Comparison of Growth, Nutrition and Soil Properties of Pure and Mixed Stands of *Populus deltoides* and *Alnus subcordata*

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Concerns about decline in soil fertility and long-term productivity of fast-growing plantations have promoted interest in using nitrogen-fixing trees in mixed species plantations. *Populus deltoides* and *Alnus subcordata* were planted in five proportions (100P, 67P:33A, 50P:50A, 33P:67A, 100A) in Noor, Iran. After 7 years, the effects of species interactions on tree growth and nutrient concentration in live and senescent leaves and soil properties were assessed. Diameter at breast height and total height of individual *Populus* trees were positively affected by the presence of *Alnus*. Nitrogen concentrations in fully expanded and senescent leaves of *Populus* were higher in mixed plantations than monoculture plantations. The results of nutrition and nutrient return and growth indicated that mixed plantations of these two species were more productive and sustainable than their monoculture plantations. Within the framework of this experiment, it appeared that production was maximized when these two species were grown together in the relative proportions of 50% *Populus* and 50% *Alnus*.

1 Introduction

Poplars (*Populus* L. spp.) are preferred plantation species, because their fast growth is expected to meet the extensive demands of wood for poles, pulp and fuel (Kiadaliri 2003, Ghasemi 2000, Zia-bari 1993). Productivity of plantations depends strongly on soil nutrient supply and it may be malleable under the influence of management practices and species (Binkley 1997). Almost all the industrial plantations are monocultures, and questions are being raised about the sustain-

ability of their growth and their effects on the site (Khanna 1997). Repeated harvesting of fast-growing trees such as poplar plantations on short rotations may deplete site nutrients. Nitrogen losses are likely to be very important for future growth. It is, therefore, appropriate to explore new systems of plantation management in which N may be added via fixation (Khanna 1997).

Mixed plantation systems seem to be the most appropriate for providing a broader range of options, such as production, protection, biodiversity conservation, and restoration (Montagnini et al. 1995, Keenan et al. 1995, Guariguata et al. 1995 and Parrotta and Knowles 1999).

Mixed plantations yield more diverse forest products than monospecific stands, helping to diminish farmer's risks in unstable markets. If planned with consideration for each species' response to mixed conditions, mixed designs can be more productive than monospecific systems. In addition, a mixture of species, each with different nutrient requirements and different nutrient cycling properties, may be overall less demanding on site nutrient than monoculture stands (Montagnini 2000).

Mixed plantations can produce more biomass per unit area because competition among individuals is reduced and the site is used integrally (Montagnini et al. 1995). The roots of different species may occupy different soil strata allowing more complete utilization of soil and water resources (Lamb and Lawrence 1993). More solar energy can be captured because different species have different light requirements and crowns are broadly distributed in the vertical plane (Guariguata et al. 1995). However, the success of the establishment of mixed forest plantations depends on plantation design and an appropriate definition of the species to be used, taking into consideration ecological and silvicultural aspects (Wormald 1992).

Concerns about decline in soil fertility and long-term productivity of fast-growing plantations have promoted interest in using nitrogen-fixing trees in mixed species plantations (Rhoades and Binkley 1996). Nitrogen-fixing trees, mainly leguminous species, have been widely extolled for their soil-improving characteristics related to their production of nitrogen-rich, often rapidly decomposing leaf litter (Parrotta 1999). Although there have been some documented cases of increased productivity in mixed-species plantations in both temperate and tropical regions, the collective results of such studies have been inconclusive and show that accurate species/site matching and choice of complementary species strongly influence mixed-species plantation productivity (FAO 1992).

Experiments in some parts of world such as North America have shown enhanced growth of *Populus* spp. when grown as an intercrop with *Alnus* L. spp. (FAO 1992, Coté and Camiré 1987, Hansen and Dawson 1982, Radwan and DeBell 1988). The present study was undertaken to assess the influence of *Alnus subcordata* C.A.Mey and *Populus deltoids* Marsh. plantations on soil fertility parameters, the influence of *Alnus* on *Populus* growth and nutrient concentration of fully expanded and senescent leaves in monocultures and mixed plantations.

