Sample sizes for estimating key ecosystem characteristics in a tropical *terra firme* rainforest.

Daniel Metcalfe [a, b, *], Patrick Meir [a], Luiz Aragão [c], Antonio da Costa [d], Samuel Almeida [e], Alan Braga [d], Paulo Gonçalves [d], Joao Athaydes [d], Yadvinder Malhi [c], Mathew Williams [a].

[a] School of Geosciences, University of Edinburgh, Edinburgh. EH8 9XP. U.K.
[b] Swedish University of Agricultural Sciences (SLU), Department of Forest Ecology and Management, SE-901 83, Umeå, Sweden.
[c] Centre for the Environment, University of Oxford, Oxford. OX1 3QY. U.K.
[d] Centro de Geociências, Universidade Federal do Pará, Belém. CP 1611 66017-970. Brazil.
[e] Museu Paraense Emilio Goeldi, Belém. CP 66077-530. Brazil
[*] Corresponding author: Tel.: + 46 (0) 907868604. E-mail address: daniel.metcalfe@sek.slu.se

Correspondence address: Daniel Metcalfe, Swedish University of Agricultural Sciences (SLU), Department of Forest Ecology and Management, SE-901 83, Umeå, Sweden.

Abstract

This study evaluated the sample sizes necessary to estimate several soil and vegetation characteristics within 10 % confidence intervals with 95 % probability in three *terra firme* tropical rainforest sites. Across all three plots, the most spatially heterogeneous variables were measurements of total standing crop root mass, ground surface litter mass, litter fall, root growth and soil respiration which required, on average, 152, 105, 52, 45 and 28 samples respectively to estimate mean values within 10 % confidence intervals with 95 % probability. Leaf area index measurements integrated canopy characteristics over a relatively large spatial area and therefore only required 5 samples, on average, to achieve the same degree of precision. Measurements of soil temperature, moisture, carbon and nitrogen content in the surface 30 cm soil layer displayed the lowest degree of spatial variation: requiring a maximum of 7 samples to estimate mean values within 10 % confidence intervals with 95 % probability. This study, together with a review of data from similar ecosystems, suggests that standing crop root mass, root growth, litter fall and ground surface litter mass are usually acutely under-sampled, which could impede detection and interpretation of patterns and processes in these potentially important ecosystem characteristics. This information may assist researchers to design effective sampling strategies for field experiments, particularly in tropical forests.

Keywords

Amazon tropical rain forest; spatial heterogeneity; coefficient of variation; sample size; plant biomass; root production; soil respiration.

1. Introduction

Terrestrial ecosystems play a key role in the global carbon (C) cycle and climate system (IPCC, 2001). The Amazon rain forest alone contains 70-80 billion tonnes of C in plant biomass, and is responsible for up to 10 % of global terrestrial net primary productivity (Houghton et al., 2001). However, accurate measurement of terrestrial C cycle rates and processes in the Amazon is hindered both by the considerable time and labour costs associated with measurements, and the high degree of spatial heterogeneity in many C stocks and fluxes.

In this context, sample size analysis is important both at the experimental design stage to calculate the sample size required to estimate mean values of chosen variables within designated confidence intervals, and after data collection to estimate confidence intervals around measurements for a chosen sample size. However, given the high costs associated with even preliminary measurements of some variables (e.g.: root standing mass and production) few studies have estimated sample size for most major C stocks and fluxes simultaneously.

The purpose of this analysis, therefore, is to provide sample size data to aid decision-making by researchers designing field experiments, particularly in tropical forests. To do this, sample size was estimated for the following ecosystem characteristics at three one-hectare plots with contrasting soil and vegetation types in an eastern Amazon rainforest:

1) Soil moisture, temperature, carbon and nitrogen content in the surface 30 cm soil layer.
2) Leaf area index (LAI), litter fall, ground surface litter, root standing crop, root growth.
3) Soil respiration.

We then placed these site-specific results into their regional context with a literature review of sample size estimates for the above ecosystem characteristics from other studies in old-growth *terra firme* Amazonian rainforest.

2. Materials and Methods

Study site

The experimental site is located in the Caxiuanã National Forest, Pará State, north-eastern Brazil (1º43’3.5”S, 51º27’36”W). The predominant vegetation of the area is of a lowland *terra firme* rainforest with no clear signs of past anthropogenic disturbance. The site experiences high annual rainfall (~ 2270 mm) and a pronounced dry season (Fisher et al., 2005). The most widespread soil type is a highly weathered yellow Oxisol (US Department of Agriculture soil taxonomy) which exhibits substantial spatial variation in the relative proportion of sand and clay, at all soil depths (Ruivo & Cunha, 2003). There are also areas of relatively fertile soil, called anthropogenic dark earths (ADE) or *Terra Preta do Indio*, which mark locations that were intensively managed by indigenous populations of pre-Columban inhabitants (Ruivo & Cunha, 2003; Lehmann et al., 2003). To represent existing variation in soil type at the site, one-hectare plots were established (see Table 1 for additional plot details) on a well drained sandy Oxisol (Sand plot), a clay-rich Oxisol (Clay plot), and an ADE (Fertile plot). The plots were selected on the basis that they appeared to be relatively internally homogenous, and samples were only collected over 10 m from the perimeter of each plot to minimize edge effects from surrounding soil and vegetation types (Figure 1). All measurements were made along a regularly spaced grid at 20 m intervals within each plot, with the exception of rhizotron root growth which was recorded every 30 m (Figure 1).

