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Large-Scale Water Manipulations

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Introduction

Researchers predict that increasing levels of greenhouse gases in the atmosphere will cause a 1 to 3.5°C increase in average global temperatures and alter regional levels of precipitation (Kattenberg et al. 1996; Rind et al. 1990). Changes in global temperature and altered precipitation patterns may lead to dramatic changes in ecosystem productivity, biogeochemical cycling, and the availability of water resources (Kirschbaum and Fischlin 1996; Melillo et al. 1990). The responses of ecosystems to decreased water availability or increased occurrence of drought is considered a key issue in climate change scenarios (Wigley et al. 1984), because changes in the carbon sequestration potential of vegetation at the global scale may alter the accumulation of carbon dioxide (CO_2) in the atmosphere, potentially moderating or accelerating climate changes (Ojima et al. 1991; Wigley and Jones 1985). Because the actual direction and magnitude of expected changes in precipitation are highly uncertain, and consensus scenarios for regional climate change do not exist, manipulation experiments can play a significant role in clarifying the potential impacts of a range of climate change scenarios on highly valued ecosystems.

Controlled experiments in greenhouses and growth chambers have provided us with a large database of information concerning the impacts of moisture manipulations on the physiology and growth of forest tree seedlings and saplings (Ellsworth and Reich 1992; Hinckley et al. 1978; Kleiner et al. 1992; Kolb et al. 1990; Pezeshki and Chambers 1986). However, concerns remain as to the appropriateness of the extrapolation of small-scale and short-term data to mature tree responses in forest stands where existing data are limited largely to short-term responses to water stress (Cregg et al. 1989; Hinckley et al. 1978) or to a limited number of trees sampled or species observed (Dougherty and Hinckley 1981; Epron et al. 1992; Ginter-Whitehouse et al. 1983). Similar concerns and arguments can be made for the extrapolation of data for other ecosystems. In response to concerns over the validity of small-scale experimental response data for environmental assessments, several recent reviews (Graham et al. 1990; Mooney 1991; Mooney et al. 1991; Woodward 1992) have called for large-scale manipulation experiments as the appropriate means by which to study the impacts of changing climates on ecosystems.

This chapter outlines important methodological issues involved in the design and operation of large-scale precipitation manipulation experiments. Previous precipitation or water manipulation studies historically focused on scenarios of increasing or decreasing precipitation patterns and the resulting impacts on small plants or saplings grown in pots or small field plots (Hinckley et al. 1978; Kozlowski 1982). The primary objective of these studies was to determine the impact of irrigation or drought on plant growth or the harvest index of a particular crop. Irrigation methods for application to agricultural crops and forest plantations have been discussed previously (Hagan et al. 1967; Stewart and Nielsen 1990) and they will not be extensively reviewed here. Instead, this chapter focuses on precipitation manipulation methods that have been used at the plot or stand level in natural ecosystems or forest plantations for studying the impacts of anthropogenic stressors (i.e., acid precipitation and/or climate change) on ecosystem and plant processes. Large-scale manipulations are defined in this chapter as those field experiments that are of sufficient size and complexity to handle questions of individual plant response as well as stand-level carbon, water, and nutrient cycling responses.