2 Materials and Methods

2.1 Site Characteristics

The study area is located at the Chamestan experiment station, in Mazandaran province, on the northern parts of Iran (36°29'N, 51°59'E). Experimental plots were located at an altitude of 100 m above sea level and with low slope (0–3%). Annual rainfall averages 803 mm, with wetter months occurring between September and February, and a dry season from April to August monthly rainfall usually averages < 40 mm for 4 months. Average daily temperatures range from 11.7 °C in February to 29.5 °C in August.

The soils are well-drained, and have a silty loam texture with a pH 7.6–8.1. Previously (approximately 50 years ago) this area was dominated by natural forests containing native tree species such as *Quercus castaneifolia* C.A.Meyer., *Gleditschia caspica* Desp., *Carpinus betulus* L., etc. The surrounding area is dominated by agricultural fields and commercial building.
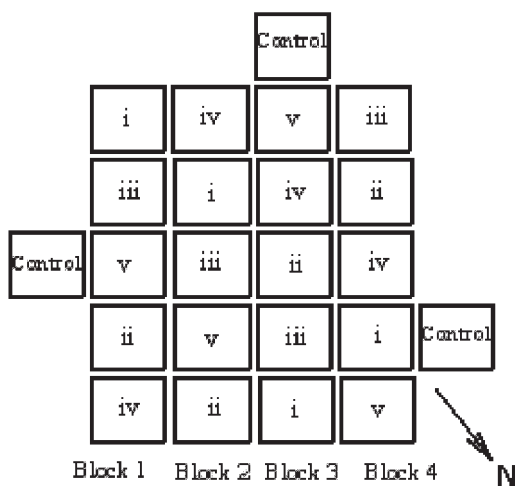
Fig. 1. Experimental plot layout. Plot treatment codes: (i) *Populus*, (ii) *Alnus*, (iii) 50% *Populus* + 50% *Alnus*, (iv) 67% *Populus* + 33% *Alnus*, (v) 33% *Populus* + 67% *Alnus*, (vi) Control.

2.2 Experimental Design

Experimental plantations were established in 1996 using a randomized complete block design (Fig. 1) that included four replicate 40 m × 40 m plots of each of the following treatments:

(i)   *Populus deltoides* (100P),
(ii) *Alnus subcordata* (100A),
(iii) 50% *P. deltoides* + 50% *A. subcordata* (50P:50A),
(iv) 67% *P. deltoides* + 33% *A. subcordata* (67P:33A),
(v)   33% *P. deltoides* + 67% *A. subcordata* (33P:67A),
(vi) Unplanted Control (grass).

Tree spacing within plantations was 4 m × 4 m and tow species were systematicly mixed within rows.

2.3 Site Preparation and Planting of Seedlings

Site preparation for all plantations and control plots consisted of disk harrowing to a depth of 10–15 cm. Containerized seedlings, 50–100 cm in height, were used for planting in April 1996.

Seedlings of both species were planted simultaneously in monocultures and mixed plantations.

2.4 Tree Survival and Growth Measurements

Diameters of trees at 1.3 m height (DBH), crown diameter, tree basal area and tree heights were measured in the central 24 m × 24 m area (sub-plot) of each plot, excluding the outer two tree rows, in July 2003.

2.5 Nutrition and Nutrient Return by the Leaves

Foliage samples were collected from the stands in September 2003. Leaves were collected from the bottom one-third of the tree by clipping two small twigs located on opposite sides of the crown. Six representative trees (two near the center of sub-plot and one in each corner of it) of each species were sampled for fully expanded leaves. In addition, senescent leaves were collected from each species in each sub-plot. The Samples were dried at 70 ℃. Nitrogen was determind using the Kjeldhal, P using Spectrophotometer (by the Olsen method), and K, Ca and Mg (by ammonium acetate extraction at pH 9) was determined using Atomic absorption spectrophotometer (Bower et al. 1952).

