Likely problems and benefits arising from mixed plantations

PREMYSL MACEL

Abstract:

There is an increasing demand to replace plantation monocultures with mixtures of different species. This article analyses the historical reasons for establishing such plantations from the very first known large monoculture systems found in Europe. The main characteristics of the conversion of monoculture plantations, the ways in which tree species might interact, and likely problems and benefits arising from mixed plantations are discussed. Places where conversions become reasonable are listed. The main focus of this study is on finding the fundamental ecological bases and eco-technical principles that should be included in the new effective forest management and that should become a part of the formulations of forest policy in the near future.

Introduction:

Whenever we have to deal with plantation monocultures* we should always have historical reasons for establishing such plantations in mind. They are usually driven by economic mechanisms in order to achieve the highest profit in the shortest period of time. The very first known large monoculture systems are from Europe where, during the 18th century, the establishment of spruce (*Picea* *abies*) monocultures took place. Reasons for their establishment are well known and understandable as the only way of quick action, possible to measure and control, which was suppose to improve overexploited natural forest resources. Reforestation with organized forest stands, for which a complete system of management methods was developed, took place on felled areas. It has emerged clearly from this practise that the artificial forest units are vulnerable to attacks by pests and diseases, and economically unstable. Reactions to this and to the ecological error of establishing monocultures without taking the natural growing conditions of spruce into account were completely empirical at the beginning. Initiatives identifying the problems associated with monocultures, and recommending constructive suggestions for solving them were given by Gayer (1886, cited in Tesař,1993) in his work *Der gemischte Wald, seine Begründung und Pflege, insbesondere durch Horst- und Gruppenwirtschaft* ("The mixed-stand forest, its establishment and cultivation, in particular through the group selection system ...."). This publication was at the beginning of the organised so called "close-to-nature" silviculture by defining the essential ideas.

Conversion of monoculture plantations into mixed stands is a problem that is so wide that it is hard to explain all the aspects in a short essay. Therefore I will concentrate mainly on facts, which in the past, at present and in the future characterise need for conversion on one hand and limitations for this process on

---

***Definitions**: (Helms, 1998)

Plantation — a stand composed primarily of trees established by planting or artificial seeding. Depending on management objectives, a plantation may be pure or mixed species, treated to have uniform or diverse structure and age classes, and have wildlife species commensurate with its stage of development and structure. Plantations may be grown on short rotations for biomass, energy, or fibre production, on rotations of varying length for timber production, or indefinitely for other values.

Monoculture — a stand of a single species, generally even aged.

Conversion — a change from one silvicultural system to another or from one tree species to another (species conversion).

the other. I will also provide examples of different problems, which still need to be explained on scientific bases.

The main characteristic of the conversion of monoculture plantations:

Apart from the definition given by Helms, (1998), in silviculture, conversion also includes restoration of degraded forest to a productive condition, leading eventually to sustained yield working under one of the silvicultural systems (Matthews, 1989). The term “conversion of forest” restricted to conversion of already existing monocultures is not very common. It may become familiar for expressing the direction of change in artificial man made forest, from monoculture plantations into a type of forest that ensures its sustainable management.

Transformation of monocultures usually involves a fundamental change in species structure and texture of the stands (i.e. spatial dislocation and presence of different growth stages and age groups). It is presumed that this new structure will lead to a better (close-to-nature) functioning of the forest ecosystem, giving possibilities of new benefits and better effectiveness of their use (Poleno,1997).

In practise, solving of the particular cases the conversion consists of closely connected activities based on change of species within the forest stands on one hand and with changes of the entire system of management methods on the other. The result of conversion will appear in a short period of time and changes in species structure will not only be visible and measurable, but from the point of proper functioning of the ecosystem will be the most important part of the process. An essential part should also involve the change from the clear-cutting even aged system to shelterwood systems. Though problem solving may look simple, the idea that we can start conversion with well known tools and methods now is somehow too simple. There will still be problems in the final concept of new sustainable forest ecosystem that will stagnate due to the limited knowledge of the ecological processes, which are still dramatically developing.

