**ONLINE SUPPLEMENTARY INFORMATION**

**Literature comparisons**

To compare our estimates of *F*he and *I* to other ecosystem sources of labile N and P, we conducted a literature search for estimates of atmospheric deposition (for N and P), biological fixation (for N) and bedrock weathering (for P) in mature tropical forests. There were generally too few estimates from montane ecosystems, so we restricted our search to lowland forests, assuming they were more representative of our two lowland study sites (TAM-06, TAM-05). For biological N fixation, we used a global synthesis (Cleveland *et al*. 1999), selected only values for the “Tropical Rainforest” vegetation type (7 studies) and updated these values to the present day with an additional 7 studies (Table 5 in Online Supplementary Information). For atmospheric N and P deposition, we selected model estimates from the tropical Andes region (Phoenix *et al*. 2006; Mahowald *et al*. 2008). Given the lack of direct measurements of atmospheric N and P deposition near to the study sites, we believe that these parameterized model values are the best estimates available. Very few estimates of P input from bedrock weathering exist for the tropics. We selected two estimates from Venezuela to derive our mean (Lewis *et al*. 1987; Ramirez & Andara 1993), since these Andean weathering rates are likely more representative of our study sites than others in central Amazonia. Ramirez & Andara (1993) present weathering as rock mass, so we convert this flux to P with an estimate of mean P content of igneous rocks of 0.95 mg g-1 (Newman 1995). The range around our mean estimate of P weathering is likely conservative, reflecting the paucity of replicates (*n* = 2) rather than real uniformity in weathering rates across the western Amazon.

 We compared our measurements of the portion of *F*p removed by invertebrate herbivores (*F*c) with global syntheses (McNaughton *et al*. 1989; Cebrian 2004). For the Cebrian (2004) synthesis, we accessed the full dataset available in online supplementary information with the article and selected available data on herbivory as a proportion of above-ground productivity, then calculated means for each of the major terrestrial biome types distinguished in the dataset. Further, we used the following relationship between *F*p and *F*c from figure 2 in McNaughton *et al*. (1989) to predict *F*c from *F*p measured at our study sites:

Log *F*c = 2.04 × (log *F*p) – 4.80

Where both *F*p and *F*c are in units of kJ m-2 yr-1. We converted units of energy to mass with the same standard factors applied in McNaughton *et al*. (1989), for tropical rainforest vegetation tissue caloric content of 3897 cal g-1 dry mass (Golley 1961).



**Fig. 1** Frequency of leaf damage amongst the 18 428 leaves analyzed in the study.

**Table 1** Summary of plot characteristics. Data are derived from previous studies at the sites (Girardin *et al*. 2010, 2013; Salinas *et al*. 2011; Fisher *et al*. 2013; Huaraca Huasco *et al*. 2013; Malhi *et al*. 2013).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Site code** | **ESP-01** | **WAY-01** | **SPD-01** | **SPD-02** | **TAM-06** | **TAM-05** |
| **Elevation (m above sea level)** | 3000 | 3025 | 1750 | 1500 | 200 | 200 |
| **Latitude** | -13.900 | -13.176 | -13.047 | -13.049 | -12.839 | -12.830 |
| **Longitude** | -71.587 | -71.594 | -71.542 | -71.537 | -69.296 | -69.271 |
| **Aspect** | E | W | W | W | — | — |
| **Slope (%)** | 28 | 27 | 0 |
| **Mean annual temperature (oC)** | 12.0 | 12.5 | 17.8 | 18.9 | 24.4 | 24.4 |
| **Mean annual precipitation (mm)** | 1706 | 1560 | 5302 | 5302 | 1894 | 1894 |
| **Geological substrate** | Paleozoic shales | Late Permian granite | Pleistocene alluvial terrace |
| **Soil pH** | 4.1 | 4.1 | 4.0 | 4.0 | 3.9 | 3.9 |
| **Soil organic nitrogen** **(g kg-1)** | — | 18.6 | — | 12.2 | — | 16.4 |
| **Soil organic phosphorus****(g kg-1)** | — | 1.1 | — | 1.1 | — | 1.4 |
| **Gross primary production (Mg C ha-1 yr-1)** | 22 ± 2 | 27 ± 3 | 39 ± 4 | 32 ± 4 | 33 ± 4 | 36 ± 4 |
| **Above-ground net primary production (Mg C ha-1 yr-1)** | 5.3 ± 0.4 | 5.9 ± 0.6 | 6.3 ± 0.4 | 9.4 ± 0.6 | 11.6 ± 1.1 | 10.0 ± 1.1 |
| **Below-ground net primary production (Mg C ha-1 yr-1)** | 1.7 ± 0.2 | 2.2 ± 0.4 | 1.6 ± 0.2 | 2.5 ± 0.3 | 2.6 ± 0.3 | 5.1 ± 0.7 |
| **Foliar production****(Mg C ha-1 yr-1)** | 2.2 ± 0.3 | 2.8 ± 0.3 | 3.1 ± 0.3 | 4.7 ± 0.4 | 4.3 ± 0.4 | 4.8 ± 0.4 |
| **Foliar biomass (Mg C ha-1)** | 5.9 ± 0.4 | 5.7 ± 0.4 | 6.1 ± 0.4 | 7.1 ± 0.4 | 6.3 ± 0.2 | 6.3 ± 0.2 |
| **Canopy turnover (yr)** | 1.5 ± 0.2 | 1.1 ± 0.1 | 1.1 ± 0.1 | 0.8 ± 0.1 | 0.8 ± 0.1 | 0.8 ± 0.1 |
| **Dominant plant families** | Cunoniaceae, Clusiaceae | Lauraceae, Rubiaceae, Melastomataceae | Myristicaceae, Fabaceae |