2.6 Soils

Soils were sampled to a depth of 60 cm in all plantations and control plots in August using a 7.6 cm diameter core sampler (n = 3 cores/plot) taken at two 15 cm and a 30 cm interval. After air drying, soils were passed through a 2.0 mm (20 mesh) sieve to remove roots prior to chemical analyses.

Soil pH was determined using an Orion Iona-lyzer Model 901 pH meter in a 1:2.5, soil: water solution. EC (electrical conductivity) was determined using an Orion Ionalyzer Model 901 EC meter in a 1:2.5, soil: water solution. Soil organic matter was determined using the Walkley-Black method. Total N was determined using the Kjeldhal method (Bremmer 1960). Available P was
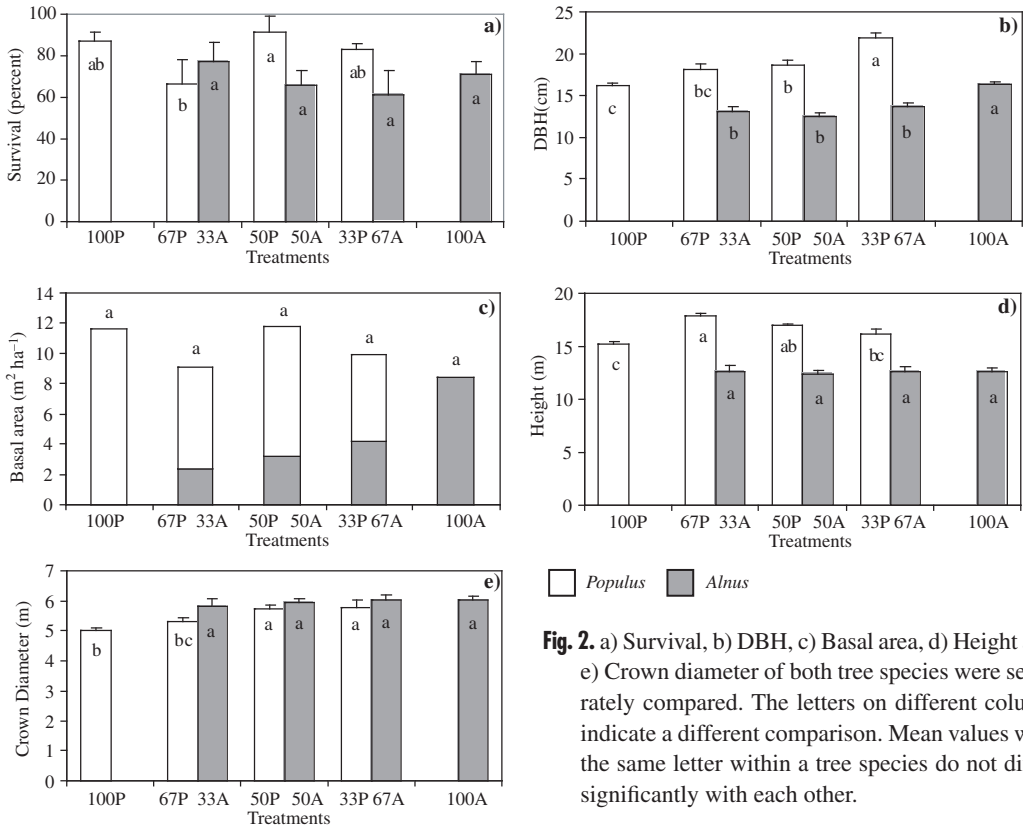
Fig. 2. a) Survival, b) DBH, c) Basal area, d) Height and e) Crown diameter of both tree species were separately compared. The letters on different column indicate a different comparison. Mean values with the same letter within a tree species do not differ significantly with each other.

determined with spectrophotometer by using Olsen method (Homer and Pratt 1961). Available K, Ca and Mg (by ammonium acetate extraction at pH 9) were determined with Atomic absorption Spectrophotometer (Bower et al. 1952).

