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The Effect of a Prescribed Burn in Southwestern Ponderosa Pine on Organic Matter and Nutrients in Woody Debris and Forest Floor

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ABSTRACT. After 100 years of fire exclusion, controlled burning in the fall was used as a first step in the reintroduction of periodic burning in a southwestern ponderosa pine ecosystem near Flagstaff, Arizona, U.S.A. Organic matter storage in woody debris was decreased 63 percent from 2,325 g/m^2 to 869 g/m^2, with a disproportionate (99 percent) decline in the large, rotten wood. Nutrient storage in the woody debris decreased by 80 percent for N, 62 percent for P, 70 percent for Ca, 71 percent for Mg, and 74 percent for K. Forest floor storages were less drastically affected, with organic matter content declining 37 percent from 3,170 g/m^2 to 1,990 g/m^2 immediately after burning. Nutrient content of the forest floor was not significantly affected by burning due, in part, to the transfer of nutrients from woody debris to the forest floor. By 7 months after burning, the forest floor had declined by an additional 440 g/m^2 of organic matter, most likely from microbial mineralization. Also during this period forest floor storages for all nutrients declined significantly, except K which was unchanged. Mg exhibited the greatest proportional decline (40 percent), followed by N, P, and Ca, all of which decreased by approximately 25 percent. Numerous potential benefits to productivity may be associated with this prescribed burn—reduced fire hazard, accelerated nutrient mobilization, and reduced forest floor interception of precipitation. FOREST SCI. 30:183–192.

ADDITIONAL KEY WORDS: *Pinus ponderosa*, fire effects, prescribed burning, nutrient cycling.

ANY SITUATION in which forest litter steadily accumulates on the surface of the mineral soil is undesirable for forest management because nutrient cycles develop progressively slower rates of turnover (Miller and others 1976) and fire hazards increase. One such situation is the exclusion of fire in southwestern ponderosa pine (*Pinus ponderosa* Laws.).

Before European settlement of northern Arizona in the 1860s, periodic natural low intensity fires in the surrounding ponderosa pine forest occurred at frequent intervals, perhaps every 2 to 12 years (Weaver 1951, Cooper 1960, Biswell 1972, and Dieterich 1980). Several factors associated with European settlement caused a reduction in fire frequency and size (Cooper 1960). Roads and trails broke up fuel continuity. Domestic livestock grazing, especially overgrazing by cattle and

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sheep in the late 1800s, greatly reduced herbaceous fuels, and through trampling, further reduced fuel structure and continuity. In fact, many of the early arguments for heavy grazing were based on the assumption that heavy grazing reduced forest fire frequency (Cooper 1960). Fire exclusion was the pricipal duty of early foresters in the Southwest beginning with active fire suppression in the Flagstaff area as early as 1908.

Forest management problems ascribed to fire exclusion in ponderosa pine include: (1) overstocked sapling patches, (2) reduced growth, (3) stagnated nutrient cycles, (4) increased disease, insect infestation, and parasites (e.g., root rot, bark beetle, dwarf mistletoe), (5) decreased seedling establishment, (6) decreased forage quality and quantity, (7) increased fuel loading, (8) increased vertical fuel continuity due to dense sapling patches, and (9) increased severity and destructive potential of wildfires (Cooper 1960, Biswell 1972, Weaver 1974, and others). Because of the exponential increase in wildfire severity over the past three decades (Barrows[1]), forest managers are turning to prescribed fire to reduce the heavy fuel loads which have accumulated in the past 50 to 100 years.

Although prescribed burning is being widely used in this forest type, very little is known about effects on organic matter and nutrient storages. This paper reports changes in forest floor and woody debris organic matter and nutrient storages during the first year following initiation of a planned long-term study of the effects of periodic burning on ecosystem physiology in ponderosa pine in northern Arizona.

METHODS

Site Description.—The study site is located in the Fort Valley Experimental Forest at the base of the San Francisco Peaks approximately 10 km northwest of Flagstaff, Arizona, at an elevation of 2,195–2,255 m. The climate is characterized as subhumid to humid with cool temperatures and deficient early summer moisture (Schubert 1974). Mean annual temperature in Flagstaff is 7.5°C; the mean annual precipitation is 56.7 cm (Schubert 1974) with approximately one-half of the precipitation falling as snow. The average frost-free growing season is 135 days (Schubert 1974).

