USE OF NITROGEN-FIXING PLANTS TO IMPROVE AND MAINTAIN PRODUCTIVITY OF FOREST SOILS

by

Sharon G. Haines and Dean S. DeBell

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IMPACT OF INTENSIVE HARVESTING ON FOREST NUTRIENT CYCLING

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USE OF NITROGEN-FIXING PLANTS TO IMPROVE AND MAINTAIN PRODUCTIVITY OF FOREST SOILS

Sharon G. Haines and Dean S. DeBell

Abstract.--Nitrogen-fixing plants can be used alone, in mixture with, or in rotation with other crop species. Much of the information required for effective use of nitrogen-fixing species in forestry is lacking, and only limited applications are immediately possible. This paper evaluates and synthesizes the available literature with respect to potential applications in forest management. Six cropping systems are proposed, and species that seem adaptable for each system are identified.

Additional keywords: legumes, actinomycete-nodulated angiosperms, crop rotations, species mixtures, biological nitrogen fixation.

INTRODUCTION

Forest soils are characteristically low in available nitrogen, and therefore tree growth is often less than optimal, even in unmanaged ecosystems. This situation can be greatly magnified in those ecosystems which are intensively managed for fiber or timber production. Silvicultural practices that affect available soil nitrogen can have a major impact on site productivity. The degree of impact will vary with the silvicultural practice itself, as well as with other preventative or ameliorative measures taken to temper any negative effects on productivity. Concern about accelerated nutrient removal as a result of intensified harvesting techniques has been widespread (Keever 1966, White 1974). Removal of nitrogen, a nutrient already in short supply, has stimulated debate about subsequent soil productivity (Bormann et al. 1967). Concern was for nitrogen removed from the site in harvested biomass (Boyle et al. 1973), as well as for leaching losses following accelerated organic matter decomposition (Cole and Gessel 1965). The impact of such losses can be alleviated by addition of nitrogen and organic matter to the system through use of nitrogen-fixing species.

The most obvious beneficial effect of biological fixation on forest nutrient cycling is the addition of nitrogen. Other potential benefits may be as or more important. For example, nitrogen-
fixing species add organic matter which may increase the availability of other nutrients, as well as nitrogen. The use of nitrogen-fixing plants can also improve the soil physical environment by decreasing bulk density and increasing moisture retention and thereby benefit companion and subsequent tree crops. Disease control and reduced competition from non-crop plants are hypothesized benefits. Certain species have potential for erosion control and prevention of topsoil losses following severe site disturbances. Leffel (1973) speculates that a certain degree of allelopathic weed control may be obtained when legumes with high alkaloid content decompose in the soil.

Historically, nitrogen-fixing plants (viz., legumes) have been used in agriculture for forage crops and green-manures, as well as food crops. Widespread use of legumes has been attributed to several factors: (i) Legumes are "soil builders", improve tilth, and help prevent erosion; (ii) They increase soil nitrogen and organic matter levels when turned under as green manures; (iii) Legumes favorably influence soil microorganisms responsible for the efficient decay of organic matter; (iv) Legumes utilize atmospheric nitrogen which is unavailable to nonlegumes (with the notable exception of some nonleguminous nitrogen-fixing species); (v) Legumes store large quantities of protein in plant tissue and make high quality forage for livestock and wildlife.

The utility of nitrogen-fixing plants in forestry can be based on similar reasoning. Moreover, most of the above factors appear to apply equally well to the actinomycete-nodulated angiosperms which are common in forest ecosystems. Specific objectives for using such species in a total forest management program include: (i) restoration of degraded sites (e.g., mine spoils, severe erosion, severe burning); (ii) amelioration or improvement of sites where some growth factor (primarily nitrogen) is naturally limiting; and (iii) preventative maintenance on sites where growth is currently at adequate or optimal levels.

Often consideration of potential uses of nitrogen-fixing plants is limited to comparing biological nitrogen fixation with chemical fertilizer application. Economics of chemical fertilization appear more favorable at this time than supplying nitrogen via biological means (Atkinson and Hamilton 1978, Atkinson et al. 1979), but future costs and availability of nitrogen fertilizers are uncertain. Although nitrogen additions are generally the major reason for considering use of nitrogen-fixing plants, the previously mentioned benefits with respect to other productivity factors should not be ignored. If the nitrogen-fixing species is the principal crop, there also may be advantages with respect to levels of management needed to insure a successful crop. In addition, there may be advantages with respect to other forest uses or problems (e.g., cover and food for wildlife). Thus, many factors in addition to nitrogen merit some consideration in assessing the potential for use of nitrogen-fixing plants.
At the outset, the reader should be forewarned that far more people have philosophized about potential uses of nitrogen-fixing species in forestry than have established well-designed research studies or attempted operational use of such plants. Most of the forestry literature deals with opportunistic evaluations of natural occurrences (or unplanned comparisons in man-made situations) coupled with speculation regarding future potential for planned use of the nitrogen-fixing species in management programs. This paper is no exception. In fact, the purpose is to evaluate and synthesize the available literature with a view toward identifying some promising species and potential cropping systems for use in forest management. Finally, factors that may limit application will be discussed, as well as research needed if speculated opportunities are to be realized in actual management programs.

**NITROGEN-FIXING PLANTS FOR USE IN FORESTRY**

Based on their estimated nitrogen-fixation rates and their adaptation to forest environments, legumes and actinomycete-nodulated angiosperms appear to have the greatest potential for use in forest management. These plants also are the only ones which offer any possibility for near-term practical application. Use of blue-green algae and symbiotic algal associations in forestry is at best decades away. Even then, rates of nitrogen fixation for the latter are low and any use would probably be confined primarily to wetland ecosystems. Thus, the scope of this paper will be restricted to use of leguminous and actinomycete-nodulated angiospermous nitrogen-fixing plants.