2.7 Statistical Analyses

One-way analyses of variance (ANOVA) were used to compare tree growth, soil properties, and leaf nutrients data among experimental treatments. Tukey-HSD and Duncan tests were used to separate the means of dependent variables which were significantly affected by treatment.

3 Results

3.1 Tree Survival and Growth

The survival of *Populus* was generally unaffected by the presence of *Alnus* with the exception of higher *Populus* survival when the two species were grown in equal proportion (50P:50A) than 67P:33A (p < .05, Duncan) (Fig. 2a). *Alnus* survival, in contrast, was unaffected by the presence of *Populus* in any proportion (p < .08, Duncan).

Mixed plantations had a positive effect on the DBH of *Populus* when compared with the trees growing in monoculture. *Populus* in the 33P:67A treatment had the highest DBH. The DBH of *Alnus* was reduced when this species was grown in combination with *Populus* as compared with monocultures but the relative proportion of *Populus* did not further affect this result (p < .01, Tukey-HSD) (Fig. 2b).

Table 1. Soil properties in plantations and control plots in different soil layers[a] with their standard deviations (below).

Soil properties	Depth cm	100P	67P:33A	50P:50A	33P:67A	100A	Control	ANOVA[b]
EC /ds/cm)	0–15	0.09 ab (0.05)	0.12 ab (0.05)	0.08 ab (0.02)	0.12 ab (0.05)	0.26 a (0.04)	0.06 b (0.01)	*
Total N (%)	0–15	0.29 ab (0.03)	0.23 b (0.01)	0.25 ab (0.02)	0.26 ab (0.09)	0.30 ab (0.04)	0.31 a (0.06)	*
	15–30	0.14 abc (0.04)	0.11 bc (0.02)	0.11 c (0.01)	0.16 ab (0.04)	0.17 a (0.05)	0.12 abc (0.01)	**
	30–60	0.08 a (0.03)	0.06 a (0.01)	0.06 a (0.02)	0.07 a (0.02)	0.08 a (0.02)	0.07 a (0.02)	ns
Organic matter (%)	0–15	4.77 a (0.05)	4.27 ab (0.48)	4.13 b (0.38)	4.17 ab (1.30)	4.42 ab (0.57)	4.69 ab (0.07)	*
P available (mg/kg)	0–15	22.79 b (4.42)	20.89 b (3.31)	20.27 ab (4.31)	16.38 b (7.96)	24.26 a (10.22)	15.23 ab (2.88)	**
Ca available (mg/kg)	0–15	18.75 b (7.50)	13.75 b (8.54)	20.00 ab (7.07)	17.50 ab (8.66)	23.75 ab (10.31)	30.00 a (18.20)	*

[a] Based on three composited 7.6 cm diameter core samples per plot
[b] ANOVA results: ns = treatment effect not significant, * = p < 0.08, ** = p < 0.05, Duncan.
 Mean values with the same letter within the soil layer do not differ significantly with each other.

Total basal area of both species was not affected by relative proportions of the two species (p < .08, Duncan) (Fig. 2c). Within the 50P:50A treatment *Populus* accounted for significantly more of the total basal area than did *Alnus*.

Height growth of *Populus* was affected by the presence of *Alnus* (Fig. 2d). In the 67P:33A and 50P:50A treatments *Populus* height was higher than in the treatment 100P (p < .01, Tukey-HSD). The height growth of *Alnus* however, was unaffected by the presence of *Populus* (p < .08, Duncan).

