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Guidelines for planning afforestation of former arable land

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CHAPTER 11

GUIDELINES FOR PLANNING AFFORESTATION OF FORMER ARABLE LAND

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Abstract. Afforestation objectives vary from one country to another and even within countries. Apart from the objectives, the specific conditions from a biophysical, environmental and socio-economic point of view should always be considered throughout the entire afforestation process, from policy decisions through location of the new forest, establishment and management, and the final utilisation of the forest. Decisions on how and where to afforest, and how much these decisions will affect the environmental impacts should ultimately be a compromise between the site quality in terms of climate, soil and preceding land-use, the initial goals set by planners and managers, and the stakeholders' preferences. The focus of AFFOREST has been on building knowledge and capacity to support decisions regarding afforestation of former arable land with respect to changes in C and N pools and fluxes and changes in

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water recharge. The guidelines in this chapter are based on literature reviews, the experimental data from chronosequences of afforested stands in Denmark, Sweden, and the Netherlands (described in Chapter 2, 3 and 4), and on the developed mechanistic metamodel (METAFORE) and the spatial Decision Support System (AFFOREST-sDSS) (Chapter 7, 8, 9 and 10). The structure of the guidelines is based on questions and corresponding answers under the main themes of water recharge, nitrate leaching, C sequestration, diversity of understory vegetation and complex questions involving more than one of the first three issues. Hopefully, the guidelines will be helpful and inspire landscape and forest planners in planning how and where afforestation should take place.

1. INTRODUCTION

In the earlier chapters, we presented some fundamental findings on the environmental effect of afforestation in north-western Europe and a new decision support tool for environmental impact assessment and planning based on these findings. In this chapter, we offer guidelines for afforestation of former arable land based on results from field measurements, modelling, and the use of the spatial Decision Support System (AFFOREST-sDSS). The guidelines are presented as questions and short answers, followed by more detailed clarifications. We start with single objective questions on water recharge, nitrate leaching, carbon sequestration and diversity of understorey vegetation, and we end with examples of multi-objective problem solving resulting from running the spatial DSS.

2. WATER RECHARGE

The water recharge (Q) of an area depends on the water balance, which can be expressed as:

$$Q = P - E - \Delta S \tag{1}$$

in which P is the precipitation, E the evapotranspiration (the loss of water to the atmosphere) and ΔS is the change in soil water storage. Water recharge consists of runoff, lateral drainage and leaching to the groundwater. Evapotranspiration occurs due to evaporation of rainfall from the canopy (interception), transpiration of the forest, and soil evapotranspiration.

2.1. Do new forests decrease water recharge relative to arable land?

It is widely accepted that trees generally use more water than any other vegetation. Specific research shows that water recharge in forests is less than under arable land since more water evaporates from higher canopies. When arable land is afforested the recharge therefore decreases. It is then a question of where and how to afforest in order to optimize the water recharge.

Mature trees use more water and their transpiration is larger than for newly planted young trees. Therefore, water recharge decreases during the transition from arable conditions over young trees to canopy closure where the decline levels off.

Literature data indicate that water recharge in afforested areas is lower than in clear-cut or agricultural areas. Observed differences in water recharge range from less than 100 mm yr^{-1} to more than 600 mm yr^{-1} and depend on the mean annual precipitation, the change in forest cover and the type of forest. The lowest reductions in water recharge are found for the conversion to open deciduous forests in dry areas. The highest values are found for dense coniferous forests in areas with a high annual rainfall (Bosch & Hewlett 1982; Sahin & Hall 1996).

The chronosequences studied within the AFFOREST project showed a decrease in annual water recharge of 20-230 mm yr^{-1} resulting from an increase in forest age over a period of 5 to 92 years. This decrease is less than indicated by the literature because AFFOREST field studies were mainly limited to areas afforested 5 to 30 years ago. When a clear-cut area or an agricultural area could be included as a reference the decrease in annual water recharge would increase by 50-200 mm. For example, at the Dutch oak site the decrease in water recharge was approximately 70 mm between the 4 and 18 year old forest and 130 mm between a grassland site and the 18 year old oak forest.

