Use of root-ingrowth cores to assess nutrient limitations in forest ecosystems

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We tested the suitability of using root-ingrowth cores to identify nutrient limitations in a Metrosideros-dominated forest in Hawaii that previously was demonstrated to be nitrogen limited. Plastic mesh cylinders filled with a calcined-clay growing medium were treated with nitrogen, phosphorus, calcium and potassium, or distilled water, and were inserted into the surface soil of the forest. After 6 months in situ, significantly more roots grew into the cores dosed with nitrogen. Fertilization trials provide the best means of identifying nutrient limitations to forest growth, but our results indicate that root-ingrowth cores can provide a reliable, alternative method of assessing nutrient limitations in forest ecosystems.


Nous avons évalué l’approprié d’utiliser des sachets de vitalité radiculaire afin d’identifier les limitations de nutriment dans une Forêt d’Hawaï dominée par Metrosideros où il avait été démontré que l’azote était un élément limitant. Des cylindres à maillage de plastique remplis avec une argile calcinée comme milieu de croissance ont été traités soit avec l’azote, le phosphore, le calcium et le potassium, ou de l’eau distillée, et ont été installés dans le sol de surface de la forêt. Après 6 mois, significativement plus de racines avaient crû dans les sachets traités à l’azote. Les essais de fertilisation demeurent le meilleur moyen d’identifier les éléments responsables des limitations de croissance des forêts nos résultats indiquent que les sachets de vitalité radiculaire peuvent consituer une méthode alternative fiable d’évaluation des limitations nutritionnelles des écosystèmes forestiers.

[Traduit par la Rédaction]

Introduction

Forest growth is often limited by low levels of nutrient availability, as evidenced by numerous experimental studies and field trials (e.g., Binkley 1986). Most such studies have been carried out to guide or evaluate forest fertilization programs, but knowing which nutrients (if any) limit forest growth also contributes to the basic understanding of forest ecosystems. For example, it is the only way to test the theory that long-term ecosystem development involves a progression from N to P limitation (Walker and Syers 1976; Walker et al. 1981; Ewel 1986). A knowledge of which nutrient limits growth in different forest types and on different soils is also important at the global scale. For instance, the potential effects of global environmental changes on forest productivity depend, in part, on the extent of N limitation in different forests (e.g., Pastor and Post 1988; McGuire et al. 1992).

The only way to determine unambiguously which nutrients limit forest growth is with fertilization experiments. However, forest fertilization trials are expensive, labor intensive, slow to yield results, difficult to interpret in mixed-species stands, and may alter the vegetation being studied. A number of methods have been used to infer nutrient limitation from simpler measurements. These include foliar analyses (e.g., van den Driessche 1974), plant-growth bioassays (e.g., Van Cleve et al. 1986; Denslow et al. 1987), analyses of element ratios in litter fall (Vitousek and Sanford 1986), and determinations of soil nutrient-supplying capacity (Powers 1980; Van Cleve et al. 1986). These approaches have proved useful in specific situations, but without calibrations against fertilizer experiments they can only suggest the existence of limitation by a particular nutrient.

Fine roots often respond to nutrient-rich microsites by proliferating in the nutrient-rich patch (Hackett 1972; Drew and Saker 1975, 1978; Sanford 1987; Crick and Grime 1987; Jackson and Caldwell 1989). Cuevas and Medina (1983, 1988) suggested that this growth response may be specific to particular limiting nutrients and, hence, could be used as an assay for nutrient limitation. Using this approach, Cuevas and Medina (1988) demonstrated that roots in an Amazonian terra firme forest responded to added P and Ca. Roots in a tall caatinga responded to N, and roots in a bana forest responded to N and P. These results were consistent with patterns of nutrient concentrations and circulation in these contrasting forests (Cuevas and Medina 1986; Medina and Cuevas 1989), but no fertilization trials were conducted to validate their results fully.

The root-ingrowth bioassay proposed by Cuevas and Medina (1988) is relatively rapid and straightforward to apply; if it proves reliable it will be a useful technique for identifying nutrient limitations in forests. We tested this method in a rain-forest site in Hawai‘i in which a factorial fertilization experiment had demonstrated forest growth to be limited by only N (Vitousek et al. 1987, 1993).

Study site

The study was done in the Thurston forest, located in the Hawaii Volcanoes National Park (19°25′N, 155°15′W) on the island of Hawaii at an elevation of 1175 m. Mean annual precipitation is about 2400 mm, and the mean annual temperature is 15.8°C. This forest developed on an ash deposit from a 1790
eruption of Kilauea Volcano. The overstory is dominated by
*Metrosideros polymorpha* Gaud., and there is a dense under-
story of *Cibotium* spp., other ferns, treelets, and shrubs. The
invasive, N-fixing shrub *Myrica faya* Alston was uncommon in the
study area. The soil is a medium, isothermal, Lithic Hapludand
classified in the Puhimau series by Sato et al. (1973). According
to their description the soil is a shallow, well-drained silt loam
developed from volcanic ash and cinder overlying pahoehoe-
 lava bedrock. Aspects of the N cycle in the forest are described
by Matson and Vitousek (1987), Vitousek et al. (1983, 1987,
1989), and Vitousek and Matson (1988).