Equipment and measurements

Soil moisture (CS616 probe, Campbell Scientific, U.K.) and soil temperature (Testo 926 probe, Testo Ltd., U.K.) were recorded to a soil depth of 30 cm, in June 2005. Soil samples were taken from the surface 30 cm soil layer of the Sand plot in November 2004, and soil organic C and nitrogen (N) content was determined with a Mass Spectrometer by the Centro de Energia Nuclear na Agricultura, University of São Paulo, Brazil.

Images of the canopy on all plots were recorded with a digital camera and fish-eye lens (Nikon Coolpix 900, Nikon Corporation, Japan) in June 2005. Measurements were taken in the late afternoon when direct sunlight was at a minimum. The images were then analyzed (using Hemiview 2.1 SR1, Delta-T Devices Ltd, U.K.) to calculate LAI over the month of measurement (Hale and Edwards, 2002).

Litter fall accumulation over April 2005 was measured on all plots using mesh traps (area = 1 m^2), placed 1 m above the ground surface. Organic litter was also removed from 154 cm^2 areas of the ground surface in June and November 2005. No attempt was made to separate ground surface litter into different fractions because there was no clear distinction between soil organic matter horizons. Collected samples of litter fall and ground surface litter were cleaned of inorganic debris, dried at 70 ^{o}C to constant mass and weighed. There is no significant difference in ground surface litter mass measured between dates and so the data were pooled to calculate CV.

To estimate standing crop root mass, soil cores (diameter = 14 cm, depth = 30 cm) were extracted from all plots in June and November 2005 using opposable semi-circular cutting blades. Roots were manually extracted from the soil cores following the method described by Metcalfe et al. (2007) which corrects for underestimates in, particularly fine, root mass. Root vitality could be reliably assessed visually, and so samples were not divided into live and dead classes. Extracted root material was cleaned of inorganic debris, dried at 70 ^{o}C to constant mass and weighed. There is no significant difference in standing crop root mass measured between dates and so the data were pooled to calculate CV.

Root production was estimated on all plots in April 2005 using both the ingrowth core (e.g.: Steingrobe et al., 2001) and rhizotron (e.g.: Sword et al., 1996) methods (for a detailed review and critique of these, and other methods, see Vogt et al., 1998; Hendricks et al., 2006). At the beginning of November 2004, soil cores (diameter = 14 cm, depth = 30 cm) were extracted from locations on each plot using opposable semi-circular cutting blades, the roots were removed by hand and the remaining soil was reinserted into the holes surrounded by plastic mesh bags (mesh aperture diameter = 1 cm). After a three month interval the process was repeated, and retrieved root material was cleaned of inorganic debris, dried at 70 ^{o}C to constant mass and weighed. Roots were manually extracted from the soil cores following the method described by Metcalfe et al. (2007) which corrects for underestimates in, particularly fine, root mass. Root vitality could be reliably assessed visually, and so samples were not divided into live and dead classes. The amount of root material which grew into the mesh bags was used to calculate production for each three-month interval. Thus, root mass production estimated from the ingrowth cores represented growth accumulated over April 2005 and the two preceding months.

Rhizotrons were constructed from frames, supporting vertically orientated transparent plastic sheets (width = 21 cm, length = 30 cm). Rhizotrons were installed in August 2004 and measurement began in November 2004. Incremental root length extension, as a percentage of existing length, was recorded every 15 days by tracing over roots visible at the transparent plastic face with a permanent marker. This recording methodology may underestimate the length of very fine roots, in comparison to minirhizotrons that use digital imaging, but is less susceptible to breakage and technical faults. This study presents data on relative root length extension nine months after rhizotron installation, by which time root dynamics on all plots had stabilized (Figure 2). This period for equilibration is similar to that reported by Hendricks et al 2006, though other studies recommend allowing for a longer period of equilibration (e.g.: Burke & Raynal, 1994; Joslin & Wolfe, 1999; Wells et al., 2002).

Soil respiration was measured on all plots in June 2005 with a closed dynamic infra-red gas analyzer (EGM-4 and SRC-1 chamber, PP Systems, U.K.). Plastic collars were inserted 2 cm into the soil at each measurement location six months prior to the initiation of respiration measurements. Collar insertion may have caused some degree of disturbance to surface soil and roots but was necessary to ensure a good seal between the IRGA chamber and soil. Soil respiration was calculated from the change in carbon dioxide (CO_2) concentration over time within the IRGA chamber (Blanke 1996).

Sample size analysis

The equation of Hammond and McCullagh (1978) was used to estimate sample size (*SS*) for a given confidence interval and probability level:

$$SS = \frac{t_\alpha^{\,2} \bullet CV^2}{D^2} \tag{1}$$

where t_α is the Student's t statistic at a chosen α probability level (0.05 in this study, t for a given α varies with dataset degrees of freedom), *CV* is the sample coefficient of variation (standard deviation of the sample as a percentage of the mean value), and *D* is the specified confidence interval (10 in this study). Confidence interval specifies the estimated range of values, expressed as a percentage of the estimate of the mean, which is likely to contain the true mean value. Probability level specifies the number of occasions $(1 - \alpha)$ expressed as a percentage that the true mean value would fall within the confidence interval if the measurement were repeated a large number of times.

3. Results and discussion

Estimates of CV provided in this study are, to an extent, specific to the methodology and equipment used. However, given that the methods and equipment used in this study are relatively widespread, CV and sample size estimates provided should still be applicable in a wide range of field studies. Relatively few studies directly present CV values of measured parameters. For purposes of comparison, we derived CV from some studies in the literature indirectly, where necessary, using cited values of sample sizes, means, standard errors, standard deviations, and confidence intervals.

