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Terrestrial ecosystem CO_2 fluxes: their role in global atmospheric change

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Terrestrial carbon fluxes and international greenhouse policies

The United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol (KP) have brought photosynthesis-derived C fluxes into the limelight. Interpretation of "terrestrial C fluxes" depends on the timescale and space scale over which fluxes are averaged. It is also dependent on whether or not one is referring to absolute fluxes or to the net fluxes attributable to the *change* of environment since a particular reference time. Also pertinent is whether one is referring to total fluxes or just certain components of total fluxes such as those attributable to specific drivers such as afforestation. Inclusion or exclusion of certain CO_2 fluxes, into or out of terrestrial ecosystems, as specified in the KP, is one of the points about which countries differed strongly leading to stalling in 2000AD of the conferences of parties (COP6) to the UNFCCC. Selective CO_2 flux accounting as required by the KP is susceptible to counter-productive outcomes (IGBP Terrestrial Carbon Working Group 1998). Comprehensive total terrestrial C-cycle accounting would inform and maintain consistency among the various purpose-designed accounts that relate to carbon trading and politically agreed definitions of "human-induced" for example.

The UNFCCC and the KP are replete with ambiguities, incompatibilities and deficiencies. But there is a critical aspect on which a sound choice was made. It stated that net annual CO_2 fluxes into or out of terrestrial ecosystems "*from land use change and forestry activities*" be "*measured as verifiable changes in stocks in each commitment period*" (United Nations 1997). That was a wise choice, because direct measurement and attribution of atmospheric fluxes at a high enough spatial resolution is probably impossible in the required 1990-2012 period. Maybe high resolution methods for direct flux determination everywhere may ultimately be devised. However, even then, the attribution of such fluxes to individual causes, man-made or otherwise, remains. Attribution to activities, events, landowners and businesses of greenhouse gas emissions and sinks is important if orderly control of emissions is to be achieved such as through C-trading. Since KP made provision for emissions trading, domestically and internationally, attribution is critical. Determining changes of C-stocks in national terrestrial ecosystems as a measure of the fluxes has a big advantage. A measured change in C-stock is a positively documented amount of C sequestered in pools other than the atmosphere. If there is a legal challenge or an abrupt event like a wildfire that causes a massive efflux event, then the stock can be re-measured. If the requirement were that fluxes into or from the atmosphere were to be measured directly, using atmospheric instrumentation combined with computer models for example, there is no second chance to re-measure it - no positive cross check of the permanence of a removal of C from the atmosphere is possible. An obvious drawback of using changes in stocks as a measure of fluxes is that it takes several year increments to detect gradual change in stocks by measurement in any one area owing to the large and spatially variable background stock in vegetation and soil. Hence annual fluxes must be interpolated in some way between stock measurements. By contrast atmospheric flux measurements by eddy covariance are best suited for short-term determinations from minutes to months. This presumably is why the compliance period target fluxes agreed at Kyoto are the average over five years, 2008-2012.

Ultimately, if effective high resolution direct monitoring of atmospheric fluxes is routinely available everywhere, a hybrid inventory system may be effective. Direct flux measurements being used to assist with the short term interpolation while the stocks-changes measured every few years check the reality of cumulative removals from or additions to the atmosphere.

Unfortunately, the UNFCCC and its KP does not address the issue of a maximum target atmospheric CO_2 *concentration* that can be accepted in the long run, dealing instead with the interim unbounded objective of reducing the annual fluxes of GHG emissions into the atmosphere. Slowing down the pace of global change without ultimate targets for atmospheric concentrations allows more time for adaptation. However, ultimately the issue of maximum target concentrations of greenhouse gases in the atmosphere will have to be addressed given that the fossil fuel resource is sufficient to cause several-fold increase in atmospheric CO_2 concentration, which we think would have enormous climatic consequences. The focus on annual fluxes distracts attention from the more important long-term consideration of the maximum tolerable atmospheric CO_2 concentration and the mechanisms to avoid surpassing it. However, the KP must be seen as just a tentative beginning to global collaboration in atmospheric composition control.