The soils are volcanic in origin with basalt and cinder parent materials. They are tentatively classified as Brolliar stony clay loam, a fine montmorillonitic, frigid, Typic, Argiboroll by an adjacent soil survey (Meurisse[2]).

The study area is dominated by an uneven-aged forest, in small even-aged groups, typical of virgin ponderosa pine. The predominant size class is 20 to 50 cm dbh (diameter at breast height) (pole-sized trees), with scattered groups of 5–20 trees over 200 yr old and ranging from 60–120 cm dbh (sawtimber trees), and dense "doghair" thickets of sapling-sized trees ranging from 2.5 to 7.6 cm dbh.

There has been no harvesting activity on the study site, except for localized fuelwood cutting of dead trees near roads. Based on fire scar analysis, the last fire on the study area occurred in 1876 but before that, fires occurred periodically at an average interval of approximately 2 years (Dieterich 1980).

Twenty-seven contiguous one hectare plots were established in the study area in 1976. Six treatments (periodic burning every 1, 2, 4, 6, 8, and 10 years) with three replicates each plus controls and extra unburned plots were randomly assigned to each plot. Each plot has a 1.5 m fireline plowed around its perimeter.

[1] Barrows, Jack S. (unpublished report). Lightning fires in southwestern forests. Final report for agreement 16-568-CA with Rocky Mountain Forest and Range Exp. Stn., Fort Collins, Colo. May 1978.

[2] Meurisse, Robert T. (unpublished report). Soils Report, San Francisco Peaks Area, Elden and Flagstaff Ranger Districts, Coconino National Forest. December 1971.

Within each plot 5 circular 0.04 ha subplots have been established. On these subplots dbh was recorded to the nearest cm for each tree. The one year interval plots reported in this paper had an average of 2,454 trees per hectare with an average dbh of 7.5 cm. Basal area was 43.8 m^2/ha.

Woody Debris Sampling.—Woody debris 2.54 cm or less in diameter was sampled by collecting material on 756 systematically located 0.093 m^2 (1 ft^2) plots and separating it into two classes (0–0.63 cm and 0.64–2.53). The planar intercept technique (Brown 1974) as modified for southwestern ponderosa pine (Sackett 1979) was used for inventorying woody debris greater than 2.55 cm in diameter before and immediately after burning. The method involves counting woody material (2.55–7.62 cm) that intersects vertical sampling planes and measuring the diameters of pieces greater than 7.62 cm in diameter for two decay classes (sound and rotten). Rotten is defined as any woody material that can be easily kicked apart. The piece counts and diameters are used to calculate weights per unit area by regression relationships. The planar intercept technique was not used for the woody debris smaller than 2.55 cm because it is much less accurate for fine material.

Separate samples of each size class were collected along systematically located transects for nutrient analysis. Five composite samples consisting of material collected from four individual locations each were analyzed for each of the following diameter size classes:

1. 0–0.64 cm
2. 0.65–2.54 cm
3. 2.55–7.62 cm
4. >7.62 cm sound
5. >7.62 cm rotten

Because of the extreme variation in woody debris associated with its markedly clumped distribution, it was necessary to include the data from all 18 plots burned in 1976 (instead of just those designed to have annual fires) to obtain a reasonable estimate of woody debris changes. However, caution must be used in interpreting woody debris organic matter and nutrient budgets since wood litter fall is so erratic and localized (see Nye 1961).

Forest Floor Sampling.—Twenty 0.093 m^2 samples of forest floor material were collected systematically (four from each of the five circular basal area plots) from each of the three 1-year burn plots (n = 60) before burning (October 28–November 2, 1976), immediately after burning (November 6–7, 1976), and 7 months after burning (June 1977). Within each 0.093 m^2 quadrat all material, including ash on post burn samples, was collected. The four samples from each of the basal area plots were composited into one sample for organic matter and chemical analysis.

Chemical Analysis.—Samples were ground in a hammer mill, subsampled, and then ground in a Wiley mill to pass a 1.3 mm sieve (20 mesh). Organic matter content was determined by loss on ignition (500°C, 4h) of a 5 g sample. Nutrient content was determined using a selenium-catalyzed, sulfuric acid, hydrogen peroxide, lithium sulfate digestion of a 1.5 g sample (Parkinson and Allen 1975). Calcium, magnesium, and potassium concentrations were determined by atomic absorption spectrophotometry. Nitrogen and phosphorus were determined colorimetrically using the Technicon AutoAnalyzer (Technicon 1974). All data are reported on an ovendry (80°C, constant weight) basis.