Possible problems arising from plantation monocultures:

The uniformity of plantation crops brings possible biological risks, loss in conservation value and other disadvantages too (Savill and Evans, 1986). Major biological risks with plantation monocultures may occur for example when the destructive influence of abiotic and biotic factors prevents monocultures reaching maturity. Soil and other site factors do not always suit a single species throughout a full rotation. They may cause faster soil degradation due to removing all the biological material from the site. Repeated harvesting of eucalypt plantations on short rotations may deplete site nutrients because of removal of nutrients in the harvested wood and other tree components, and further losses may occur due to inter-rotation site management practises, e.g. slash burn, site preparation (Nykvist et al., 1994). These risks are sometimes taken even after big disasters, such as outbreaks of insects, diseases, fire or windthrow and the affected stands are replaced with monocultures again, in many cases because it is economically and technologically the easiest way of reforestation.

Benefits arising from mixed-species plantations

Mixed-species plantations may be established for a variety of objectives:

1. To provide stand protection

In a mixed-species system, one of the tree species may act as a nurse crop, providing protection against climatic factors, improving the stem form of another species, and improving the physical stability of stands through deeper rooting of some species. A typical example is the use of mixed-species stands as wind breaks (El-Lakany and Mohamed, 1993). Windthrow may be lessened when a relatively deep-rooting species is mixed with one, which is shallow-rooting. There may be a reduced risk of damage by snow. Strategically-located lines of less combustible species may help to limit the spread of fire. Differences in vigour may be deliberately exploited in self-thinning mixtures of conifers. They are in use on sites of high windthrow hazard where conventional thinning may be unwise. An example of such mixtures may be Sitka spruce and lodgepole pine. Similar effects may also be achieved by planting different provenances of one species, having two different growth rates, e.g. in Sitka spruce, the fast-growing Queen Charlotte Island provenance with the slow Alaskan provenance (Lines 1981, 1987). Nurse species have a special place in mixtures. Nurses can form a component of mixtures, performing one or more of three functions: (i) rapidly suppressing competing vegetation (this may have an adverse effect on desirable ground flora) ; (ii) benefiting the nutrition of another species on impoverished sites, and (iii) modifying the microclimate, to protect tender species from frost exposure during their early years when they are particularly sensitive. Beech, several silver firs, and western hemlock may all grow better initially if mixed with a faster growing nurse or if planted under the canopy of a near-mature crop.

2. To enhance ecological stability

The ecological stability of a stand refers to its ability to resist external stress (resistance) and to return to its former dynamic state after perturbation (resilience). Sometimes plantation monocultures are clonal, which makes them potentially more susceptible to pests and diseases than mixed stands (Savill and Evans, 1986). Mixing species may improve both resistance and resilience by improving nutrient cycling, enhancing resistance to pests or disease, and providing resilience to climate change. Montagnini et al. (1995) monitored pest damage in mixed and pure stands in Costa Rica for two years after planting and observed no damage, or no difference between mixed and pure stands, for nine of the twelve species tested ; for three species, pest damage was less severe in mixed than in pure stands.

3. To exploit natural associations and synergy

Species in mixed stands can be selected to cover a range of roles of succession on a site, e.g., pioneer species for a rapid soil cover, climax species for a stand's final stages, and intermediate species which need neighbours to improve their growth and form. Each species is adapted to exploit one particular range of its values of a large number of environmental variables, which is described by ecologists as the "fundamental niche" of the species. Niches overlap since many resources are required by most species. Because resources are limited this overlap results in competition between species and prevents them reaching their full potential (Savill and Evans, 1986). Kelty (1992) considered the conditions under which the total yield of mixed-species stands was greater than that of monocultures of the component species, and concluded that yield of the mixture would exceed that of lower-yielding monocultures but not necessarily that of higher-yielding monocultures. Based on the degree of niche separation among species for resource utilization (aboveground and belowground components), the yield patterns in mixed stands can be explained by using the principles of competitive reduction and facilitation. Mixed climax forests use and conserve the resources of a soil in different, more effective way than plantation monocultures. According to Vandermeer (1989), the competitive reduction principle explains the yield increase in mixtures that is related to the efficient utilization of available resources by the mixtures. The facilitative production principle refers to a direct positive effect on growth. A good ecological mixture results when differences in the species' growth characteristics reduce competition and fosters facilitation. Furthermore, species interactions must increase efficiency of use of those resources that limit productivity.