Similarly the crown diameter of *Populus* was positively affect by the presence of *Alnus* (p < .01, Tukey-HSD) but the crown diameter of *Alnus* was unaffected by the presence of *Populus* (p < .08, Duncan) (Fig. 2e). When the two monocultures were compared, *Alnus* had a larger crown diameter than *Populus*.

3.2 Soil Properties

There were very few differences in soil properties between treatments. Soil pH, ranging from 5.78 to 7.12, and Carbon: nitrogen ratio, ranging from 7.56 to 18.09, did not show any signifi-

cant difference between the treatments. Soil EC in 0–15 cm depth of monoculture *Alnus* and control treatments was different and no significant differences were found in deeper soil layers (p < .08, Duncan) (Table 1). Organic matter was different between 0–15 cm depth of monoculture *Populus* and 50P:50A treatments whereas no significant differences were found in deeper soil layers (p < .08, Duncan) (Table 1). Total nitrogen had some differences between the treatments in 0–15 cm and 15–30 cm soil layers. Total nitrogen in 0–15 cm depth was significantly higher in the control plot than in the 67P:33A treatment (p < .08, Duncan). The differences in 15–30 cm depth were stronger than 0–15 cm depth (p < .05, Duncan). It seems that the treatments that had more proportion of *Alnus* had lower C:N ratio than others (Table 1). Available P in 0–15 cm depth of monoculture *Alnus* was different (p < .08, Duncan) with monoculture *Populus*, 67P:33A and 33P:67A treatments whereas no significant differences were found in deeper soil layers (Table 1). Available K, ranging from 22.5 to 61.25 mg kg^{-1}, and available Mg, ranging from 10.00 to 16.25 mg kg^{-1}, did not show any significant difference between the treatments. Available Ca in 0–15 cm depth of 67P:33A and control treatments was

Table 2. Nitrogen concentrations in fully expanded and senescent leaves with their standard error in the parenthesis.

Treatment	Populus		Alnus	
N (%)	Fully expanded	Senescent	Fully expanded	Senescent
100P	1.50 b (0.04)	0.99 b (0.07)		
67P:33A	1.91 a (0.10)	1.22 a (0.08)	2.77 a (0.12)	2.61 a (0.15)
50P:50A	1.90 a (0.15)	1.25 a (0.01)	2.73 a (0.1)	2.53 a (0.26)
33P:67A	1.88 a (0.10)	1.27 a (0.13)	2.79 a (0.05)	2.56 a (0.15)
100A			2.60 a (0.03)	2.18 b (0.13)
ANOVA	**	**	ns	ns

ANOVA results: ns – treatment effect not significant; ** = p < 0.05 Duncan. Mean values with the same letter within each column do not differ significantly with each other.

different (p<.05, Duncan) whereas no significant differences were found in deeper soil layers (Table 1).

3.2 Nutrition and Nutrient Return by the Leaves

The presence of *Alnus* as N-fixing tree had strong influence on nitrogen cycling of *Populus*. *Populus* leaves (fully expanded and senescent) had significantly higher N concentration when grown in mixtures than in monocultures (p<.05, Duncan). Nitrogen return by senescent leaves of *Alnus* in monoculture plantations was significantly lower than the ones that grown in mixed plantations (p< .05, Duncan) (Table 2). Phosphorus concentrations in fully expanded and senescent leaves of *Populus* and *Alnus* did not show any significant differences (p<.08, Duncan). K concentrations in fully expanded (ranging from 1.07% to 1.67%) and senescent (1.51% to 1.91%) leaves of *Populus* and fully expanded (0.66% to 1.07%) and senescent (1.27% to 1.34%) leaves of *Alnus* did not show any significant differences among treatments (p<.08, Duncan). Magnesium concentrations followed similar trends among treatments: ranging from 1.46% to 2.67% and 1.03% to 1.24% orderly in fully expanded leaves of *Populus* and *Alnus* and 1.48% to 2.10% and 0.96% to 1.27 orderly in senescent leaves of *Populus* and *Alnus* (p<.08, Duncan). Calcium concentrations of fully expanded leaves of *Populus* (2.67% to 3.80%) in 67P:33A treatment was different (p<.05, Duncan) with those of 50P: 50A treatment and did not show any significant differences from

Alnus (0.96% to 1.36%). The Ca concentration in senescent leaves of *Alnus* (0.73% to 1.32%) in monoculture treatments was significantly (p<.08, Duncan) lower than those in mixtures whereas it did not show any significant differences from *Populus* (1.48% to 2.10%).

