Forests for Energy: Can Productivity Be Sustained? An Overview and Personal Perspective

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Abstract

Forests are the greatest potential source of energy of any terrestrial biome because of the organic carbon in their biomass, and soils are major sinks for atmospheric carbon. Carbon storage could be enhanced either by increasing forest area (impractical), or by reducing catastrophic losses from wildfire and insects through thinning and other means of fuel reduction. The high energy value and renewability of forest biomass makes it an attractive energy alternative to fossil fuel consumption—particularly if energy harvests can reduce wildfire risk and be sustained without impairing fundamental productivity. Gaining public acceptance for increased biomass removal demands that forest productivity is not degraded, but many of the scientific challenges to increased removal rates rest on simplistic concepts lacking long-term field validation. This paper presents the author's concept of sustained productivity, issues and problems in assessing it, and the value of coordinated efforts to address the question directly. The International Long-Term Soil Productivity program is described as such an effort, and recommendations are made for sustaining similar long-term studies.

Keywords: forest bioenergy, sustained productivity, forest fuels, organic carbon, soil, LTSP.
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Introduction

Energy drawn from forest biomass dates to the birth of civilization when our ancestors recognized the value of wood for warmth and for cooking. Half of wood's dry mass is organic carbon, and this equates to potential energy. The most abundant renewable source of organic carbon on our globe's terrestrial surface is found in forests. Our global economy relies on fossil fuel sources of energy, but fossil fuels carry high social costs downstream that are not included in the costs to immediate users (MacCracken 2008). Accordingly, nations are considering other alternatives that are relatively benign and renewable. With the advent of efficient high-energy wood combustion systems, many western nations are turning again to forests as an attractive source of renewable energy. Power plants relying partially or entirely on the carbon in forest biomass range from relatively small units producing < 20 MW of electricity, such as the dozen or so in California, to the 265 MW Alholmens Kraft giant at Pietarsaari, Finland, with a steam capacity of 550 MW.

Forest biomass is not sufficient to replace all other sources of energy, but it certainly is a capable supplement from a relatively stable base. Although there has been a fairly constant annual drain of 0.37% (0.1 Giga tonnes (Gt = 10^9 kg)) in global biomass carbon since 1990 due to loss in forest area in southern Asia, western and central Africa, and South America (FAO 2006), world stocks of forest carbon in living biomass as of 2005 were estimated at 283 Gt and are stable in developed nations (FAO 2006). The potential supply of carbon energy from forests seems almost limitless because it is a renewable resource. But how limitless is it? Besides being the greatest terrestrial sink for atmospheric carbon, forests rank second only to oceans in sequestering atmospheric CO_2. We now face the question of whether we are affecting this primary function of forests by raising the rate of biomass removal. This paper presents an overview and my personal perspective on several of the issues facing forest management and the sustainable production of biomass energy.

Forest Management and Forest Carbon

2.1 Forests as Carbon Sinks

Forest ecosystems occupy about one-quarter of global land surface and contain about 638 Gt carbon—i.e., nearly one-half of terrestrial organic carbon. Of this, slightly more than half is in the topsoil (FAO 2006). Yet, the forest area existing today is estimated at only two-thirds of that present at the start of the Holocene owing to clearing for agriculture and desertification (Postel and Heise 1988). Thus, the obvious solution for advancing CO_2 sequestration is to increase forest area. China today has one of the highest rates of afforestation, but this is possible because of its extensive forest clearing that began

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about 2700 B.C. and continued unabated for 1,500 years (Hermann 1976), accelerating greatly during the recent Cultural Revolution. While China's state decision is admirable, the fact is that much of its gentler forest topography has been converted to agrarian uses and many of the most fertile bottom lands will be beneath the waters of new reservoirs—both consequences of meeting the needs of China's expanding population. In general, substantive afforestation is impractical in developed nations because it requires replacing existing agricultural and pasture land with forests. In the U.S., nearly all of the potentially convertible land is east of the Mississippi, and conversion is infeasible economically (Ryan et al. 2010).