Active Versus Passive Manipulations

Precipitation manipulation studies can be divided into two general categories: active versus passive approaches. Active precipitation manipulation studies involve the use of above-canopy irrigation methods to supplement natural rainfall or add modified rainfall chemistries. Passive approaches employ understory troughs or complete "roofs" to intercept natural throughfall or rainfall for diversion away from treatment plots. The diverted water can be discarded or channeled to alternate plots for complementary irrigation. Studies described by Abrahamsen et al. (1977), Irving and Miller (1981), and Johnston et al. (1986) all employed active irrigation methods for use in small field studies of acid precipitation impacts on crops and tree seedlings. Active plot-scale irrigations were also employed by Sala and Lauenroth (1982) and more recently by Golluscio et al. (1998) to evaluate grassland ecosystems. A good example of the passive approach would be the throughfall displacement experiment described by Hanson et al. (1995, 1998) for manipulation of rainfall quantity in an upland oak forest. A combination of active and passive approaches was employed at the plot scale by the EXMAN (experimental manipulation) projects in forest ecosystems in Europe (Beier et al. 1995) and at the watershed scale (Moldan et al. 1995; Hultberg et al. 1993) for studies of the impact of rainfall chemistries on growth and nutrient cycling of plantation-grown conifers. Table 23.1 summarizes a number of field-based studies that have attempted with various rates of success to modify natural rainfall patterns against the backdrop of natural climate variability. Total control of water quantity and chemistry is easy to attain for small plants in greenhouses and growth chambers, but is much more difficult in the field. A notable attempt to achieve such control at the level of whole catchments is the CLIMEX project (Jenkins and Wright 1995) which uses a 1200-m^2 greenhouse to attempt complete control over system precipitation, temperature, and atmospheric CO_2 concentrations. A recent mesic grassland study (Fay et al., in press) combined passive rainfall collection and subsequent active redistribution to generate multiple pre-

TABLE 23.1. Studies designed to passively manipulate throughfall quantity or quality of forest stands or grasslands for evaluating impacts on plant and soil processes.

Location	Key genera	Stand age (yr)	Treatment	Manipulated area[a] (m^2)	Reference
Walker Branch, USA	*Quercus/Acer*	80–120	±33%	12,800	Hanson et al. 1995, 1998
Lake Gårdsjön, Sweden	*Picea*	80–100	na[b]	6300	Moldan et al. 1995 Hultberg et al. 1993
Klosterhede, Denmark	*Picea*	74	−100% and variable	1176	Gundersen et al. 1995 Beier et al. 1995 Rasmussen et al. 1995
Solling, Germany	*Picea*	60	variable	300	Lamersdorf et al. 1995
Konza Prairie, USA	Grassland	na	−30% altered timing	144	Fay et al. (in press)
Ballyhooly, Ireland	*Picea*	60	−100%	100	Lamersdorf et al. 1995
Springforbi, Denmark	*Picea*	14–21	−50 to −75%	46	Holstener-Jørgensen 1994
France	*Quercus*	32	−100%	14–25	Bréda et al. 1993; 1995
Canada	*Acer*	80	−100%	16 per tree	Pilon et al. 1996

[a]Area available for manipulating throughfall. This is typically the area under a roof, troughs or tarpaulin.
[b]Not applicable.

cipitation treatments at the plot scale, including normal precipitation quantity and timing, 30% reductions in precipitation, and 30% reductions and/or extended dry periods.

With this brief introduction to the general types of precipitation and ecosystem manipulations that have been reported, consideration will be given to methodological issues important for appropriate application of water manipulations to large-scale field studies.

Artificial Rainfall

Controlled studies designed to assess the effects of rain or mist chemistries on test plants must consider several chemical and physical design criteria if results are to meaningfully address effects appropriate to field conditions. Among the parameters traditionally considered important are those related to solution chemistry (pH, ionic composition), solution physics (drop size and velocity), and the temporal and spatial characteristics of precipitation events (uniform distribution, intensity, and volume). Artificial rainfall systems can be designed in a variety of ways to meet a variety of experimental goals. Simple irrigation systems consisting of dippers, watering cans, or hoses have been used to amend soil water and nutrient levels periodically. Automated drip irrigation systems function in the same way, but do not allow for the interaction between rain and foliage characteristic of natural rainfall. The addition of water and nutrients through overhead nozzles or rotating booms represents an additional step in complexity that allows for this contact.

The primary goal of any artificial rain system for use in controlled experiments should be to imitate the chemical and physical features of natural rain events in an appropriate temporal scale and under reasonable environmental conditions. A summary of the variables of ambient rainfall that have been incorporated into existing rain simulation systems is found in Table 23.2. Hanson et al. (1990) discuss the features of appropriate rainfall simulators in some detail. The key physical and chemical features of appropriate artificial rain are repeated here. Raindrop sizes should be maintained in the range between 0.1 and 1.0 mm for most rain simulations, dispensing nozzles directed upward to allow gravity to drive deposition should be positioned 2 to 3 m above the plant leaves to allow the raindrops to attain terminal velocity before impact (an important consideration for studies of foliar nutrient deposition/leaching).