**Legumes**

Approximately 500 genera of legumes containing 11,000 species have been identified, with 4,000 species native to North America (Fernald 1950). Small (1933) identified 99 genera and 358 species of native or naturalized legumes which occur in southeastern United States forests. Obviously, many of these species have little applicability for forestry purposes; however, a number of species may prove suitable if satisfactory management techniques can be developed. For purposes of this discussion, legumes will be categorized as: (i) agronomically important legumes with potential for forestry use, and (ii) native or naturalized legumes known to occur in temperate forest ecosystems.

Legumes growing on agricultural soils have been studied extensively. Nutrient requirements of agronomically important legume species have been determined, as well as those of the Rhizobia bacteria associated with such plants. Intensive breeding programs have developed strains of plants with favorable morphological characteristics and microbial strains which efficiently fix nitrogen. Rates of fixation by legumes on agricultural soils have been relatively well-documented (e.g., Hoveland et al. 1976). Data are unavailable on fixation rates for such species growing on forest soils which are characteristically more acid and less fertile.
Rhizobia that efficiently fix nitrogen in limed, fertilized soils may be almost totally ineffective on forest soils. Without fertilizer, forage type legumes do not make sufficient growth to improve the nitrogen status on infertile forest soils (Jorgensen 1978). Additionally, seeding and fertilization regimes appropriate for agricultural purposes (e.g., forage production) may be inappropriate for forest management objectives.

Selected agriculturally important legumes with potential for forestry use are identified (Table 1). Species included are those few known to be capable of growing on forest soils as a result of direct experimentation. Others were used in research aimed at erosion control along forest roads in the West (Dyrness 1967, 1975; Berglund 1976). Also identified are those species suspected of being valuable because of traits such as tolerance of low fertility and acidic conditions and ability to grow on droughty sites.

While native or naturalized legumes are capable of growing on forest soils, few are known to have management potential on the basis of actual experimental evidence. Genera such as Cassia and Lespedeza, widely used as game foods, are noteworthy exceptions. The first obstacle to be overcome with native and naturalized species is the lack of readily available seed for experimentation. Plans for seed collections from plants growing in the wild must take into consideration the difficulties of finding adequate concentrations of seed-bearing plants which have not been devastated by insects, disease, or adverse weather. Breeding programs for native species cannot be considered until much more information on adaptability and effectiveness in nitrogen accretion is available.

Data are available as to the impact of forest management activities on the frequency and distribution of some native legumes (Stoddard 1936, Cushwa et al. 1970). Little is known about the nitrogen accretion attributable to these species in forest ecosystems. Data are unavailable on benefits of increased stocking levels of native species which tend to occur in low concentrations naturally. Some research on the nutrient quality and digestibility of native legumes has been reported (Short and Epps 1976), as well as the frequency with which these species occur in wildlife diets (Martin et al. 1951). Legume seeds may be the best source of protein and phosphorus among temperate forest forages. Selected native and naturalized legumes are characterized herein (Table 2). Species listed are those identified by Landers (1978) as potentially valuable in temperate forest management.

Actinomycete-nodulated Angiosperms

Actinomycete-nodulated nitrogen-fixing plants have not been cropped nor utilized by man to the extent that legumes have been used in agriculture. Rather interestingly, however, there are reports of use of Alnus and Casuarina (two of the major actinomycete-nodulated genera) in rotational agriculture of Taiwan and New Guinea (Silvester 1977). Nevertheless, it is widely...
Table 1.--Agriculturally important leguminous species having potential utility in forest management systems

<table>
<thead>
<tr>
<th>Species</th>
<th>Site Conditions</th>
<th>Longevity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeschynomone americana L.</td>
<td>wet soils, can tolerate flooded conditions</td>
<td>annual</td>
<td>Hodges et al. (1975)</td>
</tr>
<tr>
<td></td>
<td>following establishment</td>
<td></td>
<td>Moore (1978)</td>
</tr>
<tr>
<td>Centrosema spp.</td>
<td>droughty, relatively infertile soils</td>
<td>perennial</td>
<td>Whyte and Trumble (1953)</td>
</tr>
<tr>
<td>Desmodium canum</td>
<td>moist to well-drained acidic soils</td>
<td>perennial</td>
<td>Wells (1978)</td>
</tr>
<tr>
<td>Lespedeza spp.</td>
<td>can grow on eroded, acid soils which are low in phosphorus</td>
<td>annual or perennial</td>
<td>Wells et al. (1970)</td>
</tr>
<tr>
<td>Lotus corniculatus L.</td>
<td>deep or moderately deep, well-drained loams or clay loams developed on tuffs and breccias</td>
<td>perennial</td>
<td>Dyrness (1967, 1975) Berglund (1976)</td>
</tr>
<tr>
<td>Lupinus angustifolius L.</td>
<td>slightly acid and moderately fertile sandy to loamy soils</td>
<td>annual</td>
<td>Whyte and Trumble (1953) Haines et al. (1979)</td>
</tr>
<tr>
<td>Lupinus hispanicus spp.</td>
<td>poorly to moderately well-drained soils of low fertility</td>
<td>annual</td>
<td>Wells (1978)</td>
</tr>
<tr>
<td>Lupinus luteus Kell.</td>
<td>moderately acid, sandy soils of low fertility</td>
<td>annual</td>
<td>Whyte and Trumble (1953) Haines et al. (1979)</td>
</tr>
<tr>
<td>Medicago sativa L.</td>
<td>deep or moderately deep, well-drained loams or clay loams developed on tuffs and breccias</td>
<td>perennial</td>
<td>Berglund (1976) Miller and Zalunardo (1979)</td>
</tr>
<tr>
<td>Ornithopus spp.</td>
<td>moist, slightly acid, sandy soils of low fertility</td>
<td>annual</td>
<td>Whyte and Trumble (1953)</td>
</tr>
<tr>
<td>Vicia villosa Roth</td>
<td>sandy to loamy soils</td>
<td>annual</td>
<td>Haines et al. (1978) Jorgensen (1978)</td>
</tr>
</tbody>
</table>