2.2.1 Facing Reality: While forests are the largest terrestrial sinks for carbon and thereby something of a check on the rise of atmospheric CO_2, they withdraw only a fraction of that emitted. In the U.S., only 13% to 19% of the CO_2 emitted in fossil fuel consumption is sequestered in forest growth and harvested products. Furthermore, forest regrowth since 1940 accounts for only one-third of the carbon lost previously to the atmosphere from deforestation between 1700 and 1935 (Ryan et al. 2010). Increasing forest area in combating the global rise in atmospheric CO_2 to any significant extent simply is unrealistic. The best we can do is to protect what we have and manage it more efficiently.

If a forest management goal is to capture carbon, should we simply leave forests minimally managed to maintain closed canopy cover and an even net assimilation rate? As intriguing as this option might be if we disregard commodity production, it can have unpleasant repercussions if the future climate is warmer and drier than it has been historically. One stark example of minimal management is seen in the immense pine forest mortality caused by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) west of the crest of the Rocky Mountains. Beetle-caused mortality is believed to be due to trees weakened from overcrowding, and to milder winters that permit beetle larvae to survive in the cambium (Kurz et al. 2008). Graphic mortality has converted the region from a small net carbon sink to a region of major carbon loss. Carbon losses for 2000-2020 are projected at 270 Mt in British Columbia alone (Kurz et al. 2008).

Another example plaguing forests of western North America stems from policies that have been in place for nearly a century. Specifically, that of rapid fire suppression. Along with weak stocking control, the consequence of this in many drier regions is the buildup of understory fuel ladders—materials that would have been reduced through historic ground fires or more active management (Agee and Skinner 2005). When ignited, such fuels spread ground fire quickly to the canopy, and the carbon losses from stand-replacing wildfires can take decades to replace, even with prompt reforestation (Zhang et al. 2008). Are there other consequences of management?

2.2.2 Wildfire, an inconvenient fact: Bond et al. (2005) estimate that the area of closed forests would double globally in the absence of fire. But wildfire is a fact that accounts for one-fifth of global releases of CO_2 to the atmosphere (Levine and Cofer III 2000). Given projected climatic shifts, fire is apt to rise in frequency and intensity, particularly in western North America (Westerling et al. 2006). Thus, an issue facing forestry is how best to manage forests to reduce losses to wildfire. This issue sparks controversy.

Based on simulation models for Pacific Northwest forests, Mitchell et al. (2009) argue that treatments designed to reduce fuels and the likelihood of catastrophic wildfire may also reduce forest capacity to store carbon. Their simulations comparing wildfire in untreated stands against those with combinations of prescribed fire and thinnings suggest that fuel reduction treatments in forests with long fire-return intervals (decades or centuries) would not enhance on-site carbon retention in the event of wildfire. In contrast, Hurteau et al. (2008) argue that simulation approaches often treat thinnings in fire-prone forests as a *source* of CO_2, rather than a *sink*, and discount the conversion of carbon-neutral wood into energy to offset fossil fuel use, or into long-term storage products of value to society. Examining the four largest U.S. wildfires in 2002, they concluded that prior thinning would have reduced CO_2 evolution from live tree biomass by 98%. The effect of thinning on wildfire behavior depends on mass and continuity of residues, fuel ladders and residue levels remaining. Comparing thinned and unthinned stands in California's Sierra Nevada, Hurteau and North (2010) concluded that thinnings from below would quickly recover CO_2, but that thinning the overstory would not.

That unthinned forests store more carbon than thinned forests is not the question. Of course they do. The primary question is whether they also are more susceptible to catastrophic wildfire and whether the risk can be alleviated by timely thinning. Beyond this, the secondary question is how quickly thinned stands regain the carbon status of unthinned stands. Lacking long-term studies comparing treatments over time, researchers turn to models. However, all models are only as good as the assumptions supporting them. As Campbell et al. (2009) found, conclusions regarding carbon dynamics in thinning studies can pivot from small changes in process constants extrapolated from other locales.