Spatial variation of soil characteristics

The results of this study are consistent with data from previous studies in the Amazon (Table 3), that all point towards the existence of considerable regional scale spatial heterogeneity within ecosystems that are all usually described as lowland *terra firme* rainforest (Williams et al., 2002; Malhi et al., 2004; Aragão et al., 2005; Sotta et al., 2006). However, in this study soil temperature and moisture displayed very low spatial heterogeneity (CV of 1 – 12 %), while soil C and N content displayed higher (but still low compared to other parameters, see below) CV values of 15 and 9 % respectively (Table 3). Other studies, in comparable ecosystems in the Amazon region, displayed similar trends (Tables 2 and 3). The methods and equipment used in this study, therefore, were able to quantify surface soil C content, N content, temperature and moisture to a high degree of precision relatively easily (Table 3). Other soil characteristics, not measured in this study, may display higher levels of spatial heterogeneity. For example, in a more detailed characterization of soil chemistry at an Amazon forest site (Nepstad et al., 2002), some soil characteristics displayed CV of less than 20 % (pH, soil content of K, Mg and SO_4) while soil content of NO_3, NH_4, PO_4 and Ca displayed relatively higher CV values of 60, 28, 50, and 24 % respectively.

Spatial variation of vegetation characteristics

In comparison to the soil characteristics recorded in this study, measurements of variables relating to vegetation mass and growth were more spatially heterogeneous, and hence required more samples to achieve the same level of precision (Table 3). This result is consistent with data from other studies in the Amazon region (Tables 2 and 3). In particular, standing crop root mass displayed considerable spatial heterogeneity, both in this study (CV of 49 – 78 %, depending upon the plot and root diameter category) and in other comparable ecosystems (Table 3). Similarly, root growth quantified in this study with ingrowth cores and rhizotrons displayed CV of 34 – 63 % and 22 – 40 % respectively. Litter fall and ground surface litter mass displayed relatively high CV in this study of 30 – 54 % and 54 – 60 % respectively, and therefore required more samples to derive mean values with a high degree of precision. Leaf area index values integrated measurements over a large spatial area (> 10 m^2) compared to litter fall and ground surface litter mass (< 1 m^2), and so displayed relatively low CV. The high spatial variability of root and foliage characteristics quantified in this study, combined with the low sample size used by most studies because of substantial resources required to make these measurements, often resulted in a considerable disparity between the actual sample size used and the “ideal” sample size required to estimate values within 10 % confidence intervals with 95 % probability (Tables 2 and 3).

Spatial variation of soil respiration

In comparison to soil and vegetation characteristics, soil respiration is often more intensively sampled in Amazonian *terra firme* forests (Table 3) and usually displays a lower degree of spatial heterogeneity (CV of 27 – 34 % in this study) than roots and foliage characteristics (Tables 2 and 3). Thus, on average across all of the plots surveyed in this study and others, sample sizes chosen to measure soil respiration are usually closer to the level required to quantify the mean within 10 % confidence intervals with 95 % probability (Table 2).

Conclusion

Results from this study suggest that most sampling effort should be spent quantifying aspects of above- and below-ground biomass and growth such as root biomass and production, litter fall and ground surface litter mass. Attempts to quantify these variables, which do not take enough samples, may find that the large degree of uncertainty surrounding estimates impedes detection and interpretation of existing patterns. This is a key problem because foliage and roots play an important, but poorly understood, role in the structure and function of terrestrial ecosystems. Estimates of CV provided in this study are, to an extent, specific to the methodology and equipment used. Therefore, the sample size estimates provided are most readily applicable to researchers working in similar ecosystems, and with similar methodologies. This work could be extended by recording temporal change in spatial heterogeneity in ecosystem characteristics.

Acknowledgements

This research contributes to the Brazil-led Large Scale Biosphere - Atmosphere Experiment in Amazonia. Work was supported by a Natural Environment Research Council (U.K.) PhD studentship and a Standard Research Grant (NER/A/S/2003/1609), a Royal Society (U.K.) Dudley Stamp Memorial Fund award, and an Elizabeth Sinclair Fund award (School of Geosciences, University of Edinburgh, U.K.). All corresponding authors of articles featured in Table 3 were contacted to confirm details of experimental design. In addition we are grateful to Leonardo Sá and Ima Vieira for their scientific support and collaboration, the Museu Paraense Emilio Goeldi for the use of its field station and laboratory facilities, and Bene and Joca for their committed field work assistance.

References

Aragão, L.E.O.C., Shimabukuro, Y.E., Espírito Santo, F.D.B., Williams, M., 2005. Landscape pattern and spatial variability of leaf area index in Eastern Amazonia. For. Ecol. Manage. 211, 240-256.

Barlow, J., Gardner, T. A., Ferreira, L. V., Peres, C. A., 2007. Litter fall and decomposition in primary, secondary and plantation forests in the Brazilian Amazon. Forest Ecol. Manage., 247, 91-97.

Blanke, M.M., 1996. Soil respiration in an apple orchard. Env. Exp. Bot. 36, 339-348.

Burke, M.K., Raynal, D.J., 1994. Fine root growth phenology, production, and turnover in a northern hardwood forest ecosystem. Plant Soil 162, 135-146.

Cavelier, J., 1992. Fine-root biomass and soil properties in a semideciduous and a lower montane rain forest in Panama. Plant Soil, 142, 187-201.

Davidson, E. A., Ishida, F. I., Nepstad, D. C., 2004. Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest. Glob. Change Biol. 10, 718-730.