Species listed have been tested on forest sites or are known to grow on acidic soils with low fertility.
<table>
<thead>
<tr>
<th>Species</th>
<th>Habitat</th>
<th>Longevity</th>
<th>Growth Form</th>
<th>Typical Length/Height (cm)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ampelopsis brevipedata</em></td>
<td>moist to poorly drained soils</td>
<td>annual</td>
<td>vine</td>
<td>5-20</td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Ampelopsis brevipedata</em></td>
<td>moist to poorly drained soils</td>
<td>perennial</td>
<td>vine</td>
<td>10-30</td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Baptisia spp.</em></td>
<td>excessively drained, sandy soils</td>
<td>perennial</td>
<td>erect</td>
<td>3-15</td>
<td>Cushwa et al. (1970);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Halls et al. (1970);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Cassia spp.</em></td>
<td>moderate to well-drained, sandy soils</td>
<td>annual</td>
<td>erect</td>
<td>1.5-6</td>
<td>Whyte and Trumble (1953);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cushwa et al. (1970);</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Halls et al. (1970);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Centrosema virginianum</em></td>
<td>well-drained soils</td>
<td>perennial</td>
<td>vine</td>
<td>5-15</td>
<td>Whyte and Trumble (1953);</td>
</tr>
<tr>
<td><em>Circaea mariana L.</em></td>
<td>excessively to moderately well-drained, sandy soils</td>
<td>perennial</td>
<td>vine</td>
<td>5-10</td>
<td>Cushwa et al. (1970);</td>
</tr>
<tr>
<td><em>Crotalaria spp.</em></td>
<td>deep or moderately deep, well-drained loams or clay loams</td>
<td>perennial</td>
<td>erect to prostrate</td>
<td>35-50</td>
<td>Gynness (1967, 1975); Miller and Zalunardo (1979);</td>
</tr>
<tr>
<td><em>Crotalaria spp.</em></td>
<td>moderately to well-drained, sandy to loamy soils</td>
<td>annual or perennial</td>
<td>erect to prostrate</td>
<td>1-15</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Cynanchum app.</em></td>
<td>moderately well-drained, sandy soils</td>
<td>perennial</td>
<td>erect or vine</td>
<td>0.4-20</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Daleae spp.</em></td>
<td>moderately well-drained, sandy soils</td>
<td>perennial</td>
<td>erect or vine</td>
<td>2-15</td>
<td>Cushwa et al. (1970); Landers (1978)</td>
</tr>
<tr>
<td><em>Indigofera caroliniana</em></td>
<td>moderately well-drained, sandy soils</td>
<td>perennial</td>
<td>erect</td>
<td>5-15</td>
<td>Whyte and Trumble (1953);</td>
</tr>
<tr>
<td><em>Leptadenia spp.</em></td>
<td>moderate to well-drained, sandy soils</td>
<td>annual or perennial</td>
<td>erect to prostrate</td>
<td>1-30</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Logania spp.</em></td>
<td>excessively drained, sandy soils</td>
<td>perennial</td>
<td>erect to prostrate</td>
<td>2-4</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Medicago spp.</em></td>
<td>well-drained soils</td>
<td>annual or perennial</td>
<td>erect to decumbent</td>
<td>1-10</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Melilotus spp.</em></td>
<td>well-drained soils</td>
<td>annual or biennial</td>
<td>erect to decumbent</td>
<td>0.3-15</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Phaseolus spp.</em></td>
<td>excessively drained, sandy soils</td>
<td>annual or perennial</td>
<td>vine</td>
<td>10-40</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Convolvulus spp.</em></td>
<td>moderately well-drained, sandy soils</td>
<td>perennial</td>
<td>erect or vine</td>
<td>0.5-10</td>
<td>Whyte and Trumble (1953); Cushwa et al. (1970);</td>
</tr>
<tr>
<td><em>Raphanobothria microphylla</em></td>
<td>excessively to excessively drained sandy soils</td>
<td>perennial</td>
<td>prostrate</td>
<td>10-20</td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Rubus hispidus</em></td>
<td>moist to poorly drained soils</td>
<td>annual</td>
<td>erect</td>
<td>1-20</td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Schizonepeta tubulosa</em></td>
<td>moderately to well-drained, sandy soils</td>
<td>annual or perennial</td>
<td>vine</td>
<td>3-20</td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Tephrosia villosa</em></td>
<td>moderately well-drained, sandy soils</td>
<td>perennial</td>
<td>erect to prostrate</td>
<td>1-7</td>
<td>Whyte and Trumble (1953); Cushwa et al. (1970);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Landers (1978)</td>
</tr>
<tr>
<td><em>Trifolium spp.</em></td>
<td>well-drained soils</td>
<td>annual to perennial</td>
<td>erect to decumbent</td>
<td>1-10</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
<tr>
<td><em>Vicia spp.</em></td>
<td>well-drained soils</td>
<td>annual to perennial</td>
<td>vine</td>
<td>5-15</td>
<td>Whyte and Trumble (1953); Landers (1978)</td>
</tr>
</tbody>
</table>

2. Adapted from Landers 1978.
suspected that the total contribution of actinomycete-nodulated plants to the nitrogen economy of natural ecosystems (and particularly forested areas in temperate zones) exceeds that of legumes (Silvester 1976; Torrey 1978; Gordon and Dawson 1979). This group of plants consists of about 160 species in at least 13 genera of 7 families (Bond 1976). Most genera and even some individual species occur naturally or have been introduced over broad geographic ranges. Moreover, they appear adaptable to rather diverse site conditions, and commonly can grow on adverse sites where most other species cannot survive. Thus, the biological potential for use of these plants in forest management appears most promising.

