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Land use effects on atmospheric ^{13}C imply a sizable terrestrial CO_2 sink in tropical latitudes

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[1] Records of atmospheric CO_2 and $^{13}CO_2$ can be used to distinguish terrestrial vs. oceanic exchanges of CO_2 with the atmosphere. However, this approach has proven difficult in the tropics, partly due to extensive land conversion from C_3 to C_4 vegetation. We estimated the effects of such conversion on biosphere-atmosphere ^{13}C exchange for 1991–2000, and then explored how this ''land-use disequilibrium'' altered the partitioning of net atmospheric CO_2 exchanges between ocean and land using NOAA-CMDL data and a 2D, zonally averaged atmospheric transport model. Our results suggest sizable CO_2 uptake in C_3-dominated tropical regions in 8 of the 10 years; 1997 and 1998, which included a strong ENSO event, are near neutral. Since these fluxes include any deforestation source, our findings imply either that such sources are smaller than previously estimated, and/or the existence of a large equatorial terrestrial CO_2 sink. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1610 Global Change: Atmosphere (0315, 0325); 1699 Global Change: General or miscellaneous; 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions

1. Introduction

[2] From an atmospheric perspective, the carbon cycle in tropical regions has long been perplexing. Data from terrestrial environments strongly suggest that high rates of land-use change cause losses of CO_2 to the atmosphere; one recent estimate [*Houghton et al.*, 2000] suggested an average 1980's efflux of nearly 2 Gt yr^{-1}. Oceanic pCO_2 data also suggest that the tropical oceans should be a net source of CO_2 to the atmosphere in most years [*Takahashi et al.*, 1997]. Thus, one might expect to see clear evidence of these sources in the tropical atmosphere, yet several studies [cf. *Rayner et al.*, 1999] have suggested that the net fluxes of CO_2 from earth's equatorial regions are smaller than predicted from the sum of deforestation and oceanic sources.

[3] In part, our limited understanding of the tropical carbon cycle may be due to the fact that isotopic techniques that allow estimates of how net C fluxes are partitioned between land and ocean face some unique hurdles in equatorial latitudes. These techniques have proven to be powerful tools in other regions, and take advantage of the facts that: 1) the product of carbon and its isotopic ratio is conservative in the atmosphere, and 2) photosynthesis on land discriminates strongly against ^{13}C, whereas the effects of oceanic exchange are comparatively small [*Francey et al.*, 1995].

[4] The global atmospheric $^{13}CO_2$ budget can be expressed as:

$$\frac{d}{dt}C_a\delta_a = F_f\delta_f + N_s(\delta_a + \varepsilon_{as}) + N_b(\delta_a + \varepsilon_{ab}) + D_s + D_b \qquad (1)$$

where C_a is the atmospheric pool of C, δ_a is its ^{13}C value (in ‰ relative to PDB), F_f is the fossil fuel release, δ_f is its ^{13}C value, N_s and N_b are net ocean and land exchanges of C with the atmosphere, and ε_{as} and ε_{ab} are the isotopic fractionation factors associated with air-sea transfer and photosynthesis, respectively, expressed in per mil. The last two terms are isotopic disequilibria, defined as the product of the one-way gross flux and the average isotopic difference between reservoir-to-atmosphere fluxes and atmosphere-to-reservoir fluxes. The two disequilibria in equation (1) are non-zero due to historical changes in atmospheric $^{13}CO_2$. These changes cause today's uptake of CO_2 into land or ocean reservoirs to reflect today's atmospheric ^{13}C value, but effluxes of CO_2 from these reservoirs reflect the ^{13}C content of an historical atmosphere. It has been shown that such disequilibria can have a significant effect on isotopically-derived estimates of terrestrial vs. oceanic carbon fluxes [*Ciais et al.*, 1995].

[5] The tropics present an additional problem not reflected in equation (1): widespread areas of vegetation containing the C_4 photosynthetic pathway. Unlike C_3 plants, C_4 vegetation discriminates only slightly against ^{13}C during CO_2 uptake [*Farquhar et al.*, 1989], and therefore fluxes of carbon between C_4 areas and the atmosphere cannot be readily distinguished from those between ocean and atmosphere. Worse yet, most tropical deforestation occurs in C_3 forests, but the majority of vegetation that replaces these forests is C_4 pasture grasses or crops. This conversion causes respiration of soil carbon to be significantly lighter in ^{13}C than the newly formed plant material for several decades, in turn creating a net flux of ^{13}C from atmosphere to land (Figure 1). While the potential importance of land use change on the atmospheric ^{13}C budget has been recognized in past studies [*Ciais et al.*, 1995], attempts to use atmospheric $^{13}CO_2$ data to estimate land versus ocean carbon exchanges have not been able to account for this effect.