TABLE 23.2. Important variables to consider when simulating rainfall additions and throughfall removal.

I. Artificial rainfall additions
- A. Physical variables:
  - Drop size
  - Drop velocity
  - Rainfall distribution
  - Rainfall intensity
  - Reasonable quantities
- B. Chemical variables:
  - Inorganic ions
  - Organic constituents
- C. Temporal and environmental variables:
  - Time of day
  - Event frequency
  - Light, Temperature, Wind

II. Throughfall removal or redistribution
- A. Physical variables:
  - Rainfall distribution
  - Rainfall intensity
  - Reasonable quantities
- B. Chemical variables:
  - Inorganic ions
  - Organic constituents
- C. Temporal and environmental variables:
  - Time of day (for redistribution of throughfall)
  - Light, Temperature, Wind

To ensure adequate control over the chemical integrity of rain solutions artificial rain systems should employ the following: water purification systems, adequate clean storage capacity, and apparatus for diluting stock solutions if mixing is conducted automatically. Among the chemical variables traditionally considered important are solution pH and ionic concentrations of several macro- and microelements.

Unfortunately, many of the key elements of good artificial rain additions make their application at the field scale costly and logistically difficult. As an alternative, researchers have typically defaulted to subcanopy additions of water and/or simulated throughfall chemistries via drip or pressurized nozzle approaches. Understory additions of supplemental rainfall are the logical approach as they are easier to operate and install, but they fall short of being an accurate simulation of increased precipitation because they do not allow for the interaction of precipitation with canopy foliage, branches, and stems, and the concurrent uptake (NO_3, HN_4) or leaching (base cations and organics) of chemicals that takes place during normal rainfall events.

Throughfall Interception

As a passive means of modifying ecosystem water budgets, the interception of throughfall has proven very useful in a number of studies (see Table 23.1). Typical applications have used either complete understory roofs (Gundersen et al. 1995) or partial coverage of the ground area with gutters or troughs (Holstener-Jørgensen 1994; Hanson et al. 1995; Hanson et al. 1998) to manipulate the amount of water reaching the forest floor. The largest field manipulation of water attempted to date is the Walker Branch Throughfall Displacement Experiment (TDE) which includes 12,800 m^2 of manipulated area (Hanson et al. 1998; Hanson et al. 1995). The TDE was developed for an upland oak ecosystem located in the eastern United States (lat. 35°58′N, long. 84°17′W). Mean annual precipitation is 140 cm and mean temperature is 13.3°C. Depth to bedrock at this location is approximately 30 m. The site is dominated by *Quercus alba* L., *Quercus prinus* L., and *Acer rubrum* L., but it contains 16 other tree species with a total stand basal area that averages 20 to 25 $m^2 ha^{-1}$. Briefly, the manipulations of throughfall levels reaching the forest floor are made with a system designed to passively transfer precipitation from one experimental plot to another. There are three plots in the TDE: one wet, one dry, and one ambient. Each 80 × 80 m plot is divided into one hundred 8 × 8 m subplots that serve as the locations for repetitive, nondestructive measurements of soil and plant characteristics. Throughfall precipitation is intercepted in ≈2000 subcanopy troughs (0.3 × 5 m), each suspended above the forest floor of the dry plot (≈33% of the ground area is covered) (Fig. 23.1A). The intercepted throughfall is then transferred by gravity flow across an ambient plot and distributed onto the wet treatment plot through paired drip holes spaced approximately 1 m apart in approximately 6-cm diameter PVC pipe.