The major actinomycete-nodulated genera available for use in temperate and subtropical climates are listed (Table 3). Estimated rates of nitrogen accretion, natural habitats, and examples of use or suggested applications in forestry are also summarized. Readers interested in greater detail are referred to comprehensive reviews on this subject (Silver 1969; Youngberg and Wollum 1970; Silvester 1976, 1977; Torrey 1978) and to the specific references listed for each genus (Table 3).

A brief examination of the summarized information will reveal that some genera offer greater potential in forestry applications than others. The more promising genera have higher nitrogen accretion rates, wide ecological amplitude, and have been previously used or suggested in forestry situations. Thus, the genera Alnus, Ceanothus, and Elaeagnus appear to offer the greatest potential for use in northern United States climates (e.g., Northeast, North Central, and West). In addition to the above genera, Casuarina and Coriaria may have application in southern (e.g., Southeast, South Gulf, and Pacific Southwest) forestry. Although little is known about the ecological significance of Myrica and estimates of accretion are rather low, the authors believe that it too merits consideration in forestry applications. Many species in the genus Myrica are adaptable to a wide range of site conditions and may be suitable as understory plants in managed forests; one species had the most efficient nodules of all nitrogen-fixing species compared by Bond (1967). Both legume and actinomycete-nodulated genera and species will be discussed further as appropriate in the forthcoming section on management systems.

POTENTIAL CROPPING SYSTEMS

Six different systems or strategies for using nitrogen-fixing plants in forest management programs have been identified. Five of these are modifications of two basic systems for using a nitrogen-fixing species with a non-nitrogen-fixing principal tree crop—alternate cropping (crop rotation) and mixed-species cropping. The modifications are associated with opportunities for commercial utilization of the nitrogen-fixing plant and also with the timing of its establishment and growth in relation to the principal forest crop. The sixth system is continuous use of a commercially valuable nitrogen-fixing tree as a single species crop.
Table 3. —Actinorhizal nodulated angiospermous genera having potential utility in forest management

<table>
<thead>
<tr>
<th>Genus</th>
<th>Number of Nodulated Species</th>
<th>Estimated Mean Maximum Root Nodule Occurrence Rate</th>
<th>Habitat</th>
<th>Other Forest Genus Benefiting from Associations</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceanothus</td>
<td>31</td>
<td>0-40</td>
<td>Subalpine shrub, dry chaparral, understory in dry forests</td>
<td>Pseudotsuga, Pinus</td>
<td>None reported</td>
</tr>
<tr>
<td>Cerocarpus</td>
<td>4</td>
<td>No data</td>
<td>High altitudes, infertile soils</td>
<td>None reported</td>
<td>Harris and Morrison (1958) Silvester (1976, 1977)</td>
</tr>
<tr>
<td>Corydia</td>
<td>13</td>
<td>90-200</td>
<td>Poor, sandy, gravelly soils in lowlands and subalpine habitats; also in class, wet areas, alluvium, moraines, alpine meadows and volcanic debris</td>
<td>Pinus</td>
<td>None reported</td>
</tr>
<tr>
<td>Cima</td>
<td>2</td>
<td>No data</td>
<td>Limestones, alluvial fans, gravel areas; arid, sparsely vegetated land; low tussock grassland</td>
<td>None reported</td>
<td>None reported</td>
</tr>
<tr>
<td>Drege</td>
<td>3</td>
<td>12</td>
<td>Post-glacial areas; sandy, gravelly, and calcareous</td>
<td>Stabilizes site for Alnus, and subsequent establishment of Populus and Pinus</td>
<td>None reported</td>
</tr>
<tr>
<td>Elymus</td>
<td>16</td>
<td>No data</td>
<td>Disturbed areas, sand dunes, poor soils</td>
<td>None reported</td>
<td>Funk et al. (1979)</td>
</tr>
<tr>
<td>Parthenocissus</td>
<td>2</td>
<td>&lt; 15:50+ (7)</td>
<td>Understory in pine forests, dry pumice and sandy soils, disturbed soils</td>
<td>None reported</td>
<td>Silvester (1976) Dalton and Boshi (1977)</td>
</tr>
<tr>
<td>Sandersonia</td>
<td>3</td>
<td>No data</td>
<td>Along streams, near lakes, sandy and dry soils, poor sites, sandy sites, eroded soils</td>
<td>None reported</td>
<td>Gadd and Bond (1957) Youngberg and Wullum (1970)</td>
</tr>
</tbody>
</table>

1/ Adapted from tables and text presented in reviews by Silvester (1976, 1977) and Torrey (1978) plus other specific references cited by genera.
2/ Other genera reported to have nodules include Actinidia, Callicarpa, and Rubus. Nitrogen fixation by Acastrephaneum is doubtful (Silvester 1976) and only one species has been reported in each of the latter two groups and both are confined to the tropics.
3/ This genus includes Comptonia and Calea.
In this section, each system is defined and known or potential advantages and disadvantages are identified. Suitable species and examples of situations where the system has been tested or application proposed are cited.

Crop Rotation Systems

In crop rotation systems, the nitrogen-fixing crop is grown by itself for a given period, followed by one or more crops of non-nitrogen-fixing (and usually the principal) species, and then grown again. Problems associated with incompatibility of growth patterns of 2 crops [e.g., Pseudotsuga menziesii (Mirb.) Franco var. menziesii and Alnus rubra Bong. (Newton et al. 1968); Robinia pseudoacacia L. and conifers (Kellogg 1934)] are avoided in these systems. Each crop receives full sunlight, and growth and nitrogen fixation can therefore proceed at maximal rates for the species and existing site conditions. In addition to applications for fertility improvement, crop rotation has been used in agriculture for at least 2,000 years to ameliorate problems associated with soil-borne pathogens (Glynne 1965). If "diseases of the site" [such as the root rots of Fomes annosus, Phellinus (Poria) weirii, Phytophthora spp., and Armillaria mellea] become more serious in future rotations with increased management and utilization intensity, alternate cropping systems may attain similar importance in forestry. For example, Nelson and co-workers (1978) have suggested that Alnus rubra could control Phellinus weirii in Pseudotsuga menziesii forests via crop rotations which may reduce survival of the fungus in stumps and roots following logging and occupy the site in place of susceptible conifers until the pathogen has died out. The principal disadvantage of crop rotation is the opportunity cost for the time the land may not be producing a commercial crop or at least not the crop of highest value.