2.2.3 Biomass Removal to Reduce Wildfire Risk and Contribute to Energy Production: Intensive silviculture in fire-prone regions dramatically reduces the risk of wildfire. In following long-term trends on a variety of research sites in California, Zhang et al. (2010) showed that vegetation control, thinning, and fertilization increased tree sizes quickly in young plantations, boosting carbon sequestration rates, stand resistance to wildfire, and resilience to climate change. Thinnings of lower crown classes remove fuel ladders and sharply lower the risk of stand-replacing wildfire (Hurteau et al. 2008, Hurteau and North 2010). Often, small trees removed in such thinnings have little commercial value as solid products, but converting their biomass to energy production helps combat the global rise in CO_2 from consumption of fossil fuels (Hurteau et al. 2008, MacCracken 2008).

Righelato and Spracklen (2007), in their life-cycle analyses of energy crops, point out that large-scale energy crop substitution for petroleum fuel is impractical because a 10% substitution would require 38% to 43% of the current cropland of Europe or the U.S. Further, they conclude that woody biomass conversion from existing or restored forests is a more sensible means of retaining carbon and using it, too. But bioenergy systems based on forest biomass will succeed only if three conditions are met: (1) such systems are economically competitive; (2) the supply of raw materials is dependable; (3) convincing evidence demonstrates that systems are environmentally sustainable. The latter condition was partly the impetus for the International Energy Agency's Bioenergy Agreement beginning in 1992 (Smith 1995) and the various tasks that fell beneath this umbrella.

Will the Nutrient Cycle Be Impaired?

3.1 Are Biomass Removal and Sustained Productivity Compatible?

In both Europe and North America, most assessments and projections about future productivity are based on assumed—but unsubstantiated— relationships between nutrient export in biomass and soil nutrient supply (Switzer and Nelson 1972, Abbott and Crossley 1982, Freedman et al. 1986, Hendrickson et al. 1989, Saarsalmi et al. 2010). Such projections rest on mass-balance models of nutrient supply determined by static measures that overlook the dynamic nature of soil chemical equilibria. Unfortunately, findings tend to be anecdotal, seemingly contradictory, and limited geographically. Generally, they convey little insight beyond that presented three decades ago in a major symposium on the subject (Leaf 1979). To summarize:

- Tree crowns are richer in nutrients than bole wood and bark. Therefore, whole-tree harvesting removes more nutrients than conventional harvests that merely remove stems.

- The mass of cation nutrients removed during whole-tree harvesting may exceed that on cation exchange sites in the soil.

- Consequences of whole-tree removal on future productivity are apt to be greater on poor soils than on richer.

3.1.1 The Problem with Mass-Balance Projections: Most projections of possible productivity loss center on assumed depletion of soil cation nutrients such as calcium (Ca), potassium (K), and magnesium (Mg) as measured by exchangeable ions on soil colloids. That is, that the amount of cation nutrients removed in whole-tree harvesting approaches or exceeds that present on charged exchange sites in the soil. When this occurs, the concern is that future demand for nutrients will exceed supply and that productivity will decline.

The problem with simplistic mass-balance projections is the difference between a still photograph and a video. Cation nutrients in the soil exist in a variety of forms, ranging from those in primary minerals of silicate rocks released only through weathering, to those present as very dilute ions in the soil solution. The former are not considered biologically available, while the latter are readily available for uptake. Nutrient cations also exist in intermediate forms, varying from those in weathered secondary minerals (sparingly available) to those on electrostatically charged surfaces of soil colloids (readily available). By convention (grounded on techniques for annual agricultural crops with high nutrient demand and with meager capacity for internal recycling to perennial parts), only readily available cations are measured in soil analyses (Schoenholtz et al. 2000), and results from such analyses seldom if ever correlate with uptake or growth by forest trees (Powers et al. 1998). Undoubtedly, this is because cations in all forms are in a dynamic equilibrium between the source (primary minerals) and those released to cation exchange sites and the soil solution. As cations readily available to tree roots are removed through uptake, the equilibrium shifts to higher rates of replacement from supplies that are less available (Markewitz and Richter 2000). The rates of equilibrium shift are largely unknown, but surely vary with mineralogy, soil climate, and the influence of biological weathering agents.