Fire Description.—Rainfall on the study area was below normal during the late summer and fall prior to the initial fires in 1976. On October 21, 0.69 cm of rain

TABLE 1. Changes, by diameter size class, in the organic matter and nutrient content of woody debris following a prescribed fire in ponderosa pine.

Organic matter, nutrient	0–0.63 cm[a]		0.64–2.54 cm		2.55–7.62 cm	
	Before	After	Before	After	Before	After
	g/m²					
Organic matter	199.0	67.8	329.0	249.0	203.0	93.0
N	.145	.089	.422	.203	.259	.120
P	.014	.008	.051	.024	.035	.016
Ca	.243	.150	.650	.312	.375	.174
Mg	.045	.028	.122	.059	.082	.038
K	.022	.013	.034	.016	.040	.019
	>7.62 cm sound		>7.62 cm rotten		Total	
	Before	After	Before	After	Before	After
	g/m²					
Organic matter	525.0	450.0	1,070.0	10.0	2,325.0	869.0
N	.492	.422	3.120	.033	4.438	.867
P	.086	.074	.145	.002	.330	.124
Ca	.605	.518	2.708	.028	4.581	1.182
Mg	.192	.165	.584	.006	1.025	.296
K	.225	.193	.498	.005	.819	.246

[a] Diameter size class.

fell; 4 days later, 0.08 cm was recorded with no other recordable precipitation until several weeks after the plots were burned. On the evening of November 5, the study area was burned. Ignition began at 5:30 p.m. and continued until 11:00 p.m.

Surface needle (L-layer) moisture content increased from 8 to 12 percent during the night as temperatures fell. Similarly, lower layers (F- and H-layers) of the forest floor increased from 10 to 19 percent moisture content. Temperatures in the stand dropped from 15°C at 5:30 p.m. to 3°C at midnight, when the flaming combustion of the forest floor was complete. During the same time period relative humidity increased from 21 to 48 percent. Initially backing fires were used but when they no longer carried well, short (9–12 m between strips) strip head fires were used. Rates of spread were no greater than 3.7 m per minute, generally ranging from 1.2 to 1.8 m per minute. Flame lengths in litter fuels seldom exceeded 40 cm. Glowing combustion in deep duff fuel continued for 2–3 days. Some large woody debris and stumps smoldered for as long as 4 weeks.

Results

Woody Debris.—Overall, burning decreased the organic matter stored in woody debris 63 percent (Table 1). The largest size class (>7.62 cm) had strikingly different results depending on its decay condition. The large sound woody material decreased by only 14 percent while the rotten material was almost completely eliminated (a 99 percent reduction).

As expected, nutrient concentrations in sound woody debris were inversely related to diameter (Table 2). The large rotten class had significantly higher ($p < 0.05$) nutrient concentrations than the sound class for all nutrients except P. The N concentration ratio between sound and rotten wood was especially steep being three times higher in rotten material.

TABLE 2. Nutrient concentration in ponderosa pine woody debris, by diameter size class. Data are means of 5 composites of 4 samples each.

Diameter size class	N	P	Ca	Mg	K
	Percent of ovendry weight				
0–0.63 cm	0.279	0.026	0.468	0.086	0.042
0.64–2.54 cm	.211	.025	.325	.061	.017
2.55–7.62 cm	.143	.020	.207	.045	.022
>7.62 cm sound	.105	.018	.129	.041	.048
>7.62 cm rotten	.326	.015	.283	.061	.052

The nutrient content of the woody debris decreased as a result of the burn by 80 percent for N, 62 percent for P, 70 percent for Ca, 71 percent for Mg, and 74 percent for K (Table 1).

Forest Floor.—The organic matter content of the forest floor declined by 1,180 g/m^2, a 37 percent reduction as a direct result of burning (Table 3). Seven months after the prescribed fire the forest floor content had declined by an additional 440 g/m^2. Thus by June following burning the net effect was a 51 percent reduction in forest floor organic matter content.