Two crop rotation systems--green manuring and alternate cropping of commercial species--are discussed below. They differ primarily in commercial utilization of the nitrogen-fixing crop.

Green manuring--In green-manure cropping, a nitrogen-fixing plant cover is grown and no portion of the crop is harvested. In agriculture, legume crops such as Trifolium spp. or Vicia spp. are turned under while green or soon after maturity. The term "green manuring" is used in this paper in a broader sense to include nitrogen-fixing crops that are killed prior to or die out soon after establishment of the principal commercial crop.

This system often can be used to ameliorate adverse sites that previously could not support adequate growth of other plant species. Alnus glutinosa (L.) Gaertn. (Lowery et al. 1962), Robinia pseudoacacia (Finn 1953), and Myrica spp. (Silver 1969) have been used or suggested for use on coal mining wastes in Pennsylvania and the midwestern states. Lupinus arboreus has been used to aid sand dune stabilization in New Zealand (Gadgil 1971). There are many examples of green manuring in natural ecosystems. For example,
Dryas drummondii Richards. and Alnus sinuata (Reg.) Rydb. are pioneer invaders of post-glacial sites in Alaska (Crocker and Major 1955), and Casuarina equisetifolia L. and Coriaria arborea Lindsay have contributed significantly as seral vegetation following volcanic activity on Krakatau Island, Indonesia and in New Zealand, respectively (Silvester 1976). Disadvantages of green manuring center primarily upon the previously-mentioned opportunity costs incurred when land is not producing the commercial crop.

The legume genera that appear to be most suitable for use with this system in temperate areas include Vicia spp. and Lupinus spp. (Mulder et al. 1977). Lupinus spp. may be particularly useful in forest conditions as they are able to grow and fix nitrogen at low pH, can obtain phosphorus from relatively insoluble phosphates, and, by virtue of a deep rooting habit, can obtain water not available to other species. Among actinomycete-nodulated genera, Alnus, Coriaria, and Casuarina appear to be most promising.

The best example of modified use of green manuring in forestry is that involving Lupinus arboreus in New Zealand to stabilize sand dunes and enhance subsequent pine growth (Gadgil 1977). After stabilization, Pinus radiata is interplanted in established Lupinus cover. The Lupinus is subsequently killed with 2,4-D, but it may reestablish itself from seed remaining in the soil. When the latter occurs naturally or is so manipulated by management, the Lupinus-Pinus association is more fittingly termed a mixed species system and will be identified as such later in this paper.

A green manuring system involving Alnus rubra and Pseudotsuga menziesii has been conceptualized by Atkinson and others (1979) for the Pacific Northwest. Dense stands of Alnus would be established by seeding and grown for 8 years. During this time an estimated 660 kg-N/ha would be added to the site. The Alnus would then be killed with herbicide and Pseudotsuga menziesii seedlings planted among the standing dead Alnus. This system may therefore provide additional benefits associated with non-competitive "shade" for the young trees, a factor of particular importance in stressful environments. At current costs and stumpage values, Atkinson and his co-workers considered this to be a profitable program but not as lucrative as chemical fertilizer application.

Alternate cropping with two commercial species.--A crop rotation system which includes a legume or grass-legume forage crop at frequent intervals among grain crops (e.g., Zea mays L.) is practiced in agriculture. This system differs from green manuring in that the nitrogen-fixing crop has some value, though usually not as much as the non-nitrogen-fixing crop. Advantages and disadvantages are similar to those mentioned for green manuring, but opportunity costs are less due to the value of the nitrogen-fixing crop.

Suitable species for this system are limited by definition to those having commercial value or at least potential for utilization. In the southern and midwestern United States, opportunities may
exist for production of leguminous forage or food crops on well-prepared sites for a few years after harvest and prior to establishment of tree crops.

Wildlife cover and food species could also be considered in this category if the landowner obtained monetary returns from hunting leases or fees. Moore (1978) successfully established Aeschynomene americana L. on a wet, infertile sand in South Florida, and determined that a maintenance program including fertilization and light disking would be needed for economical forage production. Halls and his colleagues (1970) were less successful in establishing Cassia and Lespedeza on a cutover Pinus palustris Mill. site. They concluded that investment in establishment and maintenance was too high to permit economical utilization of these species as managed wildlife food on such sites. Lespedeza, however, is being managed as a wildlife food species on International Paper Company's Southlands Experiment Forest.

On most forest sites nitrogen-fixing trees are, for all practical purposes, the only species of potential use. These include Alnus rubra, Alnus glutinosa, and Robinia pseudoacacia in temperate areas. Casuarina spp. and perhaps Acacia spp. may be suitable in southern Florida or California.

The report of Carmean and his co-workers (1976) regarding growth of hardwoods on a site previously supporting Robinia pseudoacacia is the best example of opportunities for crop rotation in forestry. Liriodendron tulipifera L., Liquidambar styraciflua L., and Juglans nigra L. made far superior growth when planted after Robinia than when planted on sites which had supported other native hardwoods, Pinus spp., or herbaceous vegetation. Improved hardwood growth was attributed primarily to increased foliar nitrogen levels. Earlier work by Ike and Stone (1958) indicated net annual increases of 44 kg-N/ha under Robinia. Robinia has also been used on mine spoils to improve site conditions sufficiently to permit establishment of other species.

