton, P.K. Implications of future climate and atmospheric CO(2) content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology* **16**, 617-640 (2010).
50. Good, P. et al. Quantifying Environmental Drivers of Future Tropical Forest Extent. *Journal of Climate* **24**, 1337-1349 (2011).
51. Gumpenberger, M. et al. Predicting pan-tropical climate change induced forest stock gains and losses-implications for REDD. *Environmental Research Letters* **5**(2010).