Nutrient content of the forest floor was not significantly ($p = 0.05$) affected when sampled the first month after burning (Table 3). However by 7 months after burning all nutrients except K had decreased significantly. Mg exhibited the greatest proportional decline, approximately 40 percent (10.1 g/m^2). Declines in N (10.8 g/m^2), P (1.57 g/m^2), and Ca (11.2 g/m^2) were approximately 25 percent.

Discussion

The reintroduction of understory burning after 100 years of fuel accumulation caused substantial changes in surface organic matter and nutrient storages. In general, organic matter storages were greatly reduced; nutrient storages were somewhat less affected.

Changes in Organic Matter Storages.—Comparison of our preburn woody debris and forest floor weights (Tables 1 and 3) with the results from an extensive survey of 62 undisturbed ponderosa pine stands in Arizona, New Mexico, and southern

TABLE 3. Changes in organic matter and nutrient content of the forest floor following a prescribed fire in ponderosa pine. Data are mean/standard error, n *= 15 composites of 4 each.*

Measurement period	Organic matter	N	P	Ca	Mg	K
	g/m^2					
Before burning (October, 1976)	3,170 / 217	46.3 / 3.83	6.33 / .307	55.7 / 3.91	27.7 / 1.75	14.9 / .92
After burning (November, 1976)	1,990 / 145	41.9 / 3.38	6.53 / .509	52.8 / 6.95	22.9 / 2.08	16.8 / .84
Seven months after burning (June, 1977)	1,550 / 133	31.1 / 3.14	4.96 / .363	41.6 / 4.92	12.8 / 1.00	14.4 / 1.19

Colorado (Sackett 1979) shows that surface organic matter storages on our study area are typical of southwestern ponderosa pine stands.

Information is scant regarding natural woody debris reduction by burning in southwestern ponderosa pine. Although there are some data concerning effects of slash burning (Klemmedson 1976), we could find only one paper with quantitative data concerning natural woody debris reduction by prescribed fire in southwestern ponderosa pine. Gaines and others (1958) found reductions of approximately 50–75 percent in woody debris for two fall prescribed burns on the Fort Apache Indian Reservation, Arizona. However, comparison of these findings with our results is tenuous due to differences in both site and stand characteristics as well as burning conditions.

Our observed 63 percent decline (1,460 g/m^2) in woody debris by burning represents a major change in surface organic matter storage. The disproportionate decrease (99 percent) in the large, rotten class (Table 1) is particularly striking. This phenomenon may be explained by the higher lignin-to-cellulose ratio and larger surface-to-volume particle size of rotten material in conjunction with the ease of ignition and completeness of glowing combustion characteristic of such lignin-laden materials (Brown and Davis 1973, Rothermel 1976).

Organic matter storages in the forest floor were less drastically reduced by the prescribed fire. The 37 percent reduction (1,180 g/m^2) is similar to that found in other studies of prescribed burning in southwestern ponderosa pine. Davis and others (1968) found a 30 percent reduction in forest floor weight in one area and a 36 percent reduction in another following a 1964 prescribed fire in pole-sized ponderosa pine in Arizona. Wagle and Eakle (1979) found a 28 percent reduction in forest floor weight following a prescribed fire in the White Mountains of central Arizona.

An earlier paper (Sackett 1980) reported the results of an operational level fuel survey designed to characterize the entire area on the same study site and the same fire as reported in the present paper. This fuel survey included sapling sites which had slightly less forest floor mass, as well as sawtimber dominated sites which had three to four times as much forest floor mass (13,000 g/m^2) as the pole dominated sites reported in the present paper.

The forest floor under these sawtimber stands was completely consumed (Sackett 1980). Thus for the entire study area (all canopy cover types) there was greater reduction (63 percent) in the forest floor than the 37 percent reduction in the pole dominated sites reported in the present paper.

During the 7 months following the prescribed fire the forest floor organic matter decreased by an additional 440 g/m^2 even though needle cast during the fall and spring following burning added considerable litter to the forest floor. This additional decline is most likely due to microbial activity. Published decay rates (k) for ponderosa pine range from 1.46 to 2.93 percent per year, among the slowest for any forest type (Jenny and others 1949, Olson 1963). Multiplying preburn forest floor organic matter content (3,170 g/m^2, Table 3) by these rates gives 46–93 g/m^2 of organic matter decayed in 12 months. Thus our observed 440 g/m^2 loss in 7 months represents almost a 10 fold increase in decomposition. Results from several other studies suggest increased decay following burning in southwestern ponderosa pine. Fuller and others (1955) observed increased microbial activity following a prescribed burn as did Bennett (1974). Klemmedson (1975) found a 95 percent reduction in weight of residual unburned needles 2 years after a slash burn.