Studies on the change in water recharge during the growth of a forest stand are quite limited. Results from long-term monitoring studies indicate a quick decline in water recharge during the first 5 to 10 years after afforestation until the canopies have closed up, followed by a much slower decline when the trees grow older (Le Maitre & Versfeld 1997).

At the AFFOREST sites the water recharge follows this general pattern of a strong decline in water recharge in young stands followed by a slower decline when trees grow older (Figure 11.1).

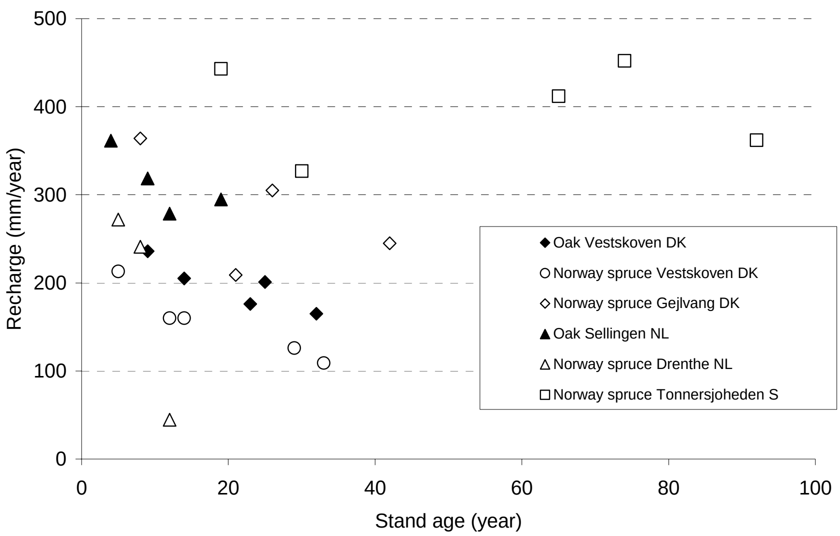

Figure 11.1. *Water recharge (mm yr^{-1}) at the five AFFOREST chronosequences of planted Norway spruce and oak as a function of age in Denmark (DK), Sweden (S) and the Netherlands (NL).*

The strongest decline in water recharge at the oak stands took place in the first 10 years. In the spruce stands the decline in water recharge is stronger and levels after 15-20 years. However, the decline in water recharge can be strongly influenced by planting density and management (See 2.4). For example, the decline in water recharge in the three Dutch spruce stands is extremely fast due to a high planting density and the absence of thinning.

2.2. Does the afforestation site selected influence the water recharge?

If it is the goal to maximize the water recharge and the choice is between afforestation of different soil types, a sandy site should be chosen to a clayey site. In a wet climate the reduction in water recharge following afforestation will be relatively higher than in a dry climate.

Water recharge varies from site to site due to differences in water holding capacity of the soil (sand vs. clay), the drainage conditions, the slope and the climatic conditions. Water recharge is normally higher from sandy soils than from clay soils due to the higher water holding capacity of clay soils (Finch et al. 1998). However, this effect may be overruled by differences in transpiration. For example, clay soils are often poorly drained, leading to transpiration reduction in wet periods due to anaerobiosis. In practice, the lowest leaching fluxes are often found on soils of intermediate texture where transpiration rates are neither reduced by drought nor by excessive wetness (van der Salm & de Vries 2000).

In general, the impact of afforestation on the water recharge will be higher in wet climates compared to dry climates (Bosch & Hewlett 1982; Sahin & Hall 1996). On dry sites the impact of afforestation will be lower compared to wet sites, because the potential evapotranspiration rates of the trees will not be reached and accordingly the differences in actual evapotranspiration between forest and arable land will be lower than under more favourable (e.g. somewhat wetter) conditions. Moreover, under dry or nutrient limited conditions growth will be lower resulting in a slower increase of evapotranspiration with age.