[6] The land-use disequilibrium can be written as:

$$D_{lu} = R_{lu}(\delta_{resp} - \delta_{assim}) \qquad (2)$$

where R_{lu} is heterotrophic respiration from lands which have been converted from C_3 forest to C_4 crops or pasture, δ_{resp} is the ^{13}C value of that flux, and δ_{assim} is the ^{13}C value of the new C_4 vegetation. In theory, D_{lu} can be added easily to equation (1), but estimating its value requires knowledge about the heterotrophic respiration and the isotopic imbalance of every parcel of cleared land which has a disequilibrium due to a change from C_3 forest to C_4 pasture or crops. Following such a change, the soil carbon pool will continue to respire C_3 carbon, but the fraction of heterotrophic respiration which is C_3 will decline (Figure 1), and frequently, the

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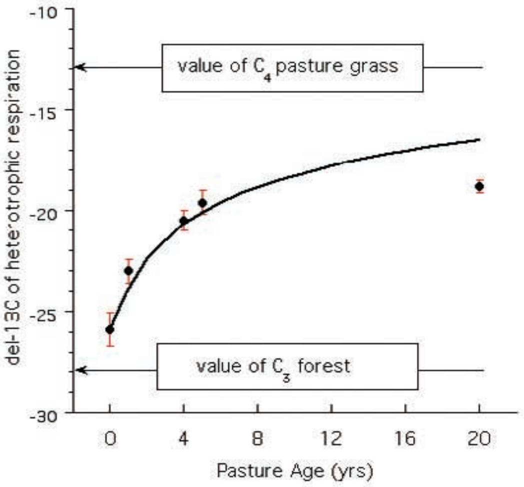

Figure 1. ^{13}C values for heterotrophic respiration following a change from C_3 forest to C_4 pasture. Data are from a pasture chronosequence in Costa Rica; solid line shows the results of a Century model [*Parton et al.*, 1994] simulation for the same sites. Units are parts per mil relative to PDB standard.

total respiration flux will also decline as land is degraded [*Davidson et al.*, 1995]. Thus, a recently cleared pasture will have a much greater D_{lu} than an old pasture. A single, global D_{lu} value for a given year must therefore account for the age of every piece of converted land that contributes to this value:

$$D_{lu} = \sum_{i=1}^{n} Ri\left(\delta_{resp} - \delta_{assim}\right) \qquad (3)$$

where i through n represent annual age classes of cleared lands.

2. Methods

[7] Our estimate of D_{lu} focused on land conversion in moist tropical forests. Most annual conversion rates were taken from two published sources [*Houghton and Hackler*, 1995; *FAO*, 1997]; the exception was for recent rates of conversion in the Amazon basin, where we used data from the Brazilian space agency INPE. The conversion rates represent net changes in forest area (from forest to pasture or agriculture). We compiled single average values for tropical Latin America, Africa and Asia for every year beginning in 1950. Not all years and continents have annual data, especially prior to the 1980's, therefore decadal averages were used for many of the early numbers. Most (but not all) converted land in Latin America and Africa is either pasture or C_4 crops [*Fearnside et al.*, 1998; *FAO*, 1997]; we assumed that 80% of the total conversion was a C_3–C_4 change. Due to widespread rice cultivation in Asia, we assumed a value of 50% in this region. Precise values for the fraction of land use change that is C_3–C_4 were not available at these scales, thus we used values that we believe to be conservative.