3.1.2 Field Experiments: Only rarely have we tried to address concerns about productivity decline through field experiments. Many claims of reduced growth attributed to harvest removals actually are confounded and can be explained by other causes (Powers et al. 1990a). Reduced stand growth after whole-tree harvesting has been reported in the U.K. for Sitka spruce (*Picea sitchensis* (Bong.)Carr.) (Proe et al. 1996, Walmsley et al. 2008); Norway spruce (*P. abies* (L.)H. Karst.) in the U.S. (Nyland et al. 1979); and for Norway spruce and Scots pine (*Pinus sylvestris* L.) in Sweden (Egnell and Leijon 1999). Working with pines on the Southern Coastal Plain of the U.S., Scott and Dean (2006) reported slight declines in absolute productivity 10 years after whole-tree harvesting. Their finding most certainly reflects the importance of an organic cycling pathway for phosphorus (P), owing to its absolute scarcity in soils of the Southern Coastal Plain of the United States because of their peculiar orogeny.

Thinning likely has little impact. Carlyle (1995), studying radiata pine (*Pinus radiata* D.Don) plantations, found that thinning did not change total N uptake despite removing about half the stand basal area. Nutrient leaching was unaffected by thinning and the same absolute uptake simply was shifted to fewer, more vigorous trees. Utilization takes many forms. Root-system removal ("stump harvesting") is practiced in some locales—particularly Europe—(Karjalainen et. al. 2004) and can account for as much as one-fifth of the biomass removed above-ground (Richardson et al. 2002). While it has practical and perceived benefits for disease control and for fossil fuel substitution, stump harvesting represents an escalation of biomass removal to below-ground structures that may have detrimental impacts on soil fertility, physical properties, and carbon storage (Walmsley and Godbold 2010). This seems an important area for research. How should we do it?

The better field experiments exist as scattered reports. Recently, Nave et al. (2010) applied a meta-analysis to a global collection of 75 peer-reviewed papers dealing with harvesting impacts in temperate forests. This afforded 432 estimates of carbon changes in varying soil layers. They concluded that on average, harvesting reduced soil carbon by 8%, but that most of this was due to reductions averaging 30% in forest floor mass. Carbon losses from mineral soils were insignificant, although Inceptisols and Ultisols seemed somewhat more vulnerable than other soil orders. Soil carbon declines were seen as temporary and readily corrected either by mitigation or by time.

Meta-analyses are a useful way to try to make sense of myriad studies, each with their individual methods of measurement and reporting. But specific questions remain, namely:

- Does biomass removal cause productivity decline?
- If so, what is the mechanism?
- Is it universal?
- How long does it last?

We need to move beyond speculation, scattered reports, and broad generalizations that fail to apply to any specific situation. A huge advance would be afforded through a coordinated network of experiments with similar protocols designed specifically to address these questions. Recognizing this need promoted a network of designed experiments in New Zealand (Smith et al. 2000) and formed the foundation for the International Long-Term Soil Productivity study (LTSP). The LTSP program is remarkable in that it endures after two decades. Important features that contribute to its strength and flexibility are described here as a possible prescription for successful research.

The Long-Term Soil Productivity Study

4.1 Historical Basis

The LTSP program began as a grass-roots response to the National Forest Management Act (NFMA) of 1976 and related legislation (USDA Forest Service 1993). NFMA requires the U.S. Secretary of Agriculture to ensure, through research and monitoring, that forest management practices do not permanently impair the productivity of the land. This requirement seems superfluous because sustaining productivity is an obvious aim of modern forest management. But surprisingly, NFMA may be the first mandate for a forest land ethic that carries the weight of law. It precedes by more than a decade the Dutch Soil Protection Act of 1987 and Australia’s National Forest Policy Statement of 1992 (Nambiar 1996, Powers et al. 1998). Thus, it is a legislative landmark.