Davidson, E. A., Verchot, L. V., Cattânio, J. H., Ackerman, I. L., Carvalho, J. E. M., 2000. Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. Biogeochemistry, 48, 53-69.

Fisher, R.A., Williams, M., do Vale, R.L., da Costa, A.L., Meir, P., 2005. Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. Plant Cell Environ. 29, 151-165.

Hale, S.E., Edwards, C., 2002. Comparison of film and digital hemispherical photography across a wide range of canopy densities. Agric. Forest. Meteorol. 112, 51-56.

Hammond, R., McCullagh, P.S., 1978. Quantitative techniques in geography. Clarendon Press, U.K.

Hendricks, J.J., Hendrick, R.L., Wilson, C.A., Mitchell, R.J., Pecot, S.D., Guo, D., 2006. Assessing the patterns and controls of fine root dynamics: an empirical test and methodological review. J. Ecol. 94, 40-57.

Houghton, R.A., Lawrence, K.T., Hackler, J.L., Brown, S., 2001. The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. Glob. Change Biol. 7, 731-746.

Intergovernmental Panel for Climate Change, 2001. Climate Change 2001: the scientific basis. In: Contribution of working group I to the third assessment report of the International Panel on Climate Change. Cambridge University Press, U.K.

Jordan, C.F., Escalante, G., 1980. Root productivity in an Amazonian rain forest. Ecol., 61, 14-18.

Joslin, J.H., Wolfe, M.H., 1999. Disturbances during minirhizotron installation can affect root observation data. Soil Sci. Soc. Am. J., 63, 218-221.

Kalácska, M., Sánchez-Azofeifa, G. A., Rivard, B., Calvo-Alvarado, J. C., Journet, A. R. P., Arroyo-Mora, J. P., Ortiz-Ortiz, D., 2004. Leaf area index measurements in a tropical moist forest: a case study from Costa Rica. Remote Sens. Environ. 91, 134-152.

Kursar, T. A., 1989. Evaluation of soil respiration and soil CO_2 concentration in a lowland moist forest in Panama. Plant Soil, 113, 21-29.

Lehmann, J., Kern, D.C., Glaser, B., Woods, W.I., 2003. Amazonian Dark Earths: Origin, Properties, Management. Kluwer Academic Publishers, Dordrecht, Netherlands.

Luizao, F. J., 1989. Litter production and mineral element input to the forest floor in a central Amazonian forest. GeoJournal, 19, 407-417.

Malhi, Y., Baker, T.R., Phillips, O.L., Almeida, S., Alvarez, E., Arroyo, L., Chave, J., Czimczik, C.I., Fiore, A. Di., Higuchi, N., Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Montoya, L.M.M., Monteagudo, A., Neill, D.A., Vargas, P.N., Patiño, S., Pitman, N.C.A., Quesada, C.A., Salomão, R., Silva, J.N.M., Lezama, A.T., Martínez, R.V., Terborgh, J., Vinceti, B., Lloyd, J., 2004. The above-ground coarse wood productivity of 104 Neotropical forest plots. Glob. Change Biol., 10, 563-591.

Martius, C., Höfer, H., Garcia, M.V.B., Römbke, J., Hanagarth, W., 2004. Litter fall, litter stocks and decomposition rates in rainforest and agroforestry sites in central Amazonia. Nut. Cyc. Agroeco., 68, 137-154.

McWilliam, A. –L. C., Roberts, J. M., Cabral, O. M. R., Leitao, M. V. B. R., de Costa, A. C. L., Maitelli, G. T., Zamparoni, C. A. G. P., 1993. Leaf area index and above-ground biomass of terra firme rain forest and adjacent clearings in Amazonia. Function. Ecol. 7, 310-317.

Metcalfe, D. B., Williams, M., Aragão, L. E. O. C., da Costa, A. C. L., de Almeida, S. S., Braga, A. P., Gonçalves, P. H. L., de Athaydes Silva Junior, J., Malhi, Y., Meir, P., 2007. A method for extracting plant roots from soil which facilitates rapid sample processing without compromising measurement accuracy, New Phytol., 174, 697-703.

Nepstad, D.C., Moutinho, P., Dias, M.B., Davidson, E., Cardinot, G., Markewitz, D., Figueiredo, R., Vianna, N., Chambers, J., Ray, D., Guerreiros, J.B., Lefebvre, P., Sternberg, L., Moreira, M., Barros, L., Ishida, F.Y., Tohlver, I., Belk, E., Kalif, K., Schwalbe, K. 2002. The effects of partial through fall exclusion on canopy processes, aboveground production and biogeochemistry of an Amazon forest. J. Geophys. Res-Atmos., 107, 1–18.

Ruivo, M.L.P., Cunha, E.S., 2003. Mineral and organic components in archaeological black earth and yellow latosol in Caxiuanã, Amazon, Brazil. In: Tiezzi, E., Brebbia, C.A., Uso, J.L. (Eds.), Ecosystems and Sustainable Development. WIT Press, U.K., pp. 319-329.

Salimon, C.I., Davidson, E.A., Victoria, R.L., Melo, A.W.F., 2004. CO_2 flux from soil in pastures and forests in southwestern Amazonia. Glob. Change Biol., 10, 833-843.

Sanford, R. L., 1990. Fine root biomass under light gap openings in an Amazon rain forest. Oecologia, 83, 541-545.

Schwendenmann, L., Veldkamp, E., Brenes, T., O'Brien, J. J., Mackensen, J., 2003. Spatial and temporal variation in soil CO2 efflux in an old-growth neotropical rain forest, La Selva, Costa Rica. Biogeochemistry, 64, 111-128.