4 Discussion

Because the survival of both species (*Populus* and *Alnus*) did not show in most cases any differences between monocultures and mixed plantations it can be concluded that there was little competition between the two species, as a result of their planting spacing. Parrotta (1999) found more survival in monoculture plantations of *Eucalyptus robusta* than mixtures with *Casuarina* and *Leucacna*. The differences between our results and those obtained by Parrotta (1999) were probably due to differences in planting space. The other reason might be the difference in growth rate and crown diameter of his target and associated species in comparison with our species. Our results were, howere, similar to those obtained by Khanna (1997) about *Eucalyptus glabulus* and *Acacia mearnsii* in monocultures and mixed plantations.

Higher *Populus* diameter growth was observed in treatments with less proportion of *Populus*. This could be due to a decrease in light competition, as the most important competition factor (Binkley 1992). Results of our work correspond with that of Khanna's work (1997) on monocultures and mixed plantations of *Eucalyptus* and *Acacia*.

It was also found that N-fixation by *Acacia* in mixed plantations resulted in increased diameter growth of *Populus* (Khanna 1998). Rapid diameter growth was also found to be due to domination of the target species (Montagnini 2000). No influence of nitrogen fixing trees on diameter growth on non nitrogen fixing tree was observed by Parrotta (1999) but Binkley (1983) found contrary results with *Alnus rubra* having a positive effect on the diameter growth of *Pesudotsuga menziesii* in poor sites.

Basal area of both *Populus* and *Alnus* did not show any significant differences in monocultures compared to mixed plantations in our study. In contrast, Parrotta (1999), Khanna (1997), Montagnini (2000) found bigger basal area for target species in mixed plantations compared to monocultures.

Increased light competition in mixed plantations containing a grater proportion of *Populus* may explain the greater height growth of this species in these plots. *Alnus* did not show any differences in height growth between the monocultures and mixtures. Our results are similar to those obtained by Parrotta (1999) and Khanna (1997), in monocultures and mixed plantations of *Eucalyptus* and *Acacia*, and Hansen and Dawson (1982) in monocultures and mixed plantations of poplar species and *Alnus glotinosa*. In contrast to our results, Heilman (1985) did not observe greater height of target species in mixed plantations (FAO 1992).

The crown diameter of *Populus* was significantly smaller in monoculture plantations in comparison with that in the 50P:50A and 33P:67A treatments. It might be the result of decreasing light competition in mixed plantations with less proportion of *Populus*. Water and light competition in mixed plantations result in decreasing crown diameter (Fisher and Binkley 1999). These results have strong correlation with other results such as increasing diameter in the treatment with high *Alnus* proportions and increasing height in treatment with low *Alnus* proportions.

No statistically significant differences were observed in soil pH between the treatments, whereas significant reductions in soil pH have been found in half of the studies about the effect of nitrogen fixing trees (NFT) on soil (Fisher and Binkley 1999). Montagnini (2000) and Gia-

rdina et al. (1995) reached the same result as we, whereas Rhoades and Binkley (1996), and Parrotta (1999) found lower soil pH in mixed plantations. Higher planting density and low age of our plantations might be the main reasons for no significant difference in soil pH.