2.3. Does the selection of tree species influence water recharge?

In general, the decrease in water recharge is larger when coniferous species are planted instead of deciduous tree species. This is due to higher interception evaporation and transpiration in the evergreen coniferous tree species because of a higher and more permanent leaf area than in the deciduous tree species. When e.g. oak is planted instead of spruce the water recharge will be 80-250 mm larger.

The AFFOREST data showed that oak forest had a 80 mm higher water recharge in Denmark and a 250 mm higher recharge in the Netherlands compared to spruce forests (Chapter 3). However, differences between tree species are overruled by differences between the countries due to climatic effects. For example, water recharge in Sweden was higher compared to Denmark and the Netherlands, where precipitation was lower and evaporation was higher.

2.4. How will management of afforested sites influence water recharge?

Different management options clearly affect the water recharge. In order to optimize the water recharge the canopy of new forest should be kept as open as possible. Removal of old drainage pipes may increase around water recharge.

The loss of water due to evaporation of intercepted rainfall by the forest canopy is a major component in the water balance of forests. The amount of water lost by interception evaporation is strongly determined by the density of the forest. The losses will be low in open forests and high in dense forests. In AFFOREST, the losses by interception in the dense spruce forests in the Netherlands amounted to 400 mm yr^{-1}, whereas interception losses in the more open Swedish spruce forests were approximately 300 mm yr^{-1}. Furthermore, losses in oak forests are lower compared to spruce forests (see 2.3).

When thinning is performed the density is reduced and interception evaporation and transpiration decrease, which will increase the water recharge. Using close-to-nature forestry or continuous cover forestry with natural regeneration, water recharge will stay more constant over time.

Another factor that may lead to a decrease in water recharge is the density of the herb and shrub layer in the forest. Herbs and shrubs will add to the loss of water by evapotranspiration. In general, the highest water recharge will be found on bare soils and recharge will decrease with density and height of the vegetation.

In agricultural areas, pipe drains and artificial ditches to facilitate the use of machinery in wet seasons (spring and autumn) often artificially drain fields. Such drainage networks lead to an enhanced transport of soil water to streams and surface water and reduce the recharge to the groundwater. When such drainage systems gradually stop functioning after afforestation the recharge to the groundwater will increase. This may (partly) compensate the reduction in groundwater recharge due to the increased losses by evapotranspiration in forests compared to agricultural areas.

2.5. Concluding guidelines for water recharge

From existing knowledge about the water cycle in forests we have the following recommendations for afforestation where high groundwater recharge is wanted:

- The new forest should preferably contain deciduous tree species since these have a higher water recharge than coniferous species.
- Open forests (low basal area and species with a low crown density) yield a higher water recharge.
- Sites with sandy soils tend to have a higher water recharge than sites with finer textured soils. However, these differences may be overruled by regional hydrological conditions.

- Theoretically, removal or decline of old drainage pipes and ditches from agriculture may compensate for the negative effects on groundwater recharge of higher evapotranspiration in forests. However, the effect of removing drainage pipes has not been assessed.

3. NITRATE LEACHING

The N cycle in agricultural soils is an open cycle. Fertilisers (NPK) are supplied regularly in large amounts and approximately the same amount of N leaves the ecosystem by leaching or in harvested products. Management is intensive, characterised by frequent intervention, particularly soil work using heavy machinery and repeated application of pesticides. The amount of N bound in organic matter is high and soils have a high nitrifying capacity. Nitrogen leaching to seepage water and stream water is large since the soils often are 'saturated' with N and the vegetation cover is sparse during the wet season. On the contrary, old forests are characterised by a tighter N cycle where losses of N are low. Nitrification rates are low. Water from old forests is therefore generally of good quality with a low concentration of dissolved N compared to other land uses.

During afforestation major changes occur in the cycling and storage of N. Afforestation of former farmland is seen as a strategy to improve water quality, especially with regard to nitrate leaching. In this context, the challenge is to keep nitrate leaching from the new forests at a low level, despite the large N pool, which is a legacy of the former land use.