Several potential forest management benefits are likely from this reduction in forest floor mass. The decline in forest floor and woody debris considerably reduces the extreme fire hazard associated with the heavy fuel buildup of the past 100 years. Furthermore, reductions in forest floor organic matter should improve moisture relations on the site. Aldon (1968) found a strong linear relationship between evaporation loss due to forest floor interception and forest floor weight in pole-size ponderosa pine near our study area. Thus our observed decreases in forest floor weight should reduce interception losses thereby allowing more moisture to reach the mineral soil. Supporting this conclusion is the observation by Ryan[3] of significantly higher soil moisture content on burned versus unburned sites on our study area during the summer, 1977.

Changes in Nutrient Storages.—Our results for nutrient storage in surface organic matter are in general agreement with existing published accounts. Klemmedson (1975 and 1976) found 22.7–50.2 g/m^2 of nitrogen in the forest floor and small woody debris of pole-size ponderosa pine near our study area. Welch and Klemmedson (1975) reported an average of 43 g/m^2 of nitrogen in the litter for several pole-size ponderosa pine plots in northern Arizona. We could not find data for Ca, Mg, or K storages in surface organic litter for southwestern ponderosa pine. However, Wooldridge (1970) working in ponderosa pine in central Washington found 60.5 g/m^2 of N, 8.9 g/m^2 of P, and 22.9 g/m^2 of K. Nissley and others (1980) found nutrient storage in the forest floor for several unburned stands of ponderosa pine in central Oregon to be 20–28 g/m^2 of N, 1.9–2.5 g/m^2 of P, 14–19 g/m^2 of Ca, 2.3–2.8 g/m^2 of Mg, and 2.6–3.7 g/m^2 of K. The generally lower forest floor nutrient contents reported by Nissley and others (1980) when compared to ours are primarily a consequence of much lower organic matter storages in the forest floor on their sites rather than lower nutrient concentrations. We could find no data regarding nutrient storages in natural woody debris in ponderosa pine. Klemmedson (1976) reported 3.8–4.0 g/m^2 of N in branches and boles in logging slash piles for two ponderosa pine stands near our study area.

The lack of a significant decline in nutrient storage in the forest floor immediately after burning (Table 3) most likely results from the selective burning of surface layers low in nutrients, the L layer in particular, and the deposition of woody debris ash, which after burning would be sampled as fine material in the forest floor. Thus nutrient losses directly from burning (e.g., nitrogen volatilization) do not appear to be a problem under our burning conditions. The 20–40 percent decline in forest floor nutrient storages for all nutrients except potassium during the 7 months following burning (Table 3) represents a substantial decrease. However, increases in ammonium and nitrate in the mineral soil (Ryan[3]) on our site suggest much of the nutrients from the forest floor may be leached into the mineral soil.

There are no other data available concerning nutrient storage impacts of prescribed understory burning in southwestern ponderosa pine. However, Klemmedson (1976) found a decline in nitrogen in the forest floor following burning of piled slash for two ponderosa pine sites near our study area. An earlier study by Klemmedson and others (1962) in ponderosa pine in northern California showed a 13.9 g/m^2 decline in N content of forest floor and slash following burning. Nissley and others (1980) found an 11.0 g/m^2 decrease in N; a 1 g/m^2 increase in each of P, Mg, and K; and a 20 g/m^2 decrease in Ca storages in forest floor and understory vegetation following prescribed burning in ponderosa pine in central Oregon.

The direct mineralization of nutrients from surface organic matter in conjunction with those released during subsequent microbial processes probably result in an overall improvement of nutrient availability in the ponderosa pine ecosystem. The mineralization of the forest floor through microbial processes may be espe-

[3] Ryan, Michael G. 1978. The effect of prescribed burning in ponderosa pine on the inorganic nitrogen content of the soil. MSF thesis, Northern Ariz Univ, Flagstaff. 54 p.

cially important since nutrients mobilized in this manner are released more gradually than the sudden surge brought about by fire. Furthermore, nitrogen released during burning often results in considerable volatilization representing a net loss to the ecosystem, whereas nitrogen released by accelerated decomposition following burning would be in a form readily absorbed by plants or retained on exchange sites.