### Methods

Based on the approach of Cuevas and Medina (1988), ingrowth
cores were constructed of high-density polyethylene tubing,
10 cm tall and 7.5 cm diameter, with 3.7 × 1.7 mm holes (total
open area = 33%). The top and bottom of the cylinders were
covered with 2-mm nylon mesh screen. The cylinders were filled
with Turface® (Applied Industrial Materials, Inc., Deerfield,
Illinois, U.S.A.), a calcined-clay plant-growth medium. The filled
cores were then dosed with 100 mL of either deionized water
or solutions of NH₄Cl (6.76 g/L), Na₂HPO₄ (8.10 g/L), or KCl
(1.57 g/L) plus CaCl₂ (0.28 g/L). These doses are equivalent to
fertilization rates of 40 g/m² of N, P, or K plus Ca, with K and
Ca being added in equal molar ratios. The P solution was adjusted
to a pH of 7 with HCl to approximate the pH of the other solutions.

The filled cores were installed into the surface soil of Thurston
Forest in locations that had never been fertilized. Cores were
put in place by removing a 7.5 cm diameter, 11 cm deep plug of
the surface horizon of soil, inserting the core, and placing the
top 1 cm of soil back on top. We utilized a stratified random
block design with blocks of four cores, one from each treat-
ment, all four cores being within 0.5 m of each other. Blocks
of cores were placed at each of two randomly selected distances
every 10 m along each of five randomly located, 30-m transects
in the forest. Two blocks of four cores were removed from each
transect at 3-, 6-, and 11-month intervals. There were, there-
fore, 10 cores per treatment and sampling date. Sorting and
washing of roots required an average of about 2 h per core.

Root growth comparisons among nutrient treatments were
based on the dry weight of fine roots that accumulated in
each cylinder. All roots found were <2 mm in diameter:
there were very few dead roots in any cores. The dry mass
of roots that accumulated in the cores was not normally
distributed (Kolmogorov-Smirnov one-sample test) and the
treatments did not have homogenous variances (Bartlett's
test). Results were therefore compared using Friedman's
method for randomized blocks, a nonparametric test (Sokal
and Rohlf 1981). Differences among treatments were then
determined with a multiple-comparison procedure for use
with the Friedman test (Daniel 1990). An experimentwise
error rate of α = 0.10 was chosen, giving an individual-
comparison error rate of α = 0.0167.

Rates of fine-root accumulation in the cores varied signif-
icantly among treatments (p < 0.005) after 6 months. Results
at 11 months were similar (Fig. 1) but only mar-
ginally significant (0.05 < p < 0.10). Rates of fine-root
accumulation in N-dosed cores were significantly greater than
rates of root accumulation in control cores after both 6 and
11 months (multiple-comparison test, p < 0.02). No other
treatments differed significantly from control cores.

### Discussion

Nitrogen limitation to growth in Thurston Forest was
demonstrated with a fertilization trial in which N, P, and
all other essential elements were added alone and in factorial
combination. Diameter increments of the dominant tree,
*Metrosideros polymorpha*, were significantly increased by
additions of N alone, with no interactions with other ele-
ments (Vitousek et al. 1987, 1993). Litter fall also increased
significantly in N-fertilized plots (Vitousek et al. 1993).

Root- ingrowth cores yielded the same results; fine-root accu-
station was significantly stimulated by N and not by P
(Fig. 1).

Root- ingrowth cores have been applied in field studies for
a variety of purposes (Steen 1991), including the measure-
ments of fine-root productivity (e.g., Persson 1979, 1980; 
Cuevas et al. 1991), biomass (e.g., Persson 1979, 1980), morpho-
logy (e.g., Persson 1980; Åhlström et al. 1988), and
cumulative growth rates in differing substrates (e.g., Matzner
et al. 1986; Hairiah et al. 1991). However, the validity of
comparing rates of fine-root accumulation in nutrient-enriched

### Table 1. Available nutrient concentrations (g/Mg) in root-ingrowth
cores after 3 months in the soil of Thurston Forest

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ca</th>
<th>K</th>
<th>N</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>541±114</td>
<td>1256±194</td>
<td>1.9±1.3</td>
<td>5.3±0.5</td>
</tr>
<tr>
<td>Ca + K</td>
<td>740±6</td>
<td>1225±61</td>
<td>0.6±0.2</td>
<td>6.2±0.9</td>
</tr>
<tr>
<td>N</td>
<td>596±17</td>
<td>884±22</td>
<td>54.3±21.4</td>
<td>3.0±0.6</td>
</tr>
<tr>
<td>P</td>
<td>596±13</td>
<td>1243±22</td>
<td>0.1±0.1</td>
<td>41.1±9.4</td>
</tr>
</tbody>
</table>

Note: Results are shown as mean ± SE, n = 4.
are disturbed and the aboveground vegetation is not altered or affected in any significant way. Root sorting is a time-consuming task but is made easier if an easily sieved, particulate substrate such as calcined clay is used. Forest fertilization experiments provide the most conclusive evidence of nutrient limitation in forest ecosystems. However, in remote sites, small forest plots, and areas such as parks and preserves where fertilization trials may not be possible, the root-ingrowth bioassay can provide an alternative, straightforward method for investigating nutrient limitations in forest ecosystems.

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Drew, M.C., and Saker, L.R. 1975. Nutrient supply and the growth of the seminal root system in barley. II. Localized, compensatory increases in lateral root growth and rates of nitrate uptake when nitrate supply is restricted to only part of the root system. J. Exp. Bot. 26: 79–90.


Gower, S.T., and Vitousek, P.M. 1989. Effects of nutrient...
amendments on fine root biomass in a primary successional forest in Hawai‘i, Oecologia, 81: 566–568.