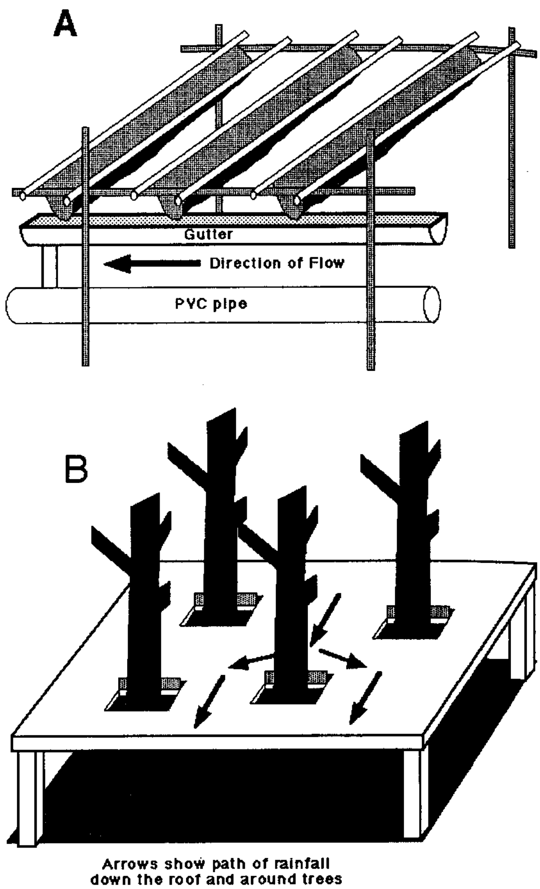

FIGURE 23.1. Schematic representations of the two types of throughfall collectors that have been used in large-scale water manipulations. A, A throughfall collection system designed to intercept a fractional amount (approximately 33%) of throughfall reaching the forest floor shown with collection gutters and transfer pipes (Hanson et al. 1995, 1998). B, An understory roof collection structure used to intercept 100% of the throughfall incident upon the forest floor (collars are used on individual trees to intercept stem flow, but are not shown).

Of the other throughfall manipulation studies listed in Table 23.1, the roofed catchment (Fig. 23.1B) located at Lake Gårdsjön, Sweden (Hultberg et al. 1993, Moldan et al. 1995) is the next largest in terms of total area manipulated (6400 m^2). However, the Lake Gårdsjön facility has not been applied to manipulations of throughfall quantity and drought. Instead they have been focusing on 100% removal of ambient throughfall chemistries followed by similar quantities added back with altered chemistries. Other roofed catchment studies (Rasmussen et al. 1995; Beier et al. 1995) involve somewhat smaller manipulation areas (i.e., typically less than 500 m^2) and they most often use 100% removal of throughfall as the primary manipulation although the duration of the treatments is variable. In most cases in which 100% throughfall removal has been applied, attempts are made to resaturate the soils periodically, especially during dormant periods.

Pilon et al. (1996) report on the use of a sealed tarpaulin around the base of individual trees as a method to eliminate throughfall inputs to the root zone of trees, but their approach was not consistently effective in the first year of their study, and the tarpaulin approach had no effect on soil water content in the second year of their study. They point out that the presence of a tarpaulin directly on the soil surface does preclude normal evaporation processes. This is a serious limitation to the ground tarpaulin approach to throughfall manipulations.

In a recent study of grasslands (Fay et al., in press), investigators employed a number of permanently installed plastic greenhouse roofs (9 × 14 m) as simultaneous shields from ambient rainfall and throughfall collectors. Together with large rainfall collection tanks, pumps, irrigation nozzles, and barriers to horizontal rooting and water movement (7.6 × 7.6 m plots under each roof), their roofed plots represent a cost effective approach for manipulating both the quantity and timing of rainfall events over a 6 × 6 m treatment area.