Synergy refers to interactions in which one species enhances the biological performance of another. In the tropics and sub-tropics almost all the industrial plantations are monocultures using fast growing species, which can meet the extensive demands of wood for construction, poles, pulp and fuel. The low growth rates of trees under monocultural industrial plantations in some areas, especially in the Tropical Asia and Pacific region, provide an additional incentive for considering mixed-species plantations. Pandey (1995) estimated that the annual wood production of teak was 2.4 to 3.0 m^3 ha^{-1} yr^{-1} in India and Bangladesh and <2 m^3 ha^{-1} yr^{-1} in Indonesia. In India, eucalypt plantations at 8 to 10 years of age produced about 6 m^3 ha^{-1} yr^{-1} and *Acacia nilotica* between 15 and 20 years of age produced around 3 m^3 ha^{-1} yr^{-1}, whereas *A. mangium* in Malaysia and Indonesia produced >20 m^3 ha^{-1} yr^{-1}. One way of improving long-term sustainable production of fast-growing species could be establishment of mixed stands with appropriate species.

The possibility of using nitrogen-fixing trees to supply nitrogen has been extensively discussed. Among the most intensively studied silvicultural systems that take advantage of nitrogen-fixing trees are mixed plantations of *Alnus* and hybrid *Populus* (Tarrant and Trappe, 1971; DeBell, 1975). Dawson et al. (1983) studied effects of *Alnus glutinosa* on hybrid *Populus* (Hansen and Dawson, 1982), and indicated that height growth of poplar in a short-rotation intensively cultured *Alnus-Populus* mixture was affected by both the percentage of *Alnus*, and distance between species. Height of 3-year-old poplar increased significantly with increasing alder in the mixture and decreased with increasing distance between poplar and alder. The mixtures containing higher percentages of alder had poplar heights comparable with those obtained from optimum rates of ammonium nitrate fertilization. The greatest growth of hybrid poplar occurred where alder comprised 66% of the mix and where alder rows were directly adjacent to poplar rows. *Alnus rubra* increases the productivity of *Pseudotsuga menziesii* in North America (Binkley et al., 1992b). On a peaty podzol in Ireland, Sitka spruce, intimately mixed with Japanese larch or lodgepole pine, grew significantly better than spruce alone due largely to improved nitrogen nutrition caused especially by the larch (O'Carroll, 1978 in Savill and Evans, 1986). In the British uplands, lodgepole pine, a well-used species on difficult mooreland when peat is prevalent, aids especially the establishment of Sitka spruce, which suffers chronic nitrogen deficiency in many infertile sites. On such sites the once common practice of planting conifers in mixtures is again being undertaken and expanded onto the deep peats of the north－previously the domain of lodgepole pine (Taylor, 1985).

Experiments in Australia and elsewhere have shown that mixtures of N-fixing species with *Eucalyptus* can provide more sustainable systems than just growing *Eucalyptus* alone. Enhanced growth of *Eucalyptus* was shown when grown as an intercrop with Acacia (Smith et al., 1989). *Albizia* sp. and *Acacia* increase the productivity of *Eucalyptus* in Hawaii (DeBell et al., 1985). *Eucalyptus saligna* and *Eucalyptus grandis* were planted in 50 : 50 row-wise mixtures with either *Acacia melanoxylon* or *Paraserianthes falcataria* (*Albizia falcataria*) at a 2 m × 2 m spacing. After 65 months, the eucalyptus trees grown with acacia were 25% taller and 28% larger in diameter and eucalyptus grown with paraserianthes were 63% taller and 65% larger in diameter than eucalyptus grown in pure stands. Annual production rates averaged 38 t/ha in pure *Eucalyptus*, 52 t/ha in *Eucalyptus/Acacia* and 95 t/ha in *Eucalyptus/Albizia*.

The increase in biomass productivity of mixed species was attributed to better cycling of N and P and to greater light capture and light use efficiency (Binkley et al., 1992). The recycling of nutrients contained in litter occurs efficiently in most mixed broadleaved temperate forests. The use of different soil resources by mixtures might ensure greater biological stability of the ecosystem (Savill and Evans, 1986). Khanna (1997) has shown that despite the competition, the growth of individual *Eucalyptus* trees was greater when in mixture with *Acacia*, suggesting that the advantage of additional N made available from N-fixation by *Acacia* outweighed losses due to competition for light and water. The success of mixed-species systems that employ N-fixing trees will depend on the continuous availability of phosphorus (Binkley et al., 1992).