3.1. Does afforestation decrease nitrate leaching relative to arable land? How fast?

All available knowledge indicates that afforestation will cause lower nitrate leaching over a tree rotation compared to leaching from arable land, as a result of ceased fertilization and less soil disturbance in the new forest.

Afforestation will cause a rather fast reduction of nitrate concentrations within the first five years after planting since the demand for N is high in the early stage of stand development. However, high N status in the afforested soils and high N deposition may cause the stands to start leaching nitrate again after canopy closure when the demand for N decreases. The long-term nitrate leaching from old afforested stands is nevertheless expected to be lower than that from fertilised arable land.

A change in land use from agriculture to forestry implies that the high level of human intervention in the annual cycle of cultivating and harvesting crops is replaced by a much longer forest cycle with a lower interference. After afforestation, the soil remains more or less undisturbed apart from a possible soil preparation at the very beginning of the establishment and harvesting impacts at the end of the rotation period.

The large pool of N stored in the mineral soil in arable land will, to some extent, be redistributed to the living biomass or built into the organic matter pool in the forest floor. Afforestation of nutrient rich arable land is therefore likely to have a large influence on the organic N equilibrium resulting in a changing pattern of net gains and losses of N from the soil organic matter pool and the plant and microbial biomass fraction.

Such changes in soil conditions may enhance minerlaization of stored soil N and contribute further to the available N pool. Losses from terrestrial ecosystems mainly occur as dissolved N in seepage water. Nitrate seriously influences water quality and it is often the main form of mineral N leached. Since its adsorption to the soil is small, it is highly mobile and easily transported down the soil profile even at N-limited conditions (Gundersen & Rasmussen 1995; Stottlemeyer & Toczydlowski 1996).

Forests on former arable land have higher soil N status as a legacy of former fertilization. Because of this forests on former arable land may be more vulnerable to disturbance of the N cycle than old forests, resulting in enhanced leaching of nitrate. On the other hand, nitrate leaching may still be less than that from arable land. In both agricultural systems and forest ecosystems leaching of nitrate is induced by external input of N or by management practices or combinations of these:

- Increased input of N (N-deposition, fertilization, planting of N_2 fixing species)
- Decreased biological uptake (harvesting, clear-cutting, thinning, weed control, site preparation)
- Increased net minerlaization (liming, soil preparation)
- Decreased denitrification (decrease in groundwater level)

Concentrations of nitrate in soil water below the root zone is a pre-condition for nitrate leaching, and it indicates loss of nutrients from the ecosystem. In Denmark, higher concentrations of nitrate in soils below the root zone were observed in afforested land as compared to old forest ecosystems (Callesen et al. 1999) (Figure 11.2). Concentrations of nitrate in agricultural soils before afforestation were also higher than concentrations 10 years after afforestation on three sites in Denmark (Hansen & Vesterdal 1999).

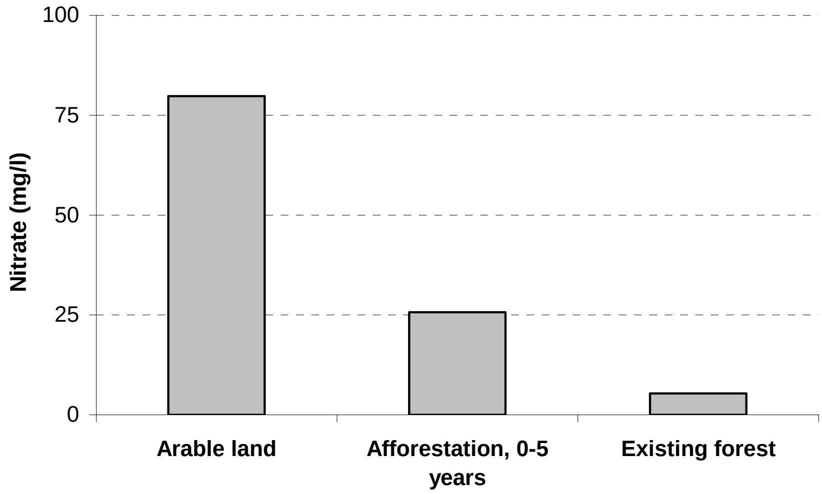

Figure 11.2. *Average nitrate concentrations (mg/l) in leaching water (at 75-100 cm depth) measured from 1986-1993 in arable land (>900 plots), afforestation areas (5 plots) and existing old forests (79 plots) in Denmark (Callesen et al. 1999).*