[8] We used Century model [*Parton et al.*, 1994] simulations to estimate the amount and ^{13}C value of heterotrophic respiration for converted lands throughout the tropics. Since estimates of D_{lu} require decades of land use data, the low spatial resolution of such data did not allow us to perform Century simulations with subcontinental resolution. Instead, we estimated continental values for D_{lu} using 5 selected sites each in tropical Latin America, Africa and Asia for which Century had already been parameterized [*Schimel et al.*, 1996]; these sites ranged from the eastern to the western margins of each continent. Simulations of land use trajectories from primary forest to 40 yr old converted land were run for each site. These simulations generated estimates of heterotrophic respiration and its isotopic value on a per area basis for a given land parcel at any time since conversion; D_{lu} can then be determined using equation (2). Isotopic values for C_3 and C_4 vegetation were set at −27 and −13‰, respectively. The average of all five sites was used as a single continental value for converted land of any given age within that continent. The conversion data referenced above were then used to derive a single average D_{lu} value for all tropical lands in any given year (equation (3)). Century simulations of isotopic values for heterotrophic respiration were also compared to data from pasture chronosequences in Costa Rica, Brazil and Hawaii. These data consisted of δ^{13}C values of CO_2 evolved from root-free soil incubations. Full descriptions of the sites and incubation methods are found in *Townsend et al.* [1997] and *Holland et al.* [2000]. In all cases the model was able to predict isotopic changes over time with reasonable accuracy (Figure 1).

[9] As can be seen in Figure 1, the greatest isotopic imbalances occur in the first few years following conversion, therefore recently cleared areas dominate D_{lu}. This is fortunate for our estimates, in that data on rates of land conversion are far better constrained in recent years than they are for earlier decades.

[10] Secondary succession of C_3 vegetation into abandoned cleared lands creates additional uncertainty for D_{lu}. Potentially, the switch from C_4 back to C_3 could help offset the size of D_{lu} by creating lands with an isotopic imbalance opposite in sign to that of the original clearing. However, unlike the original, rapid change from C_3 to C_4 vegetation, secondary succession occurs at a slower rate. The time scale of this change also depends on the age of the abandoned land. In older cleared areas, the δ^{13}C signature of soil carbon will have significantly changed from a C_3 value to one close to that of the C_4 vegetation, creating the potential for a large disequilibrium in the reverse direction. However, succession into these older areas tends to be slow, occurring on roughly the same time scales as soil carbon turnover [*Buschbacher et al.*, 1988]. In contrast, cleared lands abandoned shortly after conversion will return quickly to nearly all C_3 vegetation, but their soil carbon will also have relatively little C_4 carbon prior to abandonment. The net result in either case is that any imbalance due to secondary succession is likely to be small relative to the effects of the initial conversion. Several Century simulations (not shown) with varying rates of succession according to time since conversion supported this hypothesis.

[11] We therefore assumed that secondary succession does not create a large isotopic disequilibrium, but once land is abandoned, that land's contribution to D_{lu} ceases. Thus, although there are very old parcels of cleared land that still contribute to D_{lu}, others have been abandoned much more rapidly. This fact requires some assumptions about how far back in time we should include lands as contributing to the total disequilibrium. As a sensitivity test, we calculated several values that span a range from only the most recent 10 years of clearing up to 40 years.

[12] We then took the values for D_{lu} based on a range of average abandonment times from 10 to 40 yrs and assessed their effect on the partitioning of regional-scale, surface-atmosphere carbon exchanges between land and ocean reservoirs. Briefly, the estimates of carbon exchanges by latitude are derived as follows. For every year since 1990, the Stable Isotope Laboratory at INSTAAR has measured δ^{13}C values of CO_2 in weekly samples of air taken from a global network of sites; these isotopic data complement NOAA/CMDL's measurement of CO_2 mixing ratios from these sites [*Trolier*, 1996]. The smoothed data are then used to estimate the latitudinal distribution of net surface fluxes of CO_2 and $^{13}CO_2$ via inverse application of a two-dimensional atmospheric transport model [*Ciais et al.*, 1995]. Finally, the separation of net fluxes into

land and ocean components is done using linear equations (similar to equation (1) above) in which the known fossil fuel contribution is removed, and the various isotopic fractionation factors and disequilibria are specified. The values for D_s and D_b, their spatial structure, and the values of all other model parameters were as in *Ciais et al.* [1995], and full descriptions of the data and modeling techniques used here can be found in this paper and in *Tans et al.* [1989].