There are also several reports that suggest other opportunities in forestry, especially with Alnus species (Tarrant and Trappe 1971). Atkinson and his associates (1979) conceptualized some systems for rotating Alnus rubra and Pseudotsuga menziesii crops in the Pacific Northwest and assessed biological and economical impacts. The assessment was based upon projected yields of Pseudotsuga menziesii and Alnus rubra, patterns of nitrogen accretion over time in Alnus stands, and an estimate of the effects of nitrogen added by Alnus on Pseudotsuga growth. Estimated yields from such systems were higher than for programs involving only Pseudotsuga, but financial returns were lower. The authors concluded that future changes such as expanded wood markets (particularly for Alnus) and increased fertilizer costs could enhance profitability of the alternate cropping systems and recommended pilot-scale testing of the concepts.
Similar opportunities seemingly exist in the midwestern, eastern, and southern United States for *Alnus glutinosa*, and *Robinia pseudoacacia*, provided that problems associated with insect stem-borers in the latter species can be resolved. Both species grow rapidly at young ages (Lowery et al. 1962) and could be utilized for fuelwood, pulpwood, posts, or small sawlogs. Although suitable only to a limited geographic range, *Casuarina* spp. could also be used in this system. This genus makes rapid early growth; its wood is exceptionally strong and is an excellent fuelwood.

**Mixed Species Systems**

Mixed species systems involve a sharing of site resources between the nitrogen-fixing species and principal crop during all or selected portions of a rotation. They may involve simultaneous planting (as with nurse crop or companion crops) of both species or interplanting (subsequent planting) of the nitrogen-fixing species after the principal crop is established. Advantages of mixed species systems include the absence of any period during which the principal crop is not growing on the site. Benefits, however, may accrue from the opportunity of the nitrogen-fixing species to provide "inputs" to the principal crop during the entire rotation or when demand is greatest (e.g., during the years of fastest growth or after a thinning). Disadvantages include allocation of a portion of site resources (space, moisture, nutrients, light) to other than the principal crop. Far more serious considerations with some mixtures are compatibility problems due to differential growth patterns or to differences between the environment "created" by the principal crop and that needed by the nitrogen-fixing species.

The following three systems are variations of the mixed species theme. They differ in whether the nitrogen-fixing species has commercial value and also in the time that both species share site resources.

**Mixtures of two commercial tree species.**--This system is distinguished from the other two mixed systems in that both species have commercial value, disparate though such values may be. Moreover, there may be additional variants of this system in that the nitrogen-fixing crop may be planted simultaneously with the principal crop or interplanted in subsequent years. It may also be harvested prior to or at the same time as the principal crop.

The advantages discussed previously for mixed species systems in general are all applicable to this system. In addition, the nitrogen-fixing crop has value in its own right. Disadvantages related to occupation of growing space are presumably greater than for other mixed species systems, because the nitrogen-fixing species occupies the tree layer rather than the shrub or ground layer of vegetation. The need for information regarding just how many individual nitrogen-fixing trees are needed per hectare is more crucial for the above reason and also because options for controlling density of nitrogen-fixing trees are greater.
Suitable species for this system are the same as those listed for rotation of two commercial crops (Alnus rubra, Alnus glutinosa, Robinia pseudoacacia and Casuarina spp.). Incompatibility in early growth rates with the principal crop is likely to be a problem with all these species, particularly if light-demanding conifers are the principal crop. However, interplanting several years after the principal crop is established may do much to alleviate this concern.

The Alnus rubra-Pseudotsuga menziesii plantation at Wind River in the southern Washington Cascades is perhaps the classic example of this system. When the plantation was first studied at age 30 by Tarrant (1961), the Pseudotsuga trees were beginning to emerge from the Alnus canopy and were growing faster than trees in an adjacent, pure Pseudotsuga plantation. A more detailed study of soil properties (Tarrant and Miller 1963) indicated that Alnus has substantially increased organic matter and nitrogen in the upper soil horizons. At age 48 the mixed plantation had only two-thirds as many Pseudotsuga stems as the pure stand, but volume of Pseudotsuga alone in the mixed stand was 7 percent higher than that in the adjacent pure plantation (Miller and Murray 1978). Moreover, the dominant Pseudotsuga of the mixed stand were 20 percent taller and more than 30 percent larger in diameter than those in the pure stand. If per hectare volumes of both Alnus and Pseudotsuga are considered, production in the mixed stand was nearly double that of the pure stand.

Although simultaneous plantings of Robinia pseudoacacia and conifers inadvertently led to failure due to overtopping, Kellogg (1934) suggested that understory plantings of Robinia in native Pinus spp. plantations or mixtures with rapid growing hardwoods may be useful. Indeed, McIntyre and Jeffries (1932) documented the Robinia pseudoacacia-Catalpa bignonioides W. mixture as being beneficial. Finn (1953) found that several planted hardwood species had superior growth when associated with Robinia that had been planted simultaneously or interplanted later. Liriodendron tulipifera, Juglans nigra, and Prunus serotina Ehrh. showed the greatest response but several other species (Liquidambar styraciflua, Fraxinus pennsylvanica Marsh., and Quercus spp.) also benefited.

Working on strip mine spoils in Kentucky, Plass (1977) showed 10-year growth of 5 hardwoods and 5 conifers was improved when associated with a simultaneously planted nurse crop of Alnus glutinosa. No data are given however, on Alnus growth patterns as related to the other species nor are there any speculations as to whether Alnus will attain merchantable size.

Benefits from growing Alnus rubra and Populus trichocarpa Torr. & Gray together in coppice culture has been documented in the Pacific Northwest (DeBell and Radwan 1979). Two-year coppice yields of the mixed plantings obtained 4 years after establishment were substantially higher (35 percent plus) than yields from pure
plantings of either species. The higher yields obtained in mixed culture were attributed primarily to enhanced growth of Populus. Growth of Alnus was similar to that obtained in pure plantings of the species. Nitrogen contents of Populus twigs and soil were higher in the presence of Alnus. Such findings may have application for short-rotation systems for fiber and energy production in other parts of the country. For example, similar results seem probable through combinations of Alnus glutinosa with Platanus occidentalis L., Populus deltoides Bartr. var. deltoides and Liquidambar styraciflua.