Selva, E. C., Couto, E. G., Johnson, M. S., Lehmann, J., 2007. Litterfall production and fluvial export in headwater catchments of the southern Amazon. J. Trop. Ecol., 23, 329-335.

Silver, W. L., Neff, J., McGroddy, M., Veldkamp, E., Keller, M., Cosme, R., 2000. Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. Ecosystems, 3, 193-209.

Silver, W.L., Thompson A.W., McGroddy M.E., Varner R.K., Robertson J.R., Dias J.D., Silva H., Crill P., Keller M., 2005. Fine root dynamics and trace gas fluxes in two lowland tropical forest soils. Glob. Change Biol. 11, 290-306.

Smith, K., Gholz, H. L., de Assis Oliveira, F., 1998. Litterfall and nitrogen-use efficiency of plantations and primary forest in the eastern Brazilian Amazon. Forest Ecol. Manage., 109, 209-220.

Sotta, E. D., Meir, P., Malhi, Y., Nobre, A. D., Hodnett, M., Grace, J., 2004. Soil CO_2 efflux in a tropical forest in the central Amazon. Glob. Change Biol., 10, 601-617.

Sotta, E., Veldkamp, E., Guimarães, B.R., Paixão, R.K., Ruivo, MLP, Almeida, SS. 2006. Landscape and climatic controls on spatial and temporal variation in soil CO_2 efflux in an eastern Amazonian rainforest, Caxiuanã, Brazil. For. Ecol. Manage., 237, 57-64.

Steingrobe, B., Schmid, H., Claassen, N., 2001. The use of the ingrowth core method for measuring root production of arable crops – influence of soil and root disturbance during installation of the bags on root ingrowth into the cores. Eur. J. Agron. 15, 143-151.

Sword, M.A., Gravatt, D.A., Faulkner, P.L., Chambers, J.L., 1996. Seasonal branch and fine root growth of juvenile Loblolly pine five growing seasons after fertilization. Tree Phys. 16, 899-904.

Trumbore, S., da Costa, E. S., Nepstad, D. C., de Camargo, P. B., Martinelli, L. A., Ray, D., Restom, T., Silver, W., 2006. Dynamics of fine root carbon in Amazonian tropical ecosystems and the contribution of roots to soil respiration. Glob. Change. Biol., 12, 217-229.

Vogt, K.A., Vogt, D.J., Bloomfield, J., 1998. Analysis of some direct and indirect methods of estimating root biomass and production of forests at an ecosystem level. Plant Soil, 200, 71-89.

Wells, C. E., Glenn, D. M., Eissenstat, D. M., 2002. Changes in the risk of fine-root mortality with age: a case study in peach, *Prunus persica* (Rosaceae). Am. J. Bot., 89, 79-87.

Williams, M., Shimabukuro, Y. E., Herbert, D. A., Pardi Lacruz, S., Renno, C., Rastetter, E. B., 2002. Heterogeneity of soils in an eastern Amazonian rain forest: implications for scaling up biomass and production. Ecosystems, 5, 692-704.

Tables

Table 1. Plot mean ± SD of key plot vegetation and soil features.

	Sand	**Clay**	**Fertile**
Vegetation			
tree density (stems ha^{-1})	434	419	544
stem basal area (m^2 ha^{-1})	24	25	37
Soil			
Sand content (%)	76 ± 4	38 ± 7	53 ± 5
Silt content (%)	8 ± 2	14 ± 2	23 ± 2
Clay content (%)	16 ± 3	48 ± 9	23 ± 4
Ca^{2+}	56 ± 10	60 ± 10	1925 ± 457
Mg^{2+}	34 ± 15	33 ± 12	260 ± 75
P	3 ± 2	2 ± 2	29 ± 11

Tree number and basal area represent all individuals over 10 cm diameter at breast height, measured in January 2005. Soil data are adapted from Ruivo et al., (2003), values are a mean of 4 replicate measurements from the surface 30 cm soil layer on each plot.

Table 2. Summary of mean ± SE CV and sample size calculated for different Amazonian *terra firme* rainforest characteristics from this study, and from other estimates available in the literature.

	CV	**Actual sample size**	**Ideal sample size ***	***n***
Leaf area index	13 ± 1	16 ± 1	9 ± 1	43
Litter fall	40 ± 5	15 ± 2	68 ± 15	22
Ground litter	43 ± 6	15 ± 2	71 ± 14	8
Soil respiration	26 ± 3	24 ± 4	27 ± 6	21
Soil C content	21 ± 6	7 ± 1	30 ± 14	9
Soil N content	23 ± 6	7 ± 2	33 ± 16	7
Soil temperature	1 ± 0.3	19 ± 3	1 ± 0.1	6
Soil moisture	9 ± 1	20 ± 3	2 ± 1	5
Standing crop roots (> 2 mm)	54 ± 12	8 ± 2	168 ± 69	10
Standing crop roots (< 2 mm)	34 ± 5	13 ± 2	44 ± 11	12
Root growth	55 ± 8	16 ± 2	123 ± 41	14

* To estimate the true mean value within 10 % confidence intervals with 95 % probability. *n* indicates the number of individual plot values from this study and others (presented in Table 3) used to calculate mean ± SE values. Minimum ideal sample size is 1, though at least 2 samples are required to calculate standard deviation.

Table 3. Literature review of CV and sample size estimated for different Amazonian *terra firme* rainforest characteristics.