There are many levels (spatial and temporal) at which CO_2 fluxes can be expressed. Globally, the terrestrial ecosystem flux most pertinent to annual change in atmospheric CO_2 concentration is the annual Net Biome Exchange (NBE). NBE corresponds to the actual annual gain or loss of C in the whole terrestrial biosphere, soil included, and including the effects of major disturbances such as wildfires, plagues and deforestation. However, for most ecosystems in most years, major disturbances do not occur and so it is the Net Ecosystem Exchange (NEE) which is most significant on a small scale from year to year. Most of the time NEE of an ecosystem is positive, being negative only in the years of major disruptions like harvesting or wildfire. Thus we expect most forests to be growing most of the time in a steady state biosphere. However, the UNFCCC process must come to grips with how to treat occasional re-emission through major natural disturbance (such as wildfire or plague) of C stored previously through direct human actions.

Magnitudes of terrestrial carbon pools and fluxes

It is surprisingly difficult to estimate terrestrial CO_2 fluxes globally. To illustrate the problem of high uncertainty in estimating ecological fluxes, let us look closer at one of the most commonly discussed fluxes - global Net Primary Production (NPP). Estimates since 1970 of global NPP have ranged from 40 to 80 Gt C yr^{-1} (Alexandrov et al. 1999). This annual net fixation of CO_2 by plants into organic matter is about 10 times larger than the release of CO_2 from fossil fuel burning (6 Gt C yr^{-1}). Even the 40 Gt range of estimates in that net fixation is 7x the fossil emission of CO_2.

Actual measurements of NPP of ecosystems are surprisingly few and incomplete (a global database is at http://www-eosdis.ornl.gov/NPP/npp_home.html). For example, in a recent evaluation of existing field-data on the NPP of tropical rainforests, Clark *et al.* (2001) found that given the flaws in measurements reported they could assemble only 39 examples from the literature that could be adequately compared as global benchmark data. Even so, below ground productivity has rarely been measured. Consequently the authors had to make judgements about upper and lower bounds on how much below-ground productivity to assign with aboveground productivity reported in most cases. Measuring below ground productivity remains a major technical difficulty. Few ecosystem NPP studies deal with it. *Figure 1a* plots the various points of NPP in the Clark *et al.* (2001) database for rainforests. The data are compared with the prediction from the simplest often-used model of whole ecosystem net NPP - the Miami model (Lieth 1975). The latter model uses only annual average rainfall and annual average temperature as inputs. Using two statistical fits of ecosystem NPP, one to annual mean precipitation and one to annual mean temperature, the model chooses the minimum of those two for any location. These days we see the Approach of the Miami model as conceptually flawed. So how does it do in practice? The Miami model was fitted for ecosystems growing in annual average temperatures in the range -12C to +27C, and for rainfall in the range 100mm to 3500mm. For rainfall up to 4000mm the Miami model fits the independent rainforest data remarkably well even to the point of tracking a group of points which fall below the trend line (*Fig 1a)*. Since the Miami model was not parameterised for areas with rainfall in excess of 3500mm, it's not surprising that above 4000mm it fails to fit the independent data.

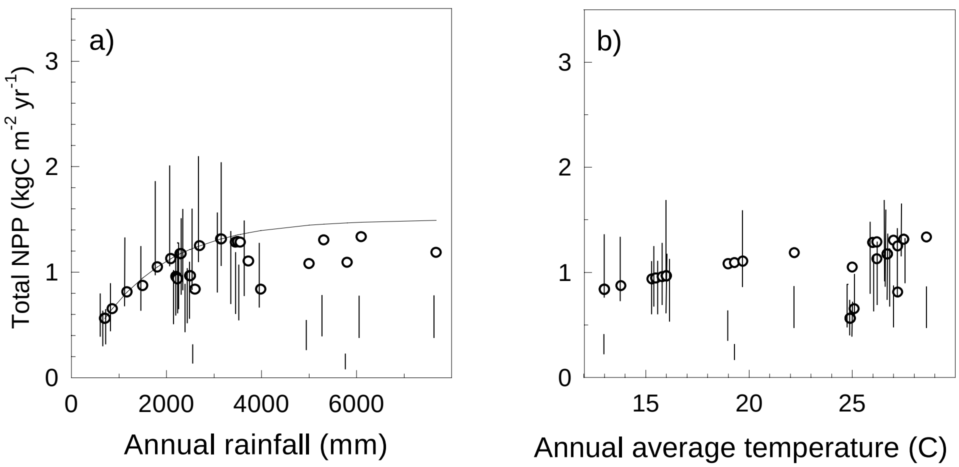
Why does NPP decline so much with annual rainfall above 4000mm? The most obvious hypothesis is that with so much rainfall there are very low solar radiation levels owing to cloudiness. When the Clark database is plotted as a function of annual average temperature and compared with Miami model predictions (*Fig. 1b*) there is again a mixed success. For each of the cases where the Miami model fails to match, the data fall below the prediction. These are the sites that had very high rainfall and hence probably represent low radiation sites.