A number of other nutrient interactions in mixed-species stands may result from the decomposition of the above-ground litter, changed microbial populations and their activities in the soil and rhizosphere (mycorrhizal effects, root diseases), and changed soil fauna (earthworms) and micro-environmental conditions (soil temperature and moisture levels). In South Carolina (Lane, 1988) over 80 woody non-leguminous nitrogen-fixing species that could be used to improve soil conditions on poor sites in forest situations from all over the world were tested. The species that appear to hold the most promise for use in improving the soil were *Alnus glutinosa*, *Alnus oblongifolia*, *Myrica cerifera*, *Eleaegnus angustifolia*, *Eleaegnus pungens* and *Eleaegnus umbellata*. *Eleaegnus* spp. have become pests in some areas. Soil changes occurring in mixed plantations of *Pinus taeda* and *A. glutinosa*, *Eleagnus* and *M. cerifera* after 4-5 years demonstrate significant increases in soil Ca, Mg, K and (in some cases) NH_4 in comparison with a monoculture of P. *taeda*.

The biomass and productivity of fine roots were studied in pure and mixed

Cunninghamia lanceolata and *Michelia macclurei* plantations in China by Liao et al., (1995). The biomass of living fine roots in three stands of pure and mixed plantations (in the order pure *Cunninghamia lanceolata*, pure *Michelia macclurei*, mixed stand) was 880 kg/ha, 3035 kg/ha and 1560 kg/ha, respectively, and that of dead ones was 235 kg/ha, 398 kg/ha and 565 kg/ha, respectively. The annual productivity of fine roots was 1137, 4318, and 2179 kg/ha, and annual mortality was 497, 595 and 1149 kg/ha, corresponding respectively to 36.8%, 21.6%, and 65.9% of annual litter fall in each stand. It is concluded that the mixed plantation had a higher productivity and better ecological conditions than the pure stands. Wang et al., (1997) studied nutrient cycling and productivity of the same mixed *Cunninghamia lanceolata* and *Michelia macclurei* plantations in comparison with those in pure *C. lanceolata* plantations. The process of nutrient return was greatly enhanced in the mixed plantations, and soil fertility and productivity were raised significantly. For example, in a 15-year-old mixed plantation, branch and leaf litter were respectively twice and triple in depth of those in a pure *C. lanceolata* plantation of the same age, with the litter mainly composed of fallen leaves of *M. macclurei*, which decompose more easily than those of *C. lanceolata*. The annual mortality of fine roots of the mixed plantation, corresponding to 65.9% of aboveground litter fall, was about twice as much as that in the pure plantation. The soil total N, NH_4 and available K contents of the mixed plantation were increased by 64.3%, 82.3% and 63.1%, respectively, compared with the pure plantation, and soil porosity and water status were also improved. The productivity, measured as annual net production, of the mixed plantation was increased by 52.7%. The ratio of return/uptake of Ca, Mg and K in the mixed plantation was twice as large as that in the pure plantation, indicating that the mixed plantation cycles its nutrients more efficiently, and sustains its productivity at a higher level.

4. To conserve biological diversity

This is characterised in terms of species richness, species rarity and species vulnerability. Mixed-species stands can be usefully developed to conserve biological diversity. Comparison of ant diversity in the leaf litter of mixed and pure native tree plantations (*Albizia guachapele*, *Dipteryx panamensis*, *Terminalia amazonia* and *Virola koschnyi*) in the humid Atlantic lowlands, Costa Rica was done by Strongin, (1997). Ants were chosen as a good indicator of biodiversity. A total of 220 ants from nine genera were collected. The results suggest that the mixed-forest plantations and those adjacent to a secondary forest supported a greater number of ant genera than monoculture plantations.

5. To obtain marketing advantages

Mixed crops, although more costly to establish and manage, often have economic advantages; for instance they may be more flexible in meeting market demands. Careful selection of species mixtures can insure against the risk of biological failure (caused by species characteristics or ecological conditions) and against economic failure (caused by excessive wood supply of a species and lack of markets for lesser-known species).