Numerous authors have attributed primary production increases following burning to improved nutrient relations. Pearson and others (1972) inferred that higher nutrient availability was primarily responsible for increased radial growth of ponderosa pine and increased understory production and nutrient content following a wildfire near our study area. Vlamis and others (1959) found higher production of lettuce and ponderosa pine seedlings in a bioassay of burned sites versus controls in California ponderosa pine. The increased production was due to higher nitrogen availability in the soils from the burned areas. Using the same techniques, Wagle and Kitchen (1972) found increased nitrogen availability and growth in soils from recently burned ponderosa pine stands in central Arizona. Ffolliott and others (1977) reported a 13 fold increase in the herbage production that lasted for at least 11 years after a prescribed fire in ponderosa pine south of our study area. Understory production on our study area was significantly higher on burned plots versus controls during the first growing season following the fire (Harris and Covington 1983). Nutrient concentrations in understory plants were also higher on burned sites.

Although improved nutrient availability may be responsible for much of the observed increases in primary production following burning in ponderosa pine, other possible explanations such as better moisture relations, decreased allelopathy (see Jameson 1968, Lodhi and Killingbeck 1980), and extended growing season (because of warmer soil temperatures and earlier thaw in the spring, cf. Bissett and Parkinson (1980)) should not be ignored.

Conclusion

After one hundred years of fire exclusion from our study site, prescribed burning appears to have alleviated some of the problems attributed to the elimination of periodic understory burning. Both woody debris and forest floor fuels were substantially reduced thus increasing the resistance of the ecosystem to damage by wildfire and reducing forest floor interception and evaporation of precipitation. Burning released much of the nutrients bound in the surface organic storages improving nutrient conditions for both plants remaining after the fire and newly germinating seedlings. Although some nitrogen was lost to volatilization, these losses appear to be minimal.

Of particular interest is the apparent microbial mineralization which occurred during the first 7 months after burning. Forest floor fuels were further reduced by this means, but without the risk of nutrient volatilization associated with fuel reduction by burning.

The reintroduction of prescribed understory burning in ponderosa pine holds considerable promise not only as a means of controlling fuel loadings, but also through manipulating surface litter, of controlling nutrient and moisture relations as well as reducing allelopathic effects, thereby improving ecosystem productivity.

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Improvement of Forest Biomass

Edited by P. K. Khoshla. 1982. Indian Society of Tree Scientists, Solan, India. 472 pages. $40.00.

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India has been the source of many ideas that have been incorporated into U.S. forestry. The classical mensuration methods used in North America, for example, were developed in the last century by British, German, and Indian foresters for the Himalayan species. Plantation teak and many other innovations started in India. Perhaps India's most significant contribution, however, is the pioneering development of social forestry—the involvement of rural people in growing fuelwood, fodder, and small timbers on farms, canal and roadsides, commonlands and wastelands. The managerial, silvicultural, and social-process techniques developed in India are being adapted in other developing nations of Asia, Africa, and Latin America.

Improvement of Forest Biomass is a collection of scientific papers that represent the results of research largely directed by the information needs of social forestry and its close relative agroforestry. The volume is impressive because of both the diversity and good quality of contributions. It is the first major effort by the Indian Society of Tree Scientists and honored Dr. S. Kedharnath, a prominent forest geneticist.

The volume opens with a keynote address by P. N. Mehra on "Fruit and Forest Tree Breeding through Tissue Culture" and a discussion of "Plus Tree Selection" by Dr. Kedharnath. While both are summary papers, obviously the "state of the arts" in India is essentially the same as elsewhere, but the species are numerous and often quite exotic by north temperate standards. The remaining papers are divided into seven sections: variation and breeding of trees, selection practices in forestry, propagation of trees, improvement of fruits other than wood, improvement of agroforestry/energy resources, tree biology, and pests and pathogens of trees.

The section on breeding gives evidence of a strong, productive applied research community. With at least 100 distinct forest ecosystems, over 5,000 woody plant species plus