**Table 2** Insect herbivore partitioning of ingested carbon, derived from studies summarized in Wiegert & Petersen (1983).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  | **Allocation of ingested carbon (% of total)** |  |
| **Order** | **Family** | **Species** | **Respiration** | **Excretion** | **Growth** | **Source** |
| Orthoptera | Acrididae | *Bootetfix punctatus* | 13 | 79 | 8 | Weidemann 1971 |
|  |  | *Encoptolophus sordidus* | 13 | 74 | 13 | Smith 1972 |
|  |  | *Melanoplus bivittatus* | 25 | 59 | 16 | Van Hook & Dodson 1974 |
|  |  | *Melanoplus femurrubrum* | 22 | 65 | 13 | Wiegert 1964 |
|  |  | *Melanoplus* sp. | 23 | 63 | 14 | Hinton 1971 |
|  |  | *Meumoplus* sp. | 24 | 63 | 13 | Hinton 1971 |
|  |  | *Trimerotropis saxatilis* | 14 | 80 | 6 | Van Hook *et al*. 1980 |
|  | Tettigonidae | *Orchelimum fidicinium* | 17 | 73 | 10 | Llewellyn 1975 |
|  | Gryllidae | *Pteronemobius fasciolus* | 28 | 59 | 13 | McNeill 1971 |
| Hemiptera | Miridae | *Leptopterna dolabrata* | 14 | 69 | 17 | Van Hook 1971 |
| Homoptera | Aphididae | *Acyrthosiphon pisum* | 4 | 90 | 6 | Smalley 1960 |
|  |  | *Eucallipterus tiliae* | 6 | 67 | 27 | Webb & Elmes 1972 |
|  | Cereopidae | *Neophilaenus lineatus* | 26 | 58 | 15 | Wiegert 1965 |
|  |  | *Philaenus spumarius* | 53 | 42 | 5 | Brown & Fitzpatrick 1978 |
|  |  | *Philaenus spumarius* | 23 | 62 | 16 | Brown & Fitzpatrick 1978 |
| Coleoptera | Cureulionidae | *Leplinotarsa decemlineata* | 40 | 49 | 11 | Chlodny *et al*. 1967 |
| Lepidoptera |  | *Lepidoptera* spp. | 15 | 60 | 24 | Coffman *et al*. 1971 |
|  | Gelechiidae | *Chimobacche tagella* | 15 | 79 | 6 | Bailey & Mukerji 1977 |
|  |  | **Mean ± SE** | **21.0 ± 2.7** | **66.1 ± 2.8** | **12.9 ± 1.4** |  |

**Table 3** Results of a Spearman’s rank correlation between mean site herbivory (percentage of area removed per leaf) and a range of abiotic and biotic factors. Mean annual temperature residuals show correlations with the residual variation left after accounting for the temperature trend in herbivory. Significant correlations (*P* < 0.005) are highlighted in bold.