No significant differences were observed in soil organic matter content in 15–30 cm and 30–60 cm soil layers between the treatments. The main reason for the reduction of soil organic matter in 0–15 cm depth in the 50P:50A treatment compared to that in the monoculture of *Populus* might be the result of increasing biological activities in the soil. Parrotta (1999) came to the same conclusion. In contrast with our results Garcia-Montiel and Binkley (1998) found that organic matter content in 0–20 cm depth of soil under NFT *Albizia* was higher than in soil under *Eucalyptus*.

It is obvious that *Alnus* increased soil nitrogen in 15–30 cm depth in comparsion with 67P:33A and 50P: 50A treatments. In 0–15 cm depth, soil nitrogen was highest in the control plot, which we can relate to grasses. The decrease in soil nitrogen of mixed plantations with high proportions of *Populus* might be the result of invading *Populus* roots to nodules of *Alnus* (Binkley 1992). Binkley (1997) and Garcia-Montiel and Binkley (1998) found that *Albizia* increased soil nitrogen more than *Eucalyptus*. Parrotta (1999) and to some extent Montagnini (2000) did not observe any significant differences in soil nitrogen between monocultures and mixed plantations. Whereas Hansen and Dawson (1982) observed that mixed plantations of *Populus* and *Alnus glutinosa* resulted in increasing soil nitrogen in comparison with their monoculture plantations (FAO 1992).

No significant differences were observed in the C:N ratio. The main reason might be the low percentage in the mixtures. Parrotta (1999) reached the same result with us in monocultures and mixed plantations of *Eucalyptus* and two NFTs.

Few significant differences were observed between the treatments in concentrations of available Mg, K, Ca and P in soil. We can relate these differences to previous soils condition such as what Parrotta (1999) did. Montagnini (2000) came to the same results in monocultures and mixed plantations as we did.

Nitrogen concentrations in fully expanded and

senescent leaves of *Populus* were higher in the mixed plantations than those in the monocultures of *Populus*. This is a good reason for the influence of mixed plantations with *Alnus* as an N-fixing tree on nutrition and nutrient return of our target species. The other result is less N of *Alnus* senescent leaves in monoculture plantations than mixed ones that shows more nitrogen return in mixed plantations. Parrotta (1999) reached to the same results and found that litterfall (leaves) of NFT and target species in mixed plantations had more N than in monocultures. In contrast to us Khanna (1997) did not observe any significant differences in fully expanded and senescent leaves of *Acacia* between monocultures and mixed plantations.

The higher concentration of Ca in senescent leaves of *Alnus* in mixed plantations than monocultures showed that more Ca can return to the soil in mixed plantations. Finally we can conclude that mixed plantations of these two species are more productive and sustainable than monocultures. The introduction of one mixture as the best one is rather difficult but 50P:50A could be the most productive and sustainable.

References

Binkley, D. 1983. Ecosystem production in Douglas-fir plantations: Intraction of red alder and sit fertility. Forest Ecology and Management 5(3): 215–227.

— 1992. Mixture of nitrogen-fixing and non-nitrogen-fixing tree species. In: Cannel, M.G.R., Malcom D.C. & Robertson P.A. (eds). The ecology of mixed species stands of trees. Blackwell Scientific Publications, Oxford. p. 99–123.

— 1997. Bioassays of the influence of Ecalyptus saligna and Albizia falcataria on soil nutrient supply and limitation. Forest Ecology and Management 91(2–3): 229–234.

Bower, C.A., Reitemeier, R.F. & Fireman, M. 1952. Exchangeable cation analysis of saline and alkali soils. Soil Science 73(4): 251–261.

Bremmer, J.M. 1960. Determination of nitrogen in soil by the Kjeldahl method. Journal of Agricultural Science 55(13): 11–33.

Coté, B. & Camiré, C.C. 1987. Tree growth and nutrient cycling in dense plantings hybrid poplar and black alder. Canadian Journal of Forest Research 17(6): 516–523.

FAO. 1992. Mixed and pure forest plantation in the tropics and subtropics. FAO Forestry Paper 103. 152 p.