6. To provide a range of goods and services

When selecting for a mixed stands, it is important to have clear objectives about products. For example, a mixed-species stand may provide wood products such as fuel and poles, fodder for animals, resin or gum for industry, and nuts or other products for human consumption. Mixed crops, especially of broadleaves and particularly if uneven-aged, have certain aesthetic attributes: their amenity, landscape, recreational and sporting attributes are generally greater (Hart, 1991).

Possible benefits arising from plantation monocultures in situations where mixed plantations are likely to fail:

One should bear in mind that it is also possible to see monocultures, which evolved naturally where all mixtures failed. Single-species even-aged forests arise in nature after catastrophes, such as fire, windthrow, floods, landslips, and insect epidemics. Examples of virtually pure even-aged stands show that low diversity in a community may produce a stable structure (Whitehead, 1982). They occur in the pine forests of the eastern United States and in the Douglas fir forests in the northwest, as well as in many other coniferous forest formations. Many of the *Nothofagus* forests in New Zealand are purely one species (Chapman, 1958, cited in Whitehead, 1982). Wardle, (1970, cited in Whitehead, 1982) concluded that *Nothofagus solandri* was often the only species present in the driest forests in the South Island and in some dry mountainous areas of the North Island. Similar situation discovered Veblen at al. (1980) in the Valdivian Andes, Chile, in old-growth *Nothofagus* forests. Monocultures have been found with low diversity especially in certain extreme environments like salt marshes (Whittaker and Woodwell, 1972) or the reed swamps of South Moravia with wild fluctuations in water levels (Fiala and Květ, 1971). It is apparent, therefore, that high diversity is not always associated with high stability and there are many examples of natural ecosystems, which are stable but exhibit low diversity, often being virtual monocultures. Plantation forestry is usually characterised by single species in uniform age classes, which may be comparable to the structure of many natural communities. Plantation forests are sometimes criticized for their low diversity and it is often concluded that this leads to instability or vulnerability to environmental change or pathogen and insect attack. It is not true that diversity in natural communities is always positively correlated with stability, although clearly the terms are difficult to define and measure (Whitehead, 1982).

Mixtures are not always beneficial. Some species can reduce the growth of companion species. Handley, (1963, cited in Savill and Evans, 1986) gives an example of the effect of the dwarf shrub heather which can inhibit the development of spruce mycorrhizae and results in very poor growth, partly through unsuccessful competition for nitrogen. Certain species of walnut (*Juglans*) also produce chemicals from leaf secretions, which reduce the growth of trees and other plants. The interactions associated with allelopathy have been discussed in detail by Inderjit and Moral, (1997) who pointed out that allelopathy can be defined as any direct or indirect effect by one plant on another through production of chemical compounds that escape into the environment. Demonstrating allelopathy involves not only isolating compounds but also demonstrating that a toxic effect on other plant species is primarily the function of a compound and that when other interactions such as resource limitations are alleviated, the allelopathic effect persists. They gave convicting evidence that allelopathy has evolved as a result of resource competition and other ecological factors.

MacLaren, (1983, cited in Savill and Evans, 1986) impeaches the widely held belief that mixed forests are exposed to fewer risks of attack from insect and fungal pathogens by giving example of the spruce gall aphid (*Adelges cooleyi*) which alternates its life cycle between interior Douglas fir and spruce in western Canada. Mixtures of these two species can lead to infestations of adelgids and reductions in the growth of spruce. Another example given by Savill and Evans, (1986) occurs in mixtures of two needled pines and aspen (*Populus tremula*), where the rust fungus *Melampsora pinitorqua* alternates parts of its life cycle between the two, and can be very damaging to pines.

Advantages of pure crops compared with mixtures include their simplicity, and ease and lower cost of establishment. They are generally of more even growth, size, grade and quality, easier to manage, thinning is less arduous, and small diameter roundwood and sawlogs are more easily harvested and marketed (Hart, 1991).

Conclusions:

Replacement of plantation monocultures with mixtures of different species is a complicated process and should be done only where appropriate conditions appear.