NPP is only weakly sensitive to annual average temperature (*Fig. 1b*). Another simple, but more mechanistically based, model (the Chikugo model of Uchijima and Seino, 1985) cleverly combines rainfall and net radiation as sole drivers of NPP. Unfortunately net radiation is not recorded in the Clark rainforest data set, so direct comparison with the Chikugo model is not possible. However, by way of exploration if we propose that net radiation declines linearly with precipitation we get the comparison shown in *Fig. 1c*. Including such a relationship between radiation and rainfall much improves the fit to the data. It is remarkable that such simple models with only two environmental inputs (annual rainfall and temperature, or annual rainfall and net radiation) and no ecosystem-specific biological information can capture so much of the independent data-set for rainforests. Considering the frequent discussion of the greater importance of extreme climatic events and variability than annual climatic means in determining ecosystem behaviour this result is surprising.

Numerous attempts have been made to represent biological processes to predict NPP through more mechanistic models. One such model (DEMETER, Foley 1994) includes solar radiation as well as rainfall and temperature as the environmental drivers of productivity flux. This model uses monthly mean data rather than annual mean data and also utilises information on leaf area index of each vegetation type in different seasons. This much more complex and data-demanding model gives good results against independent data but also gives a high level of agreement with the simple empirical Miami model with a coefficient of determination $r^2= 0.92$. Thus the simple Miami model did about as well as the mechanistic DEMETER model of NPP.

Another simple approach to modelling NPP also uses input information about leaf area index. At the large scale, leaf area index is calculated via interpretation of satellite imagery using, typically, the normalized difference vegetation index (NDVI). In principle, leaf area reflects much of the assumed route through which factors like water deficits, temperature and mineral deficiencies determine NPP. From leaf area index can be calculated the fractional interception and absorption of incoming solar radiation. Combining this with information on the incoming solar radiation gives the absorbed solar radiation. It was once proposed that the efficiency of conversion of absorbed daily solar radiation into photosynthate or into plant dry matter is relatively constant (Kumar and Montieth, 1982). However, it is now recognised that it is far from constant, varying particularly with the fraction of incoming solar radiation that is as diffuse radiation as opposed to direct beam radiation (Roderick et al. 2001), with low temperature and with water deficits.

My conclusion about models of NPP is that even with all the advantages of much greater physiological insights, of remote sensing estimates of leaf area, and of high speed computers our capacity to predict whole ecosystem NPP is not much different in practice from that of Lieth's (1975) empirical conceptually flawed 2-factor model of 30 years ago. A large part of the failure to improve our modelling capacity of NPP is the insufficiency and uncertainty of the ground truth data required to establish, calibrate and validate them. Our poor capacity to model NPP is reflected