3. Results

[13] Average D_{lu} values for the 1990s were 8.8, 14.1, and 15.8 Gt per mil, respectively, for estimates using 10, 20, and 30 yrs of clearing. A final "maximum" estimate assuming 40 yrs of clearing and 100% conversion to C_4 in cleared lands was equal to 17.5 Gt per mil. Several important attributes of the land-use disequilibrium are apparent from these values. First, because younger cleared sites have by far the greatest isotopic imbalance (Figure 1), the contribution to the total D_{lu} value is much greater from the most recent 10 years of clearing than from prior decades. Most of the difference between the 10 and 20 yr values is due to the much larger isotopic imbalance in recently cleared lands rather than to any substantive difference in clearing rates between decades. Second, assuming average ages of abandonment in excess of 20 years makes a relatively minor difference in the total D_{lu} value.

[14] Figure 2 shows the effects of adding the 20 yr land use disequilibrium values to the estimates of land vs. ocean fluxes in tropical latitudes (17°N-S; the effects of tropical C_3-C_4 conversion on higher latitudes are very minor). Incorporation of D_{lu} into this analysis alters the partitioning of fluxes by an average of 1.04 Gt yr^{-1} over the 1990's; the direction of this change is for greater carbon uptake by C_3 ecosystems. Two striking features emerge from Figure 2. First, despite abundant evidence that land use change in C_3 regions of the tropics is responsible for large losses of C to the atmosphere, these regions display net uptake of CO_2 for 8 of the 10 years in the record. The remaining two years, which span a strong ENSO event, are near neutral. This suggests the existence of a sizable terrestrial sink for atmospheric CO_2 in tropical forests, one that in some years may rival that estimated for mid-latitudes of the northern hemisphere. Several other recent approaches to understanding the carbon balance of the terrestrial tropics, ranging from flux tower measurements [*Grace et al.*, 1995], to forest inventories [*Phillips et al.*, 1998], to ecosystem modeling [*Tian et al.*, 1998], have also suggested the possibility of a sizable C sink. The mechanisms behind such a sink are unknown, though areas of regrowth [*Houghton et al.*, 2000], rising CO_2 levels [*McKane et al.*, 1995] and climatic variability [*Tian et al.*, 1998; *Rayner et al.*, 1999] have all been proposed.

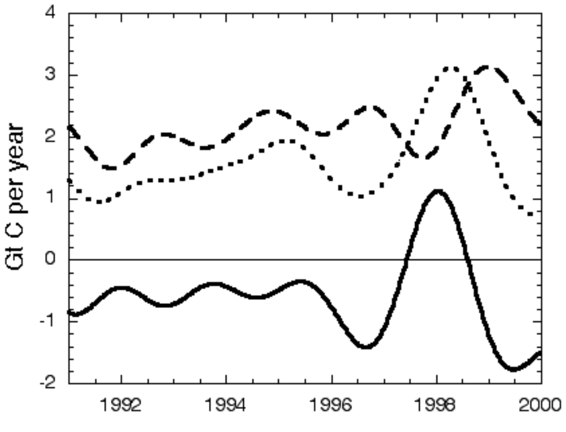

Figure 2. 1991–2000 smoothed (one year) net CO_2 fluxes between earth's surface and the atmosphere spanning 17°S and 17°N (dotted line) without the contribution of fossil fuel emissions, and the separation of those fluxes into C_3 land (solid line) and ocean plus C_4 land (heavy dashed line) components. This separation incorporates the 20 year values for D_{lu} (see figure 2). Positive values represent a net flux to the atmosphere; negative values are net uptake. Units are Gt (10^{15} g) of C per year.

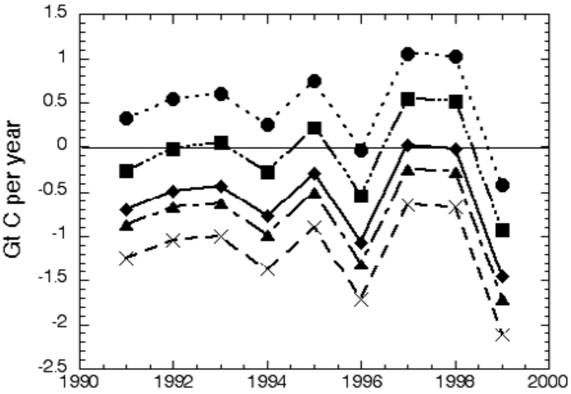

Figure 3. Net annual CO_2 fluxes between C_3 lands and the tropical atmosphere (17°N-S) assuming no land use disequilibrium (circles), D_{lu} values assuming 10, 20 and 30 year abandonment times (squares, diamonds, and triangle, respectively), and a "maximum possible" value in which a 40 year abandonment time is used and all land conversion is assumed to be C_3 to C_4 (dashed line with X's).