|  |  |
| --- | --- |
|  | **Herbivory** |
| **Ecosystem properties** | ***r*2** | **Coefficient** | ***P*-value** |
| Gross primary productivity (Mg C ha-1 yr-1) | 0.46 | 0.771 | 0.072  |
| Net primary productivity (Mg C ha-1 yr-1) | 0.61 | 0.714 | 0.111  |
| Foliar productivity (Mg C ha-1 yr-1) | 0.45 | 0.600 | 0.208 |
| Canopy mass (Mg C ha-1) | 0.20 | 0.638 | 0.173  |
| Canopy turnover (yr) | 0.41 | 0.714 | 0.173  |
| **Foliar traits** |  |  |  |
| Mass per unit area (g m-2) | **0.74** | **-0.943** | **0.005**  |
| Nitrogen concentration (%) | 0.31 | 0.714 | 0.111  |
| Phosphorus concentration (%) | 0.62 | -0.600 | 0.208  |
| Nitrogen : phosphorus ratio | **0.79** | **0.829** | **0.042**  |
| Cellulose (%) | **0.75** | **0.886** | **0.019**  |
| Lignin (%) | 0.08 | -0.029 | 0.957  |
| Calcium (%) | < 0.01 | -0.029 | 0.957  |
| Potassium (%) | 0.05 | -0.257 | 0.623  |
| Magnesium (%) | < 0.01 | 0.086 | 0.872  |
| **Site climate** |  |  |  |
| Mean annual temperature (oC) | **0.81** | **0.870** | **0.024**  |
| Mean annual precipitation (mm) | 0.01 | 0.478 | 0.338  |
| **Mean annual temperature residuals** |  |  |  |
| Gross primary productivity (Mg C ha-1 yr-1) | 0.05 | 0.493 | 0.321 |
| Net primary productivity (Mg C ha-1 yr-1) | 0.02 | 0.029 | 0.957 |
| Foliar productivity (Mg C ha-1 yr-1) | 0.04 | 0.145 | 0.784 |
| Canopy mass (Mg C ha-1) | 0.01 | 0.162 | 0.759 |
| Canopy turnover (yr) | 0.09 | 0.029 | 0.957 |
| Leaf mass per unit area (g m-2) | 0.29 | -0.551 | 0.257 |
| Leaf nitrogen concentration (%) | 0.08 | 0.435 | 0.389 |
| Leaf phosphorus concentration (%) | **0.46** | **-0.812** | **0.050** |
| Leaf nitrogen : phosphorus ratio | 0.47 | 0.783 | 0.660 |
| Leaf cellulose (%) | 0.07 | 0.232 | 0.658 |
| Leaf lignin (%) | 0.51 | 0.638 | 0.173 |
| Leaf calcium (%) | 0.22 | -0.406 | 0.425 |
| Leaf potassium (%) | 0.05 | -0.406 | 0.425 |
| Leaf magnesium (%) | 0.38 | -0.522 | 0.288 |
| Site mean annual precipitation (mm) | 0.02 | 0.303 | 0.559 |

**Table 4** Regression models fitted to herbivory rate (*H*, % of area removed per leaf). The *T* statistic describes the proportion of variance in *H* uniquely attributable to each of the independant variables in the model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model** | ***T*** | ***r*2** | ***F*** | ***P*** |
| *H* = MAT × 385 + 0.091 | — | 0.82 | 17.9 | 0.013 |
| *H* = (MAT × 0.239) + (N:P ratio × 0.365) + 5.080 | 0.57 | 0.97 | 50.4 | 0.005 |
| *H* = (MAT × 0.289) + (P concentration × -39417) + 15.467 | 0.69 | 0.94 | 22.3 | 0.016 |

**Table 5** Literature estimates of biological nitrogen fixation (g N m-2 yr-1) in lowland tropical forests.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Location** | **Symbiotic** | **Soil / Litter** | **Epiphytes / Lichens** | **Source** |
| Hawaii |  |  | 6.00 | Edmisten 1970 |
| Colombia |  |  | 0.15 | Forman 1975 |
| Central Amazonia |  | 0.25 |  | Sylvester-Bradley *et al*. 1980 |
| Northern Amazonia | 1.60 | 1.50 | 0.10 | Jordan *et al*. 1982 |
| New guinea |  |  | 0.05 | Goosem & Lamb 1986 |
| Sri Lanka |  | 0.80 |  | Maheswaran & Gunatilleke 1990 |
| Hawaii |  | 0.28 | 0.00 | Vitousek 1994 |
| Hawaii |  | 0.07 |  | Crews *et al*. 2000 |
| Hawaii |  | 0.26 |  | Crews *et al*. 2001 |
| Hawaii |  |  | 0.01 | Matzek & Vitousek 2003 |
| Costa Rica |  | 0.44 |  | Reed *et al*. 2007 |
| Puerto Rico |  | 0.67 | 0.40 | Cusack 2009 |
| Panama |  | 0.38 |  | Barron *et al*. 2009 |
| Panama | 1.00 |  |  | Barron *et al*. 2011 |
| **Mean** | **1.3** | **0.5** | **1.0** |  |
| **Minimum** | **1.00** | **0.07** | **0.00** |  |
| **Maximum** | **1.60** | **1.50** | **6.00** |  |

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