The essence of NFMA is that the U.S. Forest Service must ensure sustained forest productivity while protecting all resource values—a noble charge in principle, but vexingly vague in practice. The Forest Service knew unambiguous definitions were central to carrying out its monitoring mandate. At the fore was a clear and objective definition of “land productivity.” Accordingly, and with guidance from the U.S. Office of General Council, a working definition emerged. “Land productivity” was seen as the carrying capacity of a site for sustaining growth of native vegetation. In turn, “carrying capacity” was seen as the average periodic dry matter production when the site was fully stocked, and analogous to net primary productivity in a mature forest community. Finally, “significant change” was defined as a reduced level of carrying capacity induced by management that could be detected within practicable levels of operational monitoring. The problem now was how to do it.

4.1.1 Research Coordination Grew From Humble Beginnings: During a 1986 field trip at the Soil Science Society of America Annual Meeting in New Orleans, a colleague and I were approached by the chief National Forest System soil science administrator in Washington, D.C., who sought help from research with their NFMA mandate. We arranged a meeting of a small, but seasoned team of agency scientists and managers to tackle the problem. While agreeing that organic matter and soil porosity were of paramount importance, our team concluded that existing information was sparse, site specific, and too anecdotal to be broadly useful. We concluded that more fundamental work was needed, and we proposed a nationally coordinated field experiment to address the issue directly and unambiguously.

We developed an approach, and the proposal was presented before international groups of scientists for feedback (including IEA participants at a conference in New Zealand), peer-reviewed, and published soon thereafter (Powers et al. 1990a, b). From this, a formal study plan was prepared and reviewed both domestically and abroad. Undoubtedly, this was the most broadly reviewed research plan ever produced by the USDA Forest Service, and it was approved in 1989 by the Deputy Chiefs for Research and the National Forest System (Powers et al. 1989). The British Columbia Ministry of Forests adopted the concept in 1990 as its top new research priority, and the Canadian Forest Service joined a few years later, merging LTSP with a similar set of studies begun in Ontario. In 2011, China’s Huitong National Research Station of the National Academy of Sciences formally joined the LTSP program, expanding the study to subtropical Asia.

4.1.2 The Concept Behind LTSP: The program now known as LTSP is predicated on the principle that within climatic constraints, a site’s productive potential is strongly regulated by physical, chemical, and biotic soil processes that are affected readily by management. The key properties affected directly by management are soil porosity and site organic matter. Together, these properties regulate critical site processes through their roles in soil aggregate stability, water and gas exchange, physical restrictions on rooting, microbial activity, and resource availability. The concept is illustrated in Figure 1.

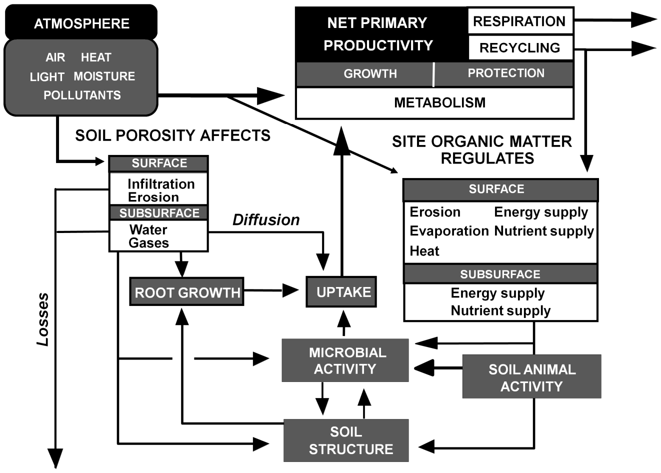

Figure 1. *Conceptual model of how soil porosity and site organic matter regulate net primary productivity within the framework of environmental controls (from Powers et al. 1990a).*

We designed LTSP to test the following hypotheses (Powers 2006).