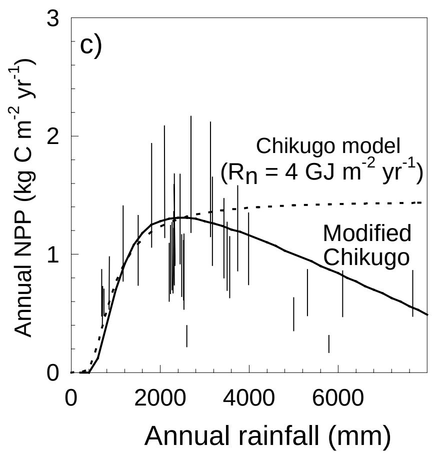


Fig.1 Rainforest net primary production. Upper and lower etimates from field data bounded by the ends of vertical lines (Clark et al. 2001): a) as a function of annual rainfall with Miami model fits for the same sites (symbols), and Miami model rainfall-driven sub-model (Lieth 1975); b) as a function of average annual temperature with Miami model values for the same sites (symbols); c) as a function of rainfall with the Chikugo model (Uchijima & Seino 1985) at fixed annual net radiation, R_n (dashed curve) and with R_n assumed to decline linearly with annual rainfall (solid curve).

equally or more so in the modelling other ecosystem C fluxes such as the net sequestration of C or loss of C into above- and below-ground pools as a result of human activities. The biggest inadequacies of the measurements lie below ground. We have little idea of even the uncertainty in estimates of below ground production rates in most ecosystems. Other uncertainties, such as uncertainties created in scaling up from local to regional or global levels are relatively small.

Global change: the global C balance and the missing CO_2 sink

The difficulties encountered in determining NPP accurately warns us to treat global CO_2 flux estimates with caution. Table 1 summarises the current best estimates of the major global terrestrial CO_2 fluxes and compares them with fossil fuel and oceanic fluxes. Oxygen isotope evidence suggests that 40% of the atmospheric CO_2 enters leaf mesophyll cells each year (270 Gt C yr^{-1}; Ciais et al. 1997). Of this, about half is fixed by photosynthesis (giving a gross primary production of about 120 Gt C yr^{-1}) of which half is re-emitted as plant autotrophic respiration leaving a net primary production of about 60 Gt C^{-1}. This annual net fixation into plant biomass is 10x the annual emission into the atmosphere from fossil fuel burning. But most of this is matched by emissions from decomposition. Similarly about 90 Gt C yr $^{-1}$ dissolves into the oceans which is matched by a similar amount of re-emission. With such a large fraction of atmospheric CO_2 cycling through the terrestrial biosphere and the oceans each year there is ample opportunity for the

8.2 Gt C yr^{-1} of human induced emission of CO_2 into the atmosphere (from industrial and land use change sources) to re-distribute between the atmospheric, terrestrial and the oceanic pools.

Table 1. *Major fluxes in the global carbon cycle (uptake from the atmosphere is positive)*

	Gt C yr^{-1}	Footnote*
Global fossil fuel + cement emission (1990s)	-6.3	1
Net source from land use change, LUC (1990s)	-1.9	2
Total human induced emission (1990s)	-8.2	
Global gross terrestrial influx into leaf mesophyll	+270	3
Global gross primary production influx (GPP)	+120	4
Global net primary production influx (NPP)	+60	5
Global net biome production (including LUC) (1990s)	+1.4	6
Global net biome production (excluding LUC) (1990s)	+3.3	7
Global gross ocean uptake	+92	8
Global net ocean uptake	+1.7	1
Accumulation in the atmosphere (1990s)	3.2	1

* (**1**) IPCC (2001) Third Assessment Report. Working Group 1 Technical Summary; (**2**) Average for 1989-1995, Houghton (2000); (**3**) Ciais et al. (1997; (**4**) Gifford (1982); (**5**) Alexandrov et al. (1999); (**6**) IPCC (2001) Third Assessment Report. Working Group 1 Technical Summary based on atmospheric measurements especially the change in atmospheric O_2; (**7**) calculated as the difference [1.4-(-1.9)]; (**8**) IPCC (1995).