Verification of Water Treatments

A key feature of any water manipulation experiment should be an adequate and comprehensive characterization of the soil water status. This is important both from the standpoint of verifying the treatments applied and for the characterization of the level of soil moisture stress experience by plants and microorganisms. Measurements of soil water status need to have adequate temporal resolution to cover important seasonal patterns, and for large-scale experiments, a clear understanding of the spatial variation in soil water status across the experimental site is essential. While these points may seem obvious, adequate soil water data are not always collected. For example, in the throughfall roof study conducted at Klosterhede, Denmark (Gundersen et al. 1995), natural throughfall was removed and replacement throughfall was added by a sprinkler system underneath the roof, and extensive measurements of the artificial throughfall reaching the forest floor were conducted both temporally and spatially. Unfortunately, neither soil water content or soil matric potential data were reported leaving us unsure of the soil water status during the experiment. As a result, direct comparisons of plant, decomposition, and nutrient cycling responses between the Klosterhede studies (Beier et al. 1995; Gundersen et al. 1995) and other large-scale water manipulation studies are hampered due to a lack of published data on soil water status. Future soil water manipulations should include adequate measurement approaches at appropriate spatial and temporal scales to avoid this problem.

Measurement Approaches

Soil water observations can be conducted using a variety of methods. Destructive gravimetric sampling, neutron probe measurements, and time domain reflectometry can be used for measurements of soil moisture content. Tensiometers and soil resistance blocks can provide a direct measurement of soil matric potential with appropriate calibration, and soil psychrometers can be installed in the field for a direct measurements of soil water potential. A detailed discussion of the advantages and disadvantages of each technique can be found in Chapter 13 and in a previous review by Rundel and Jarrell (1989). When not directly measured as matric or total soil water potential, measured soil water content data need to be translated into water potential terms (i.e., soil moisture retention curves) so that direct intercomparisons among studies can be facilitated. In many published studies it is difficult to judge the severity of drought because soil water content data are often not expressed as matric or total water potential.

Although destructive gravimetric sampling is often prohibited in an experimental setting where removal of soil over time may compromise the natural state of the soil profile, a certain amount of gravimetric soil sampling should always be conducted to complement (and if necessary calibrate) the chosen nondestructive approach. For large-scale experiments that will include drought periods, tensiometers are not recommended as they are typically only functional over a limited range of soil matric potentials (−0.00 to −0.08 MPa). Neutron probe approaches have also fallen out of favor recently because they demand site-specific calibration and additional radiation protection procedures. Soil resistance blocks, soil psychrometers, and other electronically based sensors are the best choice for a study in which detailed temporal resolutions on the order of hours or days are required, but they would be expensive to replicate over large spatial scale. Autologging of any instrument becomes a problem when replicated over large spatial scales due to signal losses over long wire lengths and the disturbance associated with wire installation. Perhaps the best approach for measuring soil water status over large spatial scales (in the absence of proven remote sensing methods, see Chapter 13) is time domain reflectometry (Topp and Davis 1985).

Time domain reflectometry (TDR) has proven to be a cost effective and durable approach for making soil water content measurements in large-scale water manipulation studies (Hanson et al. 1995). However, since TDR is only a measurement of soil moisture content, complementary information on the relationship between soil water content and soil water potential for the experimental soils (i.e., a soil moisture release curve) is required to translate water content data to soil water or matric potential. Measured TDR yields water content for the bulk soil including coarse fraction (i.e., soil particles >2 mm), but soil moisture release curves are typically conducted on soils from which the coarse fraction has been removed. Therefore, bulk or raw TDR data (TDR_r) must be corrected for coarse fraction content before it is used in a soil moisture release curve to obtain soil water or matric potential information. Alternatively, soil moisture release curves including particle size classes greater than 2 mm should be generated. Paruelo et al. (1987) took the latter approach and showed that significant soil water could be held by the 2- to 11-mm coarse fraction of a Patagonian arid steppe soil. They also showed that large coarse fraction components (i.e., rocks >11 mm) decreased soil water holding capacity nearly proportionate to their volume.

To obtain soil water potential data from TDR_r for soils having large coarse fraction components (i.e., rocks assumed to contain zero water) Hanson et al. (1998) used the following calculation to correct TDR values (TDR_c) for application to their soil moisture release curves from sieved soil:

$$TDR_c = TDR_r/(100 - C_f) * 100 \quad (23.1)$$

where C_f is the appropriate mean coarse fraction for the soil. For their soil with a mean coarse fraction of 14.2% in the surface 35 cm, TDR_c values were typically 2 to 3% higher than observed TDR_r.