There should be three main areas considered before the decision is taken:

– Reasons
– Possibilities
– Tools

The main reason is conflict between demands of benefits and restrictions coming from the character of transformed forest and from the substantiality of the ecosystem. Climate is the main variable controlling the structure, diversity and stability of ecosystems, and also determines long-term structural changes. In mature ecosystems a large proportion of the nutrients are bound up in living and dead biomass. In plantation forestry it is important to avoid destruction of the mineral cycling processes.

The possibilities should arise from the comparison of monoculture with a new system in terms of economic balance between financial inputs into a new system of management methods and their covering by outputs. The area of monoculture plantations is large and therefore it is necessary to distinguished by evaluating when the transition is necessary and in place. Not all monocultures need to be necessarily transformed.

Tools are dependent on the silviculture technique. It is unrealistic to think about conversion if it is too expensive in terms of silviculture techniques or even impossible to achieve with current silvicultural methods, technology and knowledge.

The conversion is defined by a change in the species structure of the forest stands achieved by early or faster regeneration, leading into mixed stands.

Conversions are reasonable in places, where present monoculture plantations keep failing for various reasons:
- Lack of productivity
- Absence of protective functions
- Absence of social functions
- Absence of environmental functions
- Failure in combining with the fundamentals of sustainable forest management.

Effective forest management should include fundamental ecological bases and eco-technical principles. Amongst the most important ones are:

1. Tree species and their stands grow best when an optimum array of ecological factors is achieved. It is possible to alter ecological factors but only to certain extent, usually by modifying soil conditions, for example by applying lime, fertilisers and melioration or by improving the microclimate of the stand or mezoclimate of larger forested areas which can be done by different silviculture techniques.

2. The optimal growth conditions depend on what is supplied by concrete ecotope and what is allowed by certain level of pollution. More important for decision-making about silvicultural operations is dynamical prognosis of growing time — the total lifetime of the forest (displayed by degrees or levels of damage) than present health stage of the forest.

3. Individual survival is determined also by the environment. Therefore we can see the increasing importance of maintaining the stands.

4. Long term influences of pollution narrow the gene pool and in some places cause complete extinction of native populations which considerably disrupts sustainable forest principles.

REFERENCES:

Binkley, D., Dunkin, K.A., DeBell, D., and Ryan, M.G., 1992. Production and nutrient cycling in mixed plantations of *Eucalyptus* and *Albizia* in Hawaii. Forest Science, 38: pp. 393–408.

Binkley, D., Sollins, P., Bell, R., Sachs, D., and Myrold, D., 1992b. Biogeochemistry of adjacent conifer and alder-conifer stands. Ecology, 73: pp. 2022–2033.

Dawson, J.O., Dzialowy, P.J., Gertner, G.Z., and Hansen, E.A., 1983. Changes in soil nitrogen concentration around Alnus glutinosa in a mixed, short-rotation plantation with hybrid Populus. Can. J. For. Res., 13: pp.572–576.

DeBell, D.S., 1975. Short rotation culture of hardwoods in the Pacific Northwest. Iowa State J. Res., 49: pp. 345–352.

DeBell, D.S., Whitesell, C.D., and Schubert, T.H., 1985. Mixed plantation of *Eucalyptus* and leguminous trees enhance biomass production. Research Paper, Pacific-Southwest Forest and Range Experiment Station, USDA Forest Service.

El-Lackany, M.H., and Mohamed, S.Y., 1993. Effects of species combination on the root characteristics of young *Accacia saligna, Casuaria cunninghamiana* and *Eucalyptus camaldulensis* trees. Alexandria J. Agricultural Res., 38: 211–227.

Fiala, K., and Květ, J., 1971. Dynamic balance between plant species in South Moravian reedswamps. In: Duffey, E., and Watt, A.S., (ed.). The 11th symposium of the British Ecological Society, University of East Anglia, Norwich, 7–9 July 1970. Blackwell Scientific

Publications, Oxford, UK: pp. 241–269.

Hansen, E.A., and Dawson, J.O., 1982. Effect of *Alnus glutinosa* on hybrid *Populus* height growth in a short-rotation intensively cultured plantation. Forest Science, 28: pp. 49–59.

Hart, C., 1991. Practical Forestry for the agent and surveyor. Alan Sutton Publishing Inc., Wolfeboro Falls, NH, U.S.A.