Reference	Location	Distance between replicates (m)	Replicate plot area (m^2)	CV (%)	Actual sample size	Ideal sample size *	Notes
Leaf area index							
Aragão et al. 2007	Tapajos National Forest, Pará, Brazil	10	2500	5.3	25	1	
		10	2500	5.6	25	1	
		10	2500	6.6	25	2	
		10	2500	8.6	25	3	
		10	2500	8.8	25	3	
		10	2500	9.3	25	3	
		10	2500	9.6	25	3	
		10	2500	10.4	25	4	
		10	2500	10.6	25	4	
		10	2500	10.6	25	4	
		10	2500	10.7	25	4	
		10	2500	12.1	25	5	
		10	2500	13.1	25	5	
		10	2500	13.2	25	6	
		10	2500	13.3	25	6	
		10	2500	13.6	25	6	
		10	2500	14.8	25	7	
		10	2500	15.9	25	8	
		10	2500	16.4	25	8	
		10	2500	20.5	25	13	
		10	2500	22.5	25	15	
Kalácska et al. 2004	North Guanacaste, Costa Rica		750	28.4	12	26	
McWilliam et al. 1983	Reserva Ducke, Amazônia, Brazil		400	8.8	4	5	

Nepstad et al. 2002	Tapajos National Forest, Pará, Brazil	10	10000	13.6	86	5	Control, year 1
		10	10000	15.4	100	7	Drought, year 1
		10	10000	29.4	86	24	Control, year 2
		10	10000	32.3	100	29	Drought, year 2
Williams et al. 2002	Tapajos National Forest, Pará, Brazil	10	2500	11.0	25	4	
		10	2500	12.7	25	5	
		10	2500	13.3	25	6	
		10	2500	14.0	25	6	
		10	2500	15.3	25	7	
		10	2500	15.8	25	8	
		10	2500	21.9	25	14	
		10	2500	23.1	25	16	
		10	2500	26.4	25	21	
		10	2500	26.8	25	22	
		10	2500	28.4	25	24	
		10	2500	28.6	25	24	
		10	2500	33.3	25	33	
This study	Caxiuanã National Forest, Pará, Brazil	10	10000	20.0	25	12	Sand plot
Litter Fall							
Barlow et al. 2007	Jari Estate, Pará, Brazil			14.3	5	10	
Luizao et al. 1989	Near Manaus, Amazônia, Brazil.	< 140		15.5	15	8	Plateau, year 3
		< 140		23.6	15	18	Valley, year 1
		< 140		23.6	15	18	Plateau, year 2
		< 140		24.3	15	19	Valley, year 2
		< 140		28.5	15	26	Plateau, year 1
		< 140		34.3	15	37	Valley, year 3
Martius et al. 2004	Near Manaus, Amazônia, Brazil.	< 10	1600	83.1	20	207	Year 2
		< 10	1600	92.7	20	258	Year 1
Nepstad et al.	Tapajos National		10000	57.9	25	99	Pre-drought

2002	Forest, Pará, Brazil		10000	57.9	25	99	Post-drought
			10000	60.6	25	108	Control
			10000	69.0	25	140	Control
Salimon et al. 2004	Near Rio Branco, Acre, Brazil			24.4	5	27	
				34.9	5	56	
				37.3	5	64	
				56.5	5	146	
Selva et al. 2007	Juruena river, Mato Grosso, Brazil			11.9	4	8	Samples are four different watersheds
Smith et al. 1998	Curua-Una Forest Reserve, Pará, Brazil		3000	8.9	3	7	
This study	Caxiuanã National Forest, Pará, Brazil	30	10000	30.2	20	28	Sand plot
		30	10000	37.6	20	43	Clay plot
		30	10000	53.5	20	86	Fertile plot
Ground surface litter							
Martius et al. 2004	Near Manaus, Amazônia, Brazil		1600	13.0	20	6	
			1600	35.2	20	37	
Silver et al. 2000	Tapajos National Forest, Pará, Brazil		3600	41.5	15	54	Sand soil,
			3600	58.7	15	107	Clay soil
Smith et al. 1998	Curua-Una Forest Reserve, Pará Brazil		3000	24.1	3	91	
This study	Caxiuanã National Forest, Pará, Brazil	30	10000	54.2	9	91	Sand plot
		30	10000	60.3	9	112	Clay plot
		30	10000	59.9	9	111	Fertile plot
Soil Respiration							
Davidson et al. 2000	Fazenda Vitoria, Pará, Brazil			30.0	16	28	CV includes data from pasture

Davidson et al. 2004	Tapajos National Forest, Pará, Brazil	< 40	10000	18.3	18	11	Drought
		< 40	10000	19.7	18	12	Control
Kursar et al. 1989	Barro Colorado Island, Panama	5		42.0	90	48	
		5		43.0	51	50	
Salimon et al. 2004	Near Rio Branco, Acre, Brazil			11.5	8	5	
				13.1	8	7	
				16.0	8	10	
				17.1	8	11	
Schwendenmann et al. 2003	La Selva Biological Station, Costa Rica		300	35.0	32	34	Old alluvium soil
			300	45.0	32	55	“Residual” soil
Silver et al. 2005	Tapajos National Forest, Pará, Brazil		< 100	14.6	10	10	Clay
			< 100	48.5	10	107	Sand
Sotta et al. 2004	Cuieiras Reserve, Amazônia, Brazil	10800		24.5	40	17	
Sotta et al. 2006	Caxiuanã National Forest, Pará, Brazil		10000	6.1	16	2	Sand
			2500	6.4	8	2	Clay
This study	Caxiuanã National Forest, Pará, Brazil	20	10000	33.5	25	33	Sand plot
		20	10000	26.5	25	21	Clay plot
		20	10000	31.8	25	30	Fertile plot
Soil Carbon Content							
Salimon et al. 2004	Near Rio Branco, Acre, Brazil			11.2	3 (5)	11	
				20.3	3 (5)	36	
Silver et al. 2000	Tapajos National Forest, Pará, Brazil		600	7.0	7 (10)	2	Clay
			600	9.7	7 (10)	4	Loam
			600	10.9	7 (10)	5	Clay
			600	16.3	7 (10)	10	Loam
			600	50.8	7 (10)	98	Sand
			600	51.9	7 (10)	102	Sand
This study	Caxiuanã National	30	10000	14.5	9 (30)	7	Sand plot