What is the appropriate depth for making soil water or matric potential measurements? Unfortunately, there is no simple answer to this question. Important criteria depend on the questions being addressed in a particular study and the nature of the soils being measured. If plant responses are a key component, one should consider measuring that portion of the soil profile that includes the "effective" rooting depth of the plants of interest. Multiple soil depths should be considered if time and money allow. A recent study contrasting water use by herbaceous and woody plant life-forms in a shortgrass steppe community (Dodd et al. 1998) showed that each uses water from different layers of the soil profile. In such a system it would be critical to collect water content data from multiple soil depths corresponding to the water use characteristics of the species of interest. Data on depth of water resources for plant function are available for a number of other ecosystems (Ehleringer et al. 1991; Flanagan et al. 1992; Gordon et al. 1989; White et al. 1985).

Dealing with Spatial Variation

Spatial variation in soil characteristics, species composition, vegetation cover, slope, and aspect all interact and lead to potentially significant spatial differences across sites used for large-scale manipulations. This pretreatment variation must be characterized and understood to ensure that observed differences in soil water status imposed by the treatment infrastructure are true treatments and not simply inherent patterns driven by variable site characteristics. Pretreatment data collections for soil water content and/or water potential should be available for at least one full year to characterize the soil water patterns across the experimental area of interest, and the temporal resolution of the pretreatment data should encompass periods of maximum and minimum soil water levels. Pretreatment data for other variables that might logically trend across a large experimental area (e.g., soil temperature) would also be useful.

An example of the use of pretreatment information as a base from which to judge the effectiveness of a large-scale TDE is provided by Hanson et al. (1998). They collected pretreatment measurements of soil water content by TDR at an 8 × 8 m grid across their experimental site (310 locations) from April 1992 through July 12, 1993, and they found significant pretreatment gradients in water content across their experimental area driven by slope position and soil coarse fraction. From these pretreatment observations a covariate matrix was developed based on an individual measurement's location according to the following equations:

$$Yij = \sum (Yijk)/n \qquad (23.2)$$

$$Y = \sum (Yij)/n \qquad (23.3)$$

$$CovYij = (Yij - Y)/sdY \qquad (23.4)$$

where Yij is the mean annual value for a given location, Y is the grand mean for all locations and times, i and j are the horizontal and vertical coordinates of the experimental area, k is the month of the observation, and n is the number of observations for a given summation. As an illustration of the importance of understanding pretreatment patterns, Figure 23.2 shows a contour plot of winter and summer pretreatment soil water data for the TDE (Hanson et al. 1998) along with a graph of the corresponding covariate rankings based on Equation 23.4. They found that a single covariate rank based on an entire years' worth of data was not robust enough to apply to all subsequent dates. Instead, they used two covariate ranks: one for the dormant season when soil water conditions were near saturation and one for summer periods when soils were drier. The validity of the approach used by Hanson et al. (1998) was contingent on the assumption that there was no spatial autocorrelation