Non-commercial nitrogen-fixing species in understory during most of tree rotation.—In this system, the non-commercial nitrogen-fixing species is planted simultaneously with or soon after the principal crop. It may be the dominant vegetation canopy for a short time, but usually is a component of the understory for most of the stand's life. The nitrogen-fixer may survive and grow throughout the entire rotation if the trees are spaced far enough apart. It is more probable, however, that the nitrogen-fixing species will be shaded out and reappear intermittently after thinning operations, provided that seeds remain dormant in the forest floor or mineral soil.

Advantages of this system are similar to those listed for the previous system (mixture of two commercial species). In addition, the nitrogen-fixing species in this system does not compete with the principal crop for light, except perhaps in the first few years. Other benefits may be associated with wildlife cover and food or, in some cases, disease control. The disadvantage is that the understory may be using moisture and nutrients that would otherwise be absorbed by the principal crop. Conversely, presence of the nitrogen-fixing understory may decrease such competition compared to that which would occur if other understory species occupied the site. A more important potential problem with this system is that most nitrogen-fixing species (especially domesticated ones) are intolerant of shade and nitrogen-fixation rates are reduced by shading.

There are a number of species that may be used with this system if stands remain relatively open. These include Lupinus spp. and Vicia spp. and perhaps most of the actinomycete-nodulated genera, especially Elaeagnus, Coriaria, Myrica, Ceanothus, and perhaps Purshia. The latter four genera are sometimes found naturally under open pine forests in temperate climates, particularly on dry sites.

The best example of this system is the intentional use of Elaeagnus umbellata Thunb. in widely-spaced Juglans nigra plantations in the midwest (Funk et al. 1979). After 9 years, Juglans grown in mixture with Elaeagnus averaged 70 percent taller and 76 percent larger in diameter than Juglans grown in pure stands. How long the Elaeagnus will persist in the understory is unknown. Rather interestingly, all attempts to stimulate growth of Juglans with nitrogen fertilizers have met with negligible success (Ponder 1976).
The common occurrence of Coriaria arborea as an understory shrub in Pinus radiata plantations in New Zealand (Silvester 1976) suggests its suitability for a mixed species system. Silvester (1977) showed definite benefits to early Pinus growth from Coriaria but indicated that vigorous Coriaria may suppress growth in recently planted Pinus stands. On better sites where nitrogen is not severely limiting, Coriaria is eventually shaded out by other shrub species as stands mature. However, Silvester reports that following thinning, Coriaria may reenter the Pinus stands and that Coriaria persists as long as it receives at least 30 percent full sunlight. Unless seeds remain dormant and viable over long periods in the forest floor or mineral soil, an adjacent seed-supplying stand or direct seeding would be essential.

A dense understory of Alnus rubra was established after heavy thinning in a 62-year-old Pseudotsuga menziesii stand and added nearly 880 kg-N/ha before it began to die out (Berg and Doerksen 1975). Use of Alnus species in the present system, however, would require either planting or an adjacent seed source.

Another example of this system also occurs in the Pinus radiata forests of New Zealand, the first phase of which was used as an example of green manuring. After stabilizing sand dunes, Lupinus arboresus is crushed or sprayed and Pinus radiata is planted (Gadgil 1971). A new growth of Lupinus is soon established and persists until Pinus canopy closure. Seeds of Lupinus persist in the soil, and germination is stimulated by the activity of machinery and increased light associated with the first (10-12 years) and second (18-22 years) thinnings. Thus, Lupinus is perhaps the best example of intermittent occupation of the site by an understory nitrogen-fixing species. Seemingly, opportunities may exist for similar use of other legumes and actinomycete-nodulated plants (Myrica, Ceanothus, and Purshia) with planned management programs.

Non-commercial nitrogen-fixing species in understory during early years only. --In this system, the nitrogen-fixing species is established, simultaneously with or soon after the principal crop. It acts as a nurse plant during the stand's early life, is shaded out after the canopy closes, and does not become reestablished at later stages.

Nitrogen is accumulated in the soil by the nitrogen-fixing species while available resources (space, light, other nutrients, and water) exceed demands of the principal crop. Full sunlight, especially in widely spaced stands, may result in high nitrogen-fixation rates. Channeling site resources to an ideal nitrogen-fixing species by purposeful management may also limit encroachment of non-desirable vegetation which would otherwise volunteer on the site. The greatest potential disadvantage of this system is that the period of greatest nitrogen need of the principal tree crop may not coincide with the period of occupancy by the nitrogen-fixing species. Thus, benefits for later stand use are dependent upon high nitrogen accretion in early years, good nitrogen retention on the site, and ready availability of the nitrogen for later stand needs.
High levels of insolation in this system make use of most nitrogen-fixing species possible. Probably many legumes would be suitable, provided that soil fertility and pH are at favorable levels. The latter restrictions can be rather important for many domesticated varieties (Jorgensen 1978) in forest environments, but may be less so with native legumes and actinomycete-nodulated plants. Within the latter group, several shrubby species of Alnus merit consideration.

The best example of this system in forestry is the recent study in which 5 legumes (3 Trifolium spp. and 2 Vicia spp.) were tested in a 2-year-old Platanus occidentalis plantation (Haines et al. 1978). After 4 years, total height and volume of Platanus in the legume-containing plots exceeded that in the check plots by more than twofold and threefold, respectively. Trifolium subteraneum L. and Trifolium incarnatum L. also provided the best weed control, maintained a low profile, and did not shade or vine around the young Platanus trees.

Legumes have been similarly used for several years in the Hevea brasiliensis Muell. Arg. plantations of Malaya. Nitrogen fixation by creeping legumes during a 5-year period was estimated at nearly 880 kg-N/ha (Broughton 1977). In such plantations, control of root rot diseases such as Fomes lignosus (Klotzsch) Bres. is a major benefit also (Fox 1965). Despite the fact that legumes died out after the sixth year, increases in rubber yields persisted for about 20 years.