	Forest, Pará, Brazil						
Soil Nitrogen Content							
Silver et al. 2000	Tapajos National Forest, Pará, Brazil		600	14.7	7 (10)	9	Clay
			600	15.6	7 (10)	10	Clay
			600	17.6	7 (10)	12	Loam
			600	35.3	7 (10)	47	Loam
			600	35.3	7 (10)	47	Sand
			600	61.1	7 (10)	141	Sand
This study	Caxiuanã National Forest, Pará, Brazil	30	10000	8.8	9 (30)	3	Sand plot
Soil Temperature							
Sotta et al. 2006	Caxiuanã National Forest, Pará, Brazil		5000	1.8	8 (5)	1	Clay
			10000	2.2	16 (5)	1	Sand
Kursar et al. 1989	Barro Colorado Island, Panama			1.6	15 (3)	1	
This study	Caxiuanã National Forest, Pará, Brazil	20	10000	1.1	25 (30)	1	Sand plot
		20	10000	0.6	25 (30)	1	Clay plot
		20	10000	0.7	25 (30)	1	Fertile plot
Soil Moisture							
Sotta et al. 2006	Caxiuanã National Forest, Pará, Brazil		10000	5.7	16 (30)	1	Sand
			5000	8.0	8 (30)	3	Clay
This study	Caxiuanã National Forest, Pará, Brazil	20	10000	7.2	25 (30)	2	Sand plot
		20	10000	11.1	25 (30)	4	Clay plot
		20	10000	11.5	25 (30)	4	Fertile plot
Root Standing Crop Mass							
Cavelier 1992	Barro Colorado Island, Panama		1200	12.0	10 (< 5, 25)	5	
Nepstad et al.	Tapajos National		10000	43.4	20 (< 2, 10)	57	

2002	Forest, Pará, Brazil		10000	44.7	20 (< 2, 10)	60	
			10000	34.1	3 (> 2, 1200)	99	
			10000	35.8	3 (> 2, 1200)	110	
			10000	30.4	3 (all, 1200)	79	
			10000	33.4	3 (all, 1200)	96	
Silver et al. 2005	Tapajos National Forest, Pará, Brazil	< 100		17.2	9 (< 2, 10)	11	Sand, year 1
		< 100		20.1	15 (< 2, 10)	13	Sand, year 2
		< 100		22.1	9 (< 2, 10)	17	Clay, year 1
		< 100		25.0	15 (< 2, 10)	20	Clay, year 2
Silver et al. 2000	Tapajos National Forest, Pará, Brazil		3600	19.7	7 (< 2, 10)	15	Sand
			3600	25.0	7 (< 2, 10)	24	Clay
			3600	39.9	7 (> 2, 10)	60	Clay
			3600	143.3	7 (> 2, 10)	776	Sand
Trumbore et al. 2006	Fazenda Vitoria, Pará, Brazil	50		46	4 (< 2, 10)	68	
This study	Caxiuanã National Forest, Pará, Brazil	30	10000	61.0	9 (all, 30)	115	Sand plot
		30	10000	69.9	9 (all, 30)	151	Clay plot
		30	10000	78.3	9 (all, 30)	189	Fertile plot
		30	10000	53.1	9 (< 5, 30)	87	Sand plot
		30	10000	49.0	9 (< 5, 30)	74	Clay plot
		30	10000	64.1	9 (< 5, 30)	127	Fertile plot
Root Growth							
Jordan 1980	San Carlos do Rio Negro, Venezuela			63.9	17 (all, GEC, 40)	125	
Sanford 1990	San Carlos do Rio Negro, Venezuela	< 10		56.6	28 (< 2, IGC, 10)	93	
		< 10		64.3	28 (< 2, IGC, 10)	121	
		< 10		67.5	28 (< 2, IGC, 10)	133	
Silver et al. 2005	Tapajos National Forest, Pará, Brazil	< 100		32.4	9 (< 2, SC, 10)	37	Clay, year 1
		< 100		54.3	15 (< 2, SC, 10)	92	Clay, year 2
		< 100		85.0	9 (< 2, SC, 10)	251	Sand, year 1

		< 100		140.4	15 (< 2, SC, 10)	612	Sand year 2
This study	Caxiuanã National Forest, Pará, Brazil	20	10000	63.3	16 (all, IGC, 30)	123	Sand plot
		20	10000	27.6	16 (all, IGC, 30)	24	Clay plot
		20	10000	33.8	16 (all, IGC, 30)	35	Fertile plot
		20	10000	39.9	9 (all, R, 30)	56	Sand plot
		20	10000	20.6	9 (all, R, 30)	15	Clay plot
		20	10000	22.1	9 (all, R, 30)	17	Fertile plot

* To estimate the true value within 10 % confidence intervals with 95 % probability. All studies included are from apparently primary rainforests which displayed no clear signs of past anthropogenic disturbance. Values in brackets following actual sample size values for soil and root characteristics indicate sampling depth in cm, root diameter category sampled in mm (only for root standing crop mass and growth) and root growth measurement method (only for root growth) Root growth measurement methods are: GEC = growth into excavated cavity, IGC = ingrowth core, SC = sequential core, R = rhizotron. Minimum ideal sample size is 1, though at least 2 samples are required to calculate standard deviation.