The effect on nitrate leaching of a change in land use from agriculture to forestry was evaluated using a simple modelling approach in the Netherlands (Rijtema & de Vries 1994). The change in land use led to a decrease in nitrate leaching regardless of the chosen tree species. Average nitrate leaching was estimated to be 74 kg nitrate-N ha^{-1} yr^{-1} on sandy soils under agricultural crops. This was reduced to approximately 11 kg nitrate-N ha^{-1} yr^{-1} under forest stands.

Recent studies of forests developed on former arable soils have shown that soils still have N cycling characteristics and rates of N minerlaization more comparable to cultivated soils than to soils under old forests - even 100 years after afforestation (Koerner et al. 1999; Magill et al. 1997; Jussy et al. 2000). These old arable soils have not been fertilised in the same way and with the same intensity, as we know it on the arable soils of today, but even so, the former land use is noticeable in the N cycling characteristics. The arable soils selected for afforestation today have been fertilised to a much larger extent. These soils often cannot accumulate more N, which means that the surplus of N deposited from the atmosphere is leached.

In the first years after afforestation, the large pool of available N can be converted to nitrate and leached. Leaching will most probably occur until the trees reach a certain size and ground vegetation has developed. Figure 11.3 shows average nitrate concentrations in soil water (75-90 cm depth) after afforestation at nine different sites in Denmark. High concentrations above the threshold value of 50 mg nitrate l^{-1} were only apparent in the first years after planting and the concentrations fell to a low level after approximately five years. Eight to 12 years after afforestation the stands were in good growth and the nitrate concentrations had fallen to much lower values within the range of nitrate concentrations in old forest soils.

Five years after afforestation the uptake of N in the trees increases remarkably since the trees have to build up their crown including branches, twigs and bark. The N demand of young forests is therefore believed to be greatest during canopy build-up and considerably decreases once canopy closure is reached (Miller & Miller 1988; Richter et al. 2000). Hereafter, the trees mostly grow in N-poor woody biomass. After canopy closure, deposition to the new forests will increase as a consequence of larger turbulence around higher trees. The input by atmospheric deposition will in many cases exceed the N demand of the trees and it is uncertain whether the new forests will be able to retain available N. If N cannot be retained in the soil there is a risk for renewed leaching of nitrate 20-30 years after afforestation.

Increased nitrate leaching with age has been observed for Sitka spruce in Wales 25 years after planting (Emmett et al. 1993) and with height in Denmark (Hansen 2003). In the AFFOREST chronosequences in Denmark and the Netherlands, leaching in Norway spruce only occurred after canopy closure at a stand age of 20 or more years (Figure 11.4). Leaching of nitrate from the oak stands increased with stand age in Denmark, however, leaching was high in the oak stands in the Netherlands right from the start after afforestation. No such patterns were apparent in the Swedish spruce chronosequence (12-92 years old) where no leaching took place because of a low throughfall deposition and less intensive former agriculture in the stands older than 60 years.