Indeed the evidence indicates, remarkably, that the terrestrial biosphere including the soil is absorbing a substantial fraction of anthropogenic emissions despite the rapid increases in human population, material standards of living, urban developments, agriculture, pollution, soil disturbance and degradation, and tropical deforestation. It is also despite the global rise in average air temperatures which some believe may be causing faster oxidation of the world's soil organic matter stocks (Jenkinson 1990, Woodwell et al. 1998). Furthermore, the size of this unexplained terrestrial sink has increased substantially between the 1980s and the 1990s (Battle et al. 2000, IPCC 2001). In the 1980s it is estimated that the terrestrial sink was about equal to or only slightly in excess of the tropical deforestation source. In the 1990s the global *net* terrestrial sink averaged 1.4±0.7 Gt C yr^{-1} tropical deforestation notwithstanding (Table 1). Since the CO_2 emission from net deforestation is estimated to have been 1.9 Gt C yr^{-1} at that time, the terrestrial sink in areas that were not being cut down was about 3.3 Gt C yr^{-1} - a quantity equal to half the amount being given off by fossil fuel burning. The basis of that estimate of the overall terrestrial sink is not by direct measurement of the terrestrial biosphere but by measurement of atmospheric of oxygen concentration. Given the tight stoichiomety between CO_2 and oxygen exchange and the very low solubility of oxygen in the ocean in contrast to the high solubility of CO_2 in the ocean, the annual change in atmospheric ratio of O_2 to N_2 measures the combined effects of fossil fuel burning and change of stock of organic matter in the terrestrial biosphere. The estimates for the 1990s for the redistribution of the 8.2 Gt C emitted from fossil fuels and net tropical deforestation are 40% into the terrestrial biosphere (3.3 Gt C yr^{-1}) and 40% remaining in the atmosphere 3.2 Gt C yr^{-1} and 20% into the ocean (1.7 Gt C yr^{-1}).

With such a large, and apparently increasing, global terrestrial sink it is clearly necessary to understand its spatial distribution around the world and its mechanisms in order to assess the magnitude of each country's terrestrial CO_2 sources and sinks attributable to direct human activities in the categories that are agreed under the Framework Convention on Climate Change. This issue combined with failure to agree on the interpretation of exactly what kind of fluxes were being talked about in the Kyoto Protocol, lies at the heart of the international disagreements that gave rise to the failure of the Sixth Conference of Parties to the Kyoto Protocol (COP6) in The Hague in Nov 2000. The reconvened COP 6 (July 2001) went some way to clarifying objectives and resolving those differences but also weakened the CO_2 emissions restrictions. Other problems remain.

Potential drivers of the current terrestrial CO_2 sink

So where is the "residual terrestrial sink" and what causes it? Atmospheric measurements of O_2/N_2 ratio and of delta ^{13}C have been used to try to deduce the latitudinal bands in which the sinks occur. The O_2/N_2 data for the 1990s imply that about 2 Gt C yr^{-1} are taken up by the non-tropical land of the Northern hemisphere (Battle *et al.* 2000). In the tropics the O_2/N_2 evidence indicated overall neutrality of the tropical biosphere. Given that the tropical latitudes are estimated to be a deforestation source of 1.9 Gt C yr^{-1} (Houghton 1999), this implies that there was a sink in the tropics of that same magnitude balancing the land clearing source. Thus the residual terrestrial sink is essentially distributed over all the land areas of the world and not particularly concentrated in any one area. Suggestions that have been made include the effects of globally increasing CO_2 concentration; global warming; wildfire suppression; N-deposition; chance effects of climate variability. It is possible that there are several reasons but the apparent wide distribution of the sink seems to direct attention towards globally active drivers such as the CO_2 fertilisation effect.

The CO_2 fertilising effect on net C storage is an expression of a several decade time lag between CO_2 stimulation of NPP and its re-emission by decomposition. This time lag between increased input and output from ecosystems causes stocks of C in the various living and dead C pools to increase. If atmospheric CO_2 concentration were to stop increasing, then over a few decades, the CO_2 sink from CO_2 fertilisation would gradually stop too. In the meantime, is the CO_2 fertilising effect big enough to alone account for the globally distributed terrestrial sink of about 4 Gt C yr^{-1}? This is a large topic. Briefly the answer is that it is well within the bounds of physiological possibility that the global CO_2 fertilising effect could account for a large fraction of the global terrestrial sink but definitive evidence of it is not yet available and will remain difficult to obtain.

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