Null hypothesis	Alternative hypothesis
(1) Pulse changes in site organic matter and/or soil porosity do not affect the sustained productive potential of a site (sustained capacity to capture carbon and produce phytomass).	Critical changes in site organic matter and/or soil porosity have a lasting effect on potential productivity by altering soil stability, root penetration, soil air, water, and nutrient balances, and energy flow.
(2) If impacts on productivity occur from changes in organic matter and porosity, they are universal.	The biological significance of a change in organic matter or porosity varies by climate and soil type.
(3) If impacts do occur, they are irreversible.	Negative impacts are reversible.
(4) Plant diversity has no impact on the productive potential of a site.	Diverse communities affect site potential by using resources more fully and/or through changes that affect the soil.

Sites were selected across the U.S. and Canada to span the range of soils and climates characterizing a broad variety of commercial forest types. Stands were chosen to reflect the age and size classes most apt to be managed for wood production, and standing biomass and soil properties were measured before the stands were harvested. The experimental design for each field installation followed the same format (Table 1).

Table 1. *Description of main effect treatments in the core LTSP experiment.*

Main effect	Symbol	Description of treatment
Modify site organic matter	OM_0	Tree boles removed. Slash, woody, and herbaceous understory killed, and forest floor retained.
	OM_1	All living vegetation removed. Forest floor retained.
	OM_2	All above-ground biomass removed. Bare soil exposed.
Modify soil porosity	C_0	No soil compaction.
	C_1	Compacted to an intermediate bulk density.
	C_2	Compacted to an unusually high bulk density.

By applying these main effect treatments factorially, we avoided possible confounding when different types of equipment are used for some treatments but not for others. On most sites, plots for each treatment cell were split. Emerging native vegetation was controlled on one-half and allowed to develop on the other half. Plots were then regenerated with tree species native to the site, and growth and soil changes were followed on each plot (Figure 2). Taken together, the total biomass (trees plus emerging vegetation) provided fundamental measures of net primary productivity. Where emerging vegetation was controlled, all factors of productivity were focused on a single target—trees. By this, we were able to avoid confounding that can occur when the nature of competing vegetation varies by treatment, possibly masking the true effect of soil disturbance on tree growth. Measurements were repeated regularly, and more than 200 papers have been published on findings from individual studies. More comprehensive analyses of both 5- and 10-year responses have been published for soil (Page-Dumroese et al. 2006) and vegetation (Powers et al. 2005, Fleming et al. 2006, Ponder et al. 2012).

We knew studies similar to LTSP were appearing on both university and private lands, and many included mitigation treatments missing from our core design. Accordingly, in hope of promoting collaboration rather than rivalry, we convened a 1994 meeting of both public and private sector research leaders from the U.S. and Canada. We agreed to work toward a common goal. From this we expanded the network to nearly four dozen affiliate sites in Canada and the United States. Combined, more than 100 LTSP core and affiliate installations comprise the world’s largest network of studies aimed at understanding how management affects the fundamental productivity of forest land (Figure 3). Characteristics are summarized in Fleming et al. (2006) and Powers (2006).

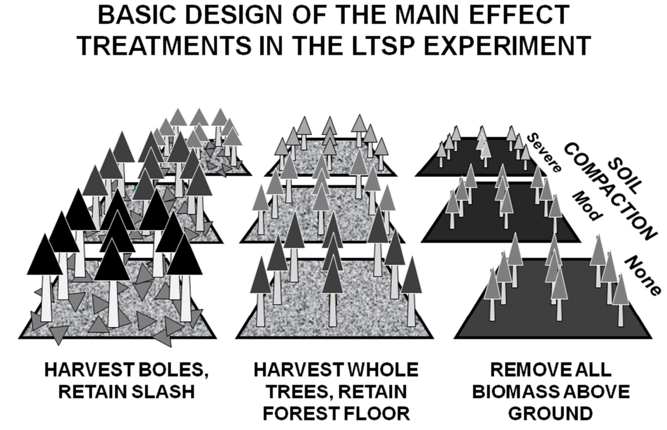

Figure 2. *Core LTSP design. Following harvest, treatments of decreasing organic matter retention and increasing soil compaction are applied factorially. Plots are regenerated and split with and without vegetation control (not shown). Biomass production differences indicate treatment effects.*