Fisher, R. & Binkley, D. 1999. Ecology and management of forest soil. JohnWiley&Sons, Inc., Third edition. 489 p.

Garsia-Montiel, D.C. & Binkley, D. 1998. Effect of Eucalyptus saligna and Albizia falcataria on soil processes and nitrogen supply in Hawaii. Oecologia 113(4): 547–556.

Giardina, C.P., Huffman, S., Binkley, D. & Caldwell, B.A. 1995. Alder increase soil phosphorus availability in a Douglas-fir plantation. Canadian Journal of Forest Research 25: 1652–1657.

Ghasemi, R. 2000. Study of phenology of different Populus in Karaj and Safrabasteh Gilan. M.Sc. thesis of Tarbiat Modarres University. 171 p.

Guariguata, M.R., Rheingans, R. & Montagnini, F. 1995. Early woody invasion under tree plantations in Costa Rica: implications for forest restoration. Restoration Ecology 3(4): 252–260.

Hansen, E.A. & Dawson, J.O. 1982. Effect of Alnus glutinosa on hybrid poplar height growth in a short-rotation intensively cultured plantations. Forest Science 28(1): 49–59.

Homer, C.D. & Pratt. P.F. 1961. Methods of analysis for soils, plants and waters. University of California, Agricultural Sciences Publications, Berkeley. 309 p.

Keenan, R.J., Lamb, D. & Sexton, G. 1995. Experience with mixed species rainforest plantations in North Queensland. Commonwealth Forestry Review 74(4): 315–321.

Khanna, P.K. 1997. Comparison of growth and nutrition of young monocultures and mixed stands of Eucalyptus globules and Acacia mearnsii. Forest Ecology and Management 94(1–3): 105–113.

— 1998. Nutrient cycling under mixed-species tree systems in Southeast Asia. Agroforestry Systems 38(1–3): 99–120.

Kiadaliri, Sh. 2003. Study of populus plantations on different soils in western parts of Mazandaran. M.Sc. thesis of Tarbiat Modarres University. 94 p.

Lamb, D. & Lawrence, P. 1993. Mixed species plantations using high value rainforest trees in Australia. In: Lieth, H. & Lohmann, M. (eds.). Restoration of Tropical Forest Ecosystems. Kluwer Academic Publishers, Holanda. p. 101–108.

Montagnini, F. 2000. Accumulation in above-ground

biomass and soil storage of mineral nutrients in pure and mixed plantations in a humid tropical lowland. Forest Ecology and Management 134(1–3): 257–270.

— , Gonzalez, E., Rheingans, R. & Porras, C. 1995. Mixed and pure forest plantations in the humid neotropics: a comparison of early growth, pest damage and establishment costs. Commonwealth Forestry Review 74(4): 306–314.

Parrotta, J.A. 1999. Productivity, nutrient cycling, and succession in single- and mixed-species plantations of Casuarina equisetifolia, Eucalyptus robusta, and Leucaena leucocephala in Puerto Rico. Forest Ecology and Management 124(1): 45–77.

— & Knowles, O.H. 1999. Restoration of tropical moist forests on bauxite-mined lands in the Brazilian Amazon. Restoration Ecology 7(2): 103–116.

Radwan, M.A. & DeBell, D.P. 1988. Nutrient relations in coppiced black cottonwood and red alder. Plant and Soil 106(2): 171–177.

Rhoades, C. & Binkley, D. 1996. Factors influencing decline in soil pH in Hawaiian Eucalyptus and Albizia plantations. Forest Ecology and Management 80(1–3): 47–56.

Wormald, T.J. 1992. Mixed and pure forest plantations in the tropics and subtropics. FAO no. 103. 166 p.

Ziabari, Z.F. 1993. The importance of Populus in forestry. Proceedings of forest restoration and forestry. Research Institute of Forests and Range Lands publication, Iran. 11 p.

Total of 27 references