Helms, J.A., 1998. The dictionary of Forestry. CABI Publishing, Oxon, UK. Inderjit, and Moral, R.D., 1997. Is separating resource competition from allelopathy realistic? The Botanical Review, 63(3): pp. 221–230.

Kelty, M.J., 1992. Comparative productivity of monocultures and mixed-species stands. In: Kelty, M.J., (ed). *The ecology and silviculture of mixed-species forest*, pp. 125–141. Kluwer Academic Publ., The Netherlands.

Khanna, P.K., 1997. Comparison of growth and nutrition of young monocultures and mixed stands of *Eucalyptus globulus* and *Accacia mearnsii*. Forest Ecology and Management, 94: pp. 105–113.

Lane, C.L., 1988. Evaluation of native and exotic non-leguminous nitrogen fixing species for use as soil improvers in South Carolina. Nitrogen-fixing Tree Research Reports, 6: pp. 24–25.

Liao, L.P, Chen, C.Y., Zhang, J.W., Gao, H., 1995. Chinese Journal of Applied Ecology, 6(1): pp. 7–10.

Lines, R., 1981. Self-thinning mixtures. FC Report on forest research 1981.

Lines, R., 1987. Choice of seed origins for the main forest species in Britain. FC Bulletin, 66.

Matthews, J.D., 1989. Silvicultural systems. Oxford University Press, Oxford, UK.

Montagnini, F., Gonzalez, E., Porras, C., and Rheingans, R., 1995. Mixed and pure forest plantations in the humid neotropics: a comparison of early growth, pest damage and establishment costs. Commonwealth Forestry Review, 74: 306–314.

Nykvist, N., Grip, H., Sim, B.L., Malmer, A., and Wong, F.K., 1994. Nutrient losses in forest plantations in Sabah, Malaysia. Ambio, 23: 210–215.

Pandey, D., 1995. Forest resources assessment 1990. Tropical forest plantation resources. FAO Forestry paper128. FAO, Swedish University of Agricultural Sciences, Swedish International Development Cooperation Agency.

Poleno, Z., 1997. Trvale udržitelné obhospodařování lesů. MZe ČR, Czech Republic.

Savill, P.S. and Evans, J., 1986. Plantation silviculture in temperate region. Caledon Press, Oxford, UK.

Smith, I.W., Marks, G.C., Featherston, G.R., and Geary, P.W., 1989. Effects of inter-planted wattles on the establishment of eucalyptus planted on forest sites affected by *Phytophthora cinnamomi*. Aust. For., 52: pp. 74–81.

Strongin, S., 1997. Comparison of ant diversity in the leaf litter of mixed and pure native tree plantations in the humid Atlantic lowlands, Costa Rica. TRI News, 16(1): pp. 6–8.

Tarrant, R.F., and Trappe, J.M., 1971. The role of *Alnus* in improving the forest environment. Plant Soil, Spec, Vol.: pp. 335–348.

Taylor, C.M.A., 1985. The return of nursing mixtures. Forestry and British timber, 14(5): pp. 18–19.

Tesař, V., 1993. Základní představy o nutných systémových změnách lesního hospodářství v důsledku globálních změn klimatu. In: Rožnovský, J., (ed). Klimatické změny a lesní hospodářství. Brno, Československá bioklimatologická společnost, sekce bioklimatologie rostlin, pp. 77–82.

Vandermeer, J., 1989. The ecology of intercropping. Cambridge Univ. Press, Cambridge.

Veblen, T.T., Schlegel, F.M., and Escobar, R., 1980. Structure and dynamics of old-growth *Nothofagus* forests in Valdivian Andes, Chile. Journal of Ecology, 68: pp. 1–31.

Wang, S.L., Liao, L.P., Ma, Y.Q., 1997. Nutrient return and productivity of mixed *Cunninghamia lanceolata* and *Michelia macclurei* plantations. Chinese Journal of Applied Ecology, 8(4): pp. 347–352.

Whitehead, D., 1982. Ecological aspects of natural and plantation forests. Forestry Abstracts, 43(10): pp. 615–624.

Whittaker, R.H., Woodwell, G.M., 1972. Evolution of natural communities. In: Wiens, J.A., (ed.). Ecosystem structure and function. Cornvallis, Oregon State University Press, Oregon, U.S.A.: pp. 137–159.