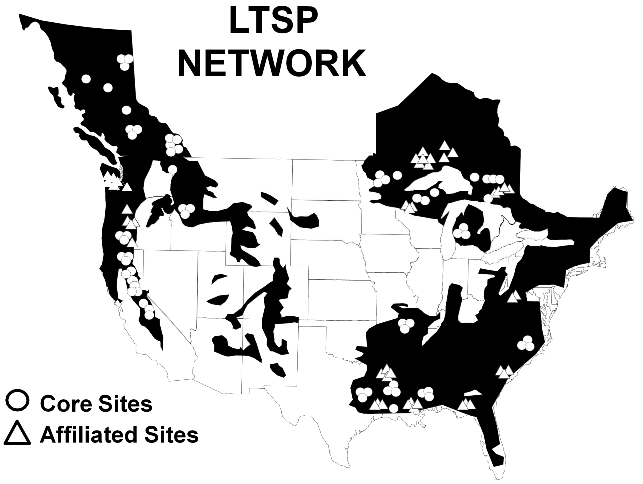

Figure 3. *Distribution of North American core and affiliate LTSP installations. Shading shows forest area capable of mean annual increments of 1.4* m^3 ha^{-1} *or more of merchantable wood. Work is under way for new installations in subtropical China.*

Lessons Learned and Suggestions for Sustaining Field Studies

Our collective experience in establishing LTSP as a large-scale field research network may be helpful to future scientists contemplating long-term manipulative experiments, regardless of purpose. These and other elements key to success are detailed elsewhere (Powers 1999, Powers and Van Cleve 1991). Highlights follow:

1. Any research with staying power must have a broad and enduring appeal that transcends more ephemeral issues of the moment. A timeless social theme is an umbrella that shields more mundane but necessary projects from the drizzle of public apathy.

2. Treatments must be robust—sufficiently extreme to alter site processes and elicit substantive responses—of which some, ideally, may be unforeseen. If the outcome already is known, why do the experiment?

3. Treatment plots should be large enough to maintain stand-like conditions for decades, while allowing smaller treatments to be embedded to test emerging hypotheses.

4. Forests comprise the most complex ecosystems on earth and should be magnets for drawing bright minds from multiple disciplines. Ideally, others would be brought in early enough to create a sense of ownership. Collaboration among disciplines adds staying power to any study, because intellectual diversity can build resilience.

5. Long-term field trials can be established anywhere, but the trick to sustaining them includes protecting the sites from "demonic intrusion" that includes trespass, ownership changes, and myriad other factors. I'm reminded of a phrase I think was attributed to Ian Craib in Swaziland to the effect of "*Just when you think you have it all figured out, an elephant runs through your plots*." Plan ahead for "elephants."

6. Success for a sustainable network requires both vertical and horizontal buy-in from research scientists and all others involved throughout the administrative network. Sustained commitment is the single most important element towards long-term success.

7. Most scientists are reticent to reach beyond the traditional comfort of scholarly publications and scientific conferences. But enduring studies require bold "champions" who, through personal charisma and the power of conviction, can carry the message of long-term research to a much larger audience. Recognize those individuals and encourage them to be cheerleaders.

8. "Grass-roots" studies can expand to national and international scope if the concept is appealing, there is careful planning, and there is commitment from a cadre of individuals treated as peers.

9. Innovation, rather than rigid conformity, is a critical element because it sparks creativity.

Being human means having biases. Accordingly, this overview reflects mine drawn from four decades of research on the general subject of sustainable forest productivity. I hope the reader finds this discourse objective, reasonable, and provocative. I offer it in hope that the issues described and approaches to addressing them will stimulate others to tackle the matter of sustainable biomass harvesting with the rigor that it deserves.

Acknowledgments

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