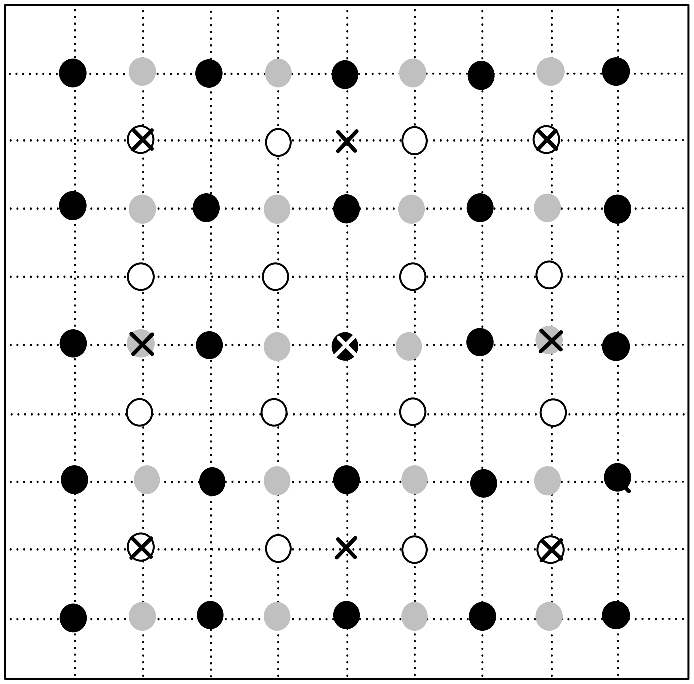

Figure 1. Spatial sampling strategy within each plot in this study. Solid line = plot perimeter (each side is 100 m); dashed line = 10 meter grid within the plot; closed black circles = soil respiration, moisture, temperature, and LAI; open black circles = ingrowth cores; grey circles = litter fall; crosses = rhizotrons, root standing crop, ground surface litter mass, soil C and N content.

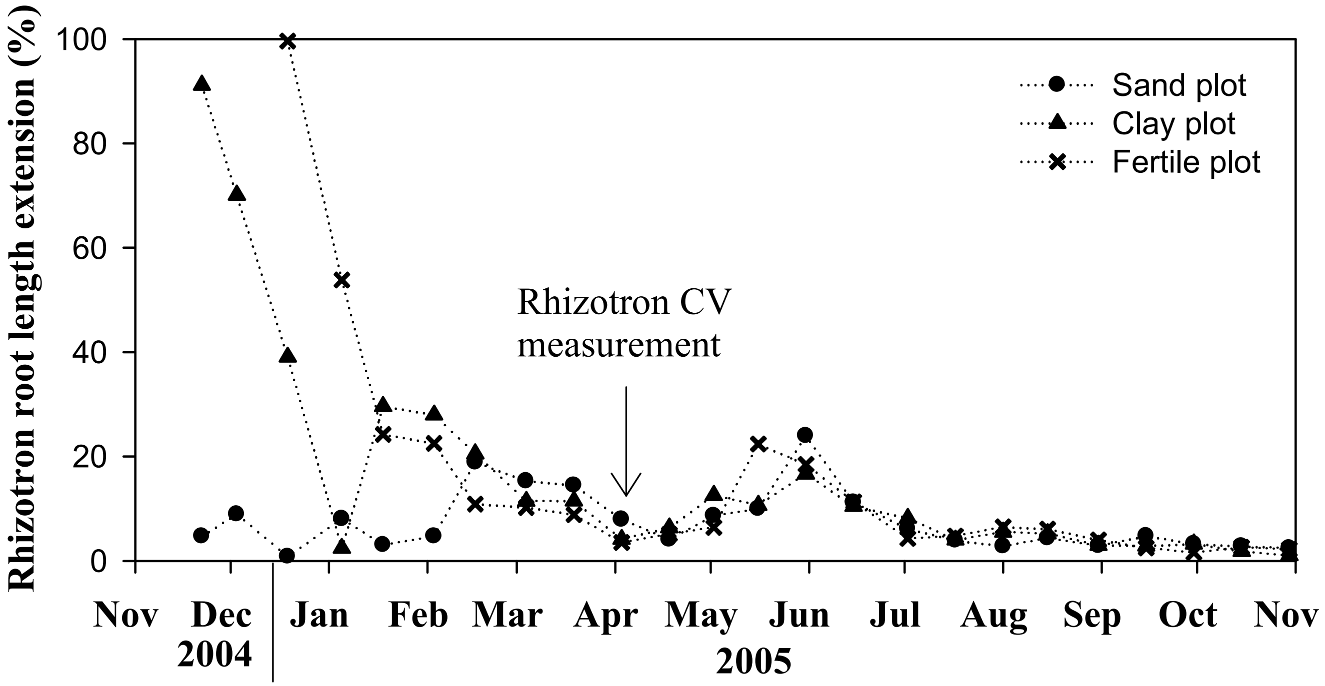

Figure 2. Relative root length extension for all plots, over one year. Measurements of CV and sample size were based upon extension in April 2005, allowing sufficient time for equilibration after the initial disturbance of rhizotron installation. We attribute the later increase in growth (peaking around June 2005), synchronous across all plots, to a real seasonal pattern rather than a disturbance effect