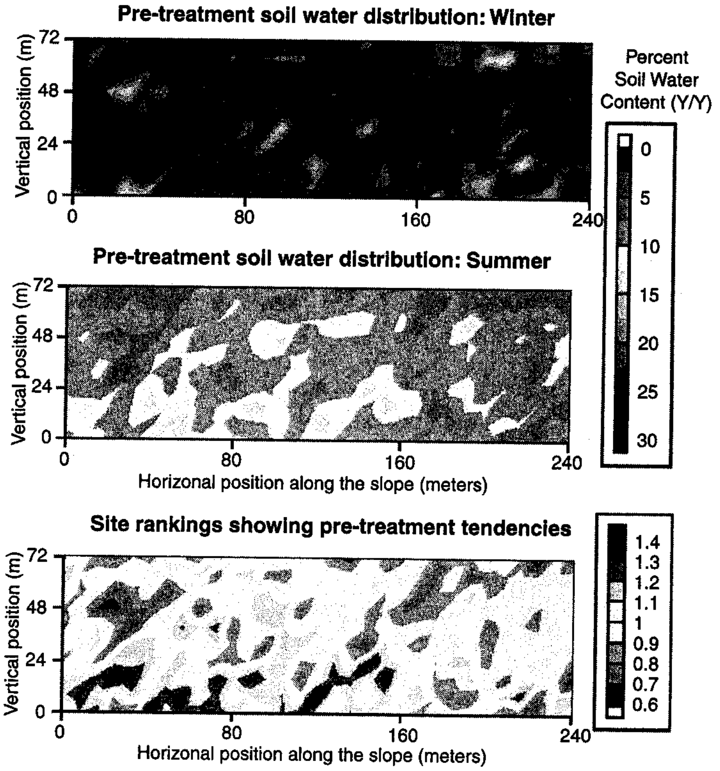

FIGURE 23.2. Winter and summer soil water content (% v/v) across the Walker Branch Throughfall Displacement Experiment area (Hanson et al. 1995) prior to the initiation of treatments (top two graphs) shown together with a contour plot of the derived covariate rankings (see Equation 23.4) for each of the measurement locations. Rankings greater than or less than one correspond to wetter versus drier than average pretreatment measurement positions.

among the individual rod pairs located 8 m apart. To evaluate this assumption, they constructed semivariograms (Turner et al. 1991) based on TDR measurements of soil water content at a 0.15-m spacing along both vertical and horizontal transects within the TDE area and demonstrated that beyond 4 to 5 m the individual soil water measurements could be considered independent.

Collection of Adequate Weather Data

All large-scale manipulation studies must collect adequate weather data to allow for the evaluation of impacts of the treatment infrastructure on uncontrolled environmental variables (i.e., air temperature, humidity). A complete set of variables to be monitored should include the following: incoming rainfall, irradiance, photosynthetic photon flux density, air temperature, and relative humidity or dewpoint. Understory climate data should also include photosynthetically active radiation (PAR) at ~1.5 m, air temperature, soil temperatures (multiple depths), and relative humidity. Collecting weather data at an hourly resolution is recommended, as many current process models of forest stand or ecosystem function demand this level of time resolution of weather input data sets.

Confounding Issues

Any experimental design involves compromises between ideal conditions and logistical reality. Gundersen (1995) discusses some of the common unintended consequences of large-scale manipulation studies in detail. Gundersen concludes that large manipulations often lead to modified microclimatic conditions (i.e., light, temperature, and humidity) due to the presence of experimental structures. Those studies using complete understory roofs (near 100% interception) do show temperature differences between roofed and control plots (Gundersen et al. 1995), but the sign of the differences is seasonally dependent. In the TDE, Hanson et al. (1995, 1998) originally anticipated that the presence of the troughs, gutters, and pipes might act as a radiation barrier or thermal blanket during periods of incomplete canopy leaf coverage and lead to changes in the understory microclimate. However, they found little evidence of any changes in air or soil (10 cm) temperatures during the growing season when the canopy is fully leafed out. Large gaps between collection troughs in the study design of the TDE probably allowed for adequate turnover and circulation of air around the trough infrastructure. Fay et al. (in press) found that soil temperatures under their grassland roofs were elevated 1.2 to 1.8°C over ambient conditions, and attributed the temperature increase to reduced nighttime radiative loss. The grassland roofs also reduced radiation reaching the plant canopy, and unroofed control plots were incorporated into the experimental design to assess the long-term impact of the altered light environment.