Attempts to establish legumes (Aeschynomene, Melilotus, Indigofera, Desmodium, Lespedeza, and Vigna) in newly planted Pinus elliottii Engelm. var. elliottii on infertile sands were unsuccessful (Anonymous 1974). Even with disking, liming, and fertilization, none of the legumes established themselves to any marked degree.

Nitrogen-fixing Trees as the Principal Crop

This system differs from the others in that the nitrogen-fixing tree is the crop species of prime interest. Advantages of such culture lie in the fact that most nitrogen-fixing trees grow very rapidly (especially at young ages), are adaptable over a wide range of sites, and appear to require lower management inputs for excellent growth than most non-nitrogen-fixing trees. Thus, nitrogen-fixing species appear particularly well-suited for short-rotation production of fuel and fiber and possibly small sawlogs and posts. Disadvantages include the fact that current stumpage values are usually lower for these species than for others which might occupy the site. Also questions persist about potential detrimental effects on soil pH and base status over the long term, particularly with Alnus (Bollen et al. 1967, Franklin et al. 1968).

Alnus species offer by far the greatest opportunities for commercial production in temperate climates. Robinia pseudoacacia may also have potential in temperate climates if insect problems
can be resolved. A number of Casuarina and Myrica species have potential for local consideration in tropical and subtropical environments (Gordon and Dawson 1979).

Yield data collected in young, natural stands of Alnus rubra (Zavitkovski and Stevens 1972, Smith and DeBell 1974) show that 15-25 tons/ha/yr of aboveground biomass are possible. Such data are indicative of the potential of this species. Recently estimates of yields that might be obtained with spacing alone in conventional management systems (pulplogs and sawlogs) have been published (DeBell et al. 1978).

Where winter hardiness is important; Alnus glutinosa may have utility. This species has been planted on mine spoils, and recently has received serious attention as a fiber source (particularly for silage cellulose systems) in the Southeast (Saucier 1977).

Nitrogen-fixing trees deserve consideration in research and development programs on "biomass for energy" plantations. They may also have future importance in areas where synthetic nitrogen fertilization has been a necessary requisite to adequate growth of other commercial species.

FUTURE CONSIDERATIONS

The future use of biological nitrogen fixation in forest management programs will depend, in part, on development of essential information via research, but other factors also impact implementation. For example, changes in the availability and cost of chemical nitrogen fertilizer and associated application costs may enhance or detract from the potential utility of nitrogen-fixing plants in forest management systems. One frequently overlooked obstacle to use of nitrogen-fixing species is the fact that foresters' experiences with these plants have in many cases been limited to Pueraria thunbergiana (S. & Z.) Benth. or some similarly "noxious weed." Thus, many foresters need to be educated as to the benefits that accrue from use of nitrogen-fixing plants.

Gaps in the knowledge of biological nitrogen fixation in forest ecosystems are large. Areas requiring attention include: (i) screening of the most promising native and domesticated species and genera, (ii) methods of establishing these plants on forest sites (including species propagation), (iii) development of effective inocula and inoculation techniques, (iv) assessment of nitrogen fixed and its benefits to the tree crop, and (v) assessment of auxiliary effects of nitrogen-fixing plants on the forest environment.

Critical ecological requirements will vary with species and with the cropping system proposed, particularly light requirements. Species needing full or a large percentage of insolation will have little utility in developed stands where shading is heavy. Transfer of agricultural legumes to forest ecosystems will depend on satisfactorily resolving fertility, moisture, and pH (as well as light)
requirements of these species. Use of native legumes and actinomycete-nodulated plants should present fewer problems.

Optimal site preparation and fertilization prescriptions are needed. Methods of establishment (broadcast seeding, strip seeding, containerized seedlings, etc.) must be evaluated. For example, a legume that grows so tall and rank that it severely shades and crowds newly planted seedlings may still have utility when strip planted between the tree rows.

Prior to testing native species, seed collection and treatment techniques must be developed. Survival mechanism in some native species is seed dispersal as a result of seed pod "explosion." While this type of dehiscence may be beneficial once the species is established, it creates problems during seed collection. Seeds cannot be collected before they mature, but must be harvested before they are dispersed. Many native legumes have extremely hard seed coats, requiring drastic treatment before germination occurs. Some seeds germinate only after exposure to high temperatures (e.g., prescribed burning Martin et al. 1975).

Development of the most effective inocula for agronomic legumes has taken decades; foresters cannot expect to discover the best inocula overnight. Those strains discarded by agronomists in their breeding programs may be the ones of most value on forest soils. Development of inocula for native species has received only casual consideration.

Techniques for assessing fixation rates and nitrogen accretion in forest ecosystems are not refined. Fixation rates for native and agricultural species growing on forest soils must be determined. Direct comparisons on the same site of biological nitrogen fixation and chemical nitrogen fertilization are needed.

Assessment of beneficial and detrimental auxiliary effects of nitrogen-fixing plants on the forest environment should be made. Beneficial effects include increased organic matter, decreased bulk density, and possible disease control. Conversely, increased soil pH needed to establish some nitrogen-fixing plants may be detrimental to the tree crop. These plants may attract insects or animals to a greater degree than would occur if only the tree crop were present on the site.

CONCLUDING REMARKS

Nitrogen-fixing plants can provide a useful and versatile tool for improving and maintaining forest productivity. Cropping systems involving these plants impact other productivity factors as well as add nitrogen. Present use of nitrogen-fixing species is largely confined to special situations, such as mine spoils, road cuts and fills, and wildlife management areas. A number of factors limit immediate implementation on most other lands. A comprehensive program of applied research and development, however, could soon provide information needed to exploit this tool for more general use in forest management.