[15] Second, the dashed line in Figure 2 shows the net flux for oceans and lands dominated by C_4 vegetation; these cannot be separated in this analysis. Our results suggest that when the land use effect is considered, the majority of the net CO_2 efflux from the earth's surface to the atmosphere in tropical latitudes is due to net losses from oceanic or C_4 vegetation realms. This result is consistent with oceanic pCO_2 data, and is also consistent with the fact that C_4 dominated lands are subjected to heavy anthropogenic use throughout the tropics, which frequently leads to degradation and net C losses.

[16] Finally, we note that the partitioning of net C fluxes into land and ocean components depends strongly on the values chosen for D_s and D_b, and the ocean disequilibrium value (D_s) we used was smaller than more recent estimates [e.g. *Gruber and Keeling*, 2001]. However, recent tests with our 2D model showed that while incorporation of a new, larger D_s value does make a significant difference in the flux partitioning at a global scale, it makes a very minor difference in the tropical latitudes.

4. Discussion

[17] The values in Figure 2 assume a 20 yr contribution of cleared lands to the land use disequilibrium; Figure 3 shows the net flux from C_3 lands using a range of D_{lu} values from 10–40 yr abandonment times, as well as the net flux assuming no land use effect. It is possible that the 20 yr value is an overestimate. However, for several reasons we believe that this value is unlikely to represent a large deviation from reality. First, we assumed that only 80% of clearing in tropical Latin America and Africa represented a C_3-C_4 shift, and that only half did so in Asia; this is quite possibly an underestimate. Several studies have shown that nearly all forests cleared in the Amazon are converted to areas of C_4 vegetation [*Fearnside et al.*, 1998]. Second, as noted above, D_{lu} is dominated by the contribution of more recently cleared lands; for example, cutting the 20 yr value in half only reduces D_{lu} by 30%. Third, even if our chosen value for D_{lu} is somewhat high, the value is growing every year as more land is cleared, unless average abandonment times for cleared lands are decreasing. Finally, and

perhaps most importantly, the implication that a significant terrestrial sink exists in tropical forest regions — and/or of much smaller values for deforestation losses than typically assumed — would remain even if we used a D_{lu} value that only accounted for the last 10 yrs of clearing (Figure 3).

[18] The difficulties of quantifying C_3-C_4 conversion areas and their average time until abandonment at a pan-tropical scale unquestionably introduce error into any estimate of D_{lu}. For example, although we assumed C_3-C_4 conversions represented a complete change in photosynthetic pathways, most tropical pastures contain some C_3 woody vegetation at nearly any age. In part, this is why we attempted to use conservative values for the fraction of all deforestation that is a C_3-C_4 change. Moreover, we recognize that inverse modeling results are most uncertain in the tropics due to vigorous vertical mixing in the equatorial atmosphere. However, we believe the range of values shown in Figure 3 makes it clear that the isotopic imbalance created by land use changes is large enough to require its incorporation into any estimate of tropical carbon fluxes that is based upon atmospheric ^{13}C data, and we wish to stress that no matter what atmospheric modeling approach is used, the direction of the land use correction is for much greater terrestrial uptake.

[19] Finally, we recognize that any estimates of a sizable terrestrial sink in the tropics create some substantial discrepancies with several other global estimates of the recent carbon budget. Many global-scale atmospheric approaches to the C budget, including those based on both $^{13}CO_2$ and O_2/N_2 ratios [*Rayner et al.*, 1999; *Battle et al.*, 2000], suggest oceanic and mid-latitude terrestrial sinks that are comparable to or greater than what we and others suggest may be occurring in the tropics. The sum of all such sinks is greater than the difference between anthropogenic emissions of CO_2 and the observed atmospheric increase. One potential explanation that would help resolve this discrepancy is that net carbon losses from C_4 dominated lands in the tropics might roughly balance any C gain seen in C_3 forest regions. From an atmospheric perspective, such losses cannot be distinguished from net ocean fluxes (e.g. Figure 3), and thus might be attributed to an oceanic flux. However, given the enormous human impacts on C_4 dominated lands — not just on converted pastures and croplands, but also on large areas of savannas and mixed woodlands — the potential for a sizable net carbon loss from these regions is entirely possible, if not likely.

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