Unintentional modifications of rainfall chemical inputs also often accompany large-scale water manipulations. Chemicals derived from atmospheric dry and wet deposition and from canopy leaching are normally transferred to the forest floor in throughfall. In the attempt to modify the water budget of forest stands using understory troughs (Hanson et al. 1995) or roofs (Beier et al. 1995; Fay et al., in press; Gundersen et al. 1995; Rasmussen et al. 1995), unavoidable chemical transfers are also made. Rasmussen et al. (1995) showed that treatments in which 100% of the intercepted throughfall was extracted also removed significant potassium from the site, and they concluded that such a change would accumulate and become biologically significant over time. Hanson et al. (1998) stated that some changes in chemical inputs due to ±33% throughfall alterations on their upland oak site were taking place, but concluded that the biological impact for their system would be minimal. Even if the anticipated level of biological response to small changes in chemical inputs/outputs resulting from an experimental manipulation is expected to be small, some measurements of the level of chemical transfers taking place should be included.

Plot Size and Edge Effects

Small-scale water manipulation studies having manipulated areas less than 50 m^2 (Bréda et al. 1993, 1995; Fay et al., in press; Holstener-Jørgensen 1994) often use belowground barriers to root and water migration to control edge effects. While this can be an effective and appropriate solution, it can also generate experimental artifacts for studies of large plants. Root barriers may reduce the "true" rooting volume and lead to unintended changes in root/shoot relationships of large trees. In experiments without barriers, the issue of water migration between plots and root growth beyond plot boundaries is a serious potential problem. Hanson et al. (1995, 1998) addressed this issue by choosing very large plots with predefined buffer zones to allow for potential overlap of water or roots. During the course of their experiment, incidental treefalls within treated plots showed that the effective rooting area under a tree was highly correlated with each tree's crown spread. This observation suggests that a conservative approach for edge effects would be to allow a minimum of two mean crown widths between water manipulation plots. However, this "rule-of-thumb" should not substitute for good surveys of the water distribution patterns throughout any large-scale water manipulation study.

Statistical Replication

Because of costs and logistics associated with stand- or catchment-level manipulation experiments, true replication is often very limited or lacking in large-scale water manipulation experiments. This lack of replication leads to the unfortunate consequence of researchers having to resort to subsampling within treated areas or "pseudoreplication" (Eberhardt and Thomas 1991). Recognizing pseudoreplication in any large-scale manipulation study design is critical (Hurlbert 1984). Without this recognition, simple differences in site characteristics might be overlooked and be totally confounded with the interpretation of the treatment response.

The practical and scientific need for large contiguous albeit unreplicated water manipulation structures must be preceded by serious evaluation of the uniformity of the pretreatment site variables (i.e., soil type and vegetation distribution, slope, etc.). Although unreplicated experimental designs are clearly not ideal, pseudoreplication has been recognized as a reasonable limitation and an acceptable approach when costly experimental designs are being initiated for answering scientific questions that can not be addressed at smaller scales (Eberhardt and Thomas 1991). Eberhardt and Thomas (1991) recommend that unreplicated experiments be supported by adequate sampling of site environmental parameters (including climatic conditions), comparable ambient areas, and pretreatment observation of critical variables.

Conclusions

Large-scale water manipulation experiments represent the only logical choice for scientific questions demanding an understanding of integrated responses of plants and soils in a natural microclimate. Large-scale manipulations were defined as field experiments that are of sufficient size and complexity to handle questions of individual plant response, interplant interactions, as well as stand-level carbon, water, and nutrient cycling responses. Because large-scale manipulations are intended to retain all features of natural forest stands or ecosystems except those being manipulated (i.e., precipitation inputs), extreme care must go into the planning and design of the experimental approach so that normal physical, chemical, and climatic features of the forests or ecosystems are retained.

A commitment to multi-year maintenance and operation of large-scale water manipulation facilities should be demonstrated during the planning and design of such studies. Maintaining large-scale manipulations over multiple years minimizes the initial costs of construction to levels that are comparable to more traditional experimental designs. Multi-year studies also provide an opportunity to see the impacts of a given manipulation against natural year-to-year variations in weather, thus expanding the scope of the planned manipulations. Finally, it is important to understand that sustained treatments on large-scale water manipulation studies may be the only way that we can detect responses that are normally manifested only slowly in a natural ecosystem (e.g., changes in stored carbohydrates or nutrient cycling processes).

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