Figure 11.3. *Nitrate concentrations (mg/l) in 75-90 cm depth in new forests after afforestation on former arable land. Average of nine afforestation sites in Denmark. Shading indicates the standard deviation.*

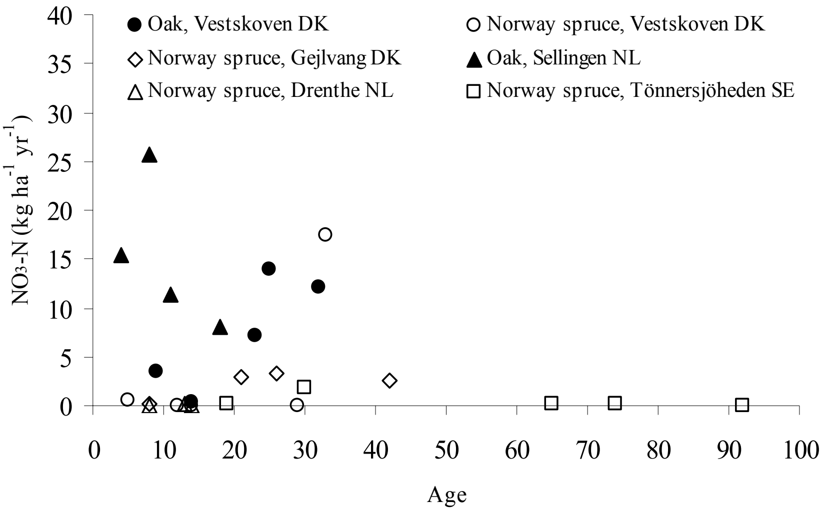

Figure 11.4. *Leaching of NO_3^--N (kg N ha^{-1} yr^{-1}) in stands of different ages in the AFFOREST chronosequences for oak and Norway spruce at sites in Denmark and the Netherlands.*

3.2. Does the selection of afforestation site influence nitrate leaching?

Nitrate leaching following afforestation will mostly be higher from nutrient-rich clayey soils when these are afforested than from more nutrient-poor sandy soils. The clayey soils already have enough N for the new forest to grow while the nutrient-poor soils will be able to immobilize the available N, and trees will take up most of the available N.

In areas with high atmospheric deposition of the risk of N leaching is higher. This is why afforestation areas should be located as distant as possible from local N emission sources.

A decisive factor for nitrate leaching under the new forests is the quality of the soil. Literature points to the fact that nitrate concentrations in soil water are lower in sandy soils than they are in clay soils. The clay soils are more N-rich and less additional N can be built into these soils. This means that when atmospheric deposition of N exceeds the amount used for building up the canopy a certain surplus of N is available for leaching. In contrast, the trees on nutrient-poor sandy soils with organic matter of high C/N ratio will be able to take up all available N in organic matter or by tree growth so that leaching of nitrate is lower or zero. The difference between N-rich and N-poor soils is also seen in their C/N-ratio where the N-poor sites have high C/N-ratios. The leaching of nitrate is in this way also connected with the C/N-ratio. At C/N-ratios less than 25 in the organic layer, literature almost always finds high nitrate concentrations in the deeper soil horizons (Gundersen et al. 1998).

Nitrate leaching is influenced by the atmospheric deposition of N. European data has shown that leaching of nitrate starts to increase at about 8-10 kg N ha^{-1} yr^{-1} (Kristensen et al. 2004). On average, the European forests leach approximately half of the deposited N (Gundersen et al. 1998) and the new forests will probably leach more since they are already very rich in N. The ammonium part of the N deposition is influenced by local N emission sources. Especially areas with intensive agriculture and livestock will experience a high input of ammonium N. To avoid high deposition of N to the new forests, afforestation areas should be located as distant as possible from local sources.

3.3. Does forest structure influence nitrate leaching?

Higher deposition has been observed in forest edges than in the interior forest, which is reflected in higher fluxes through the soil close to the edge (up to 50 meters). In order to lower the N deposition and leaching of nitrate in the new forests they should preferably consist of larger forest stands in connection with already existing forests.

The size and structure of the new forest will affect the deposition to the forest. For example, a much higher atmospheric deposition was observed at the forest edge in several studies. Indirectly, these variations in input to the forest might affect the soil properties as well. In southern Sweden, soil solution (30-40 cm) was sampled at different distances from the edge and into the forest (Påhlsson & Bergkvist 1995) in both a *Picea abies* (30 years and planted on former agricultural soils) and a *Fagus sylvatica* forest (approx. 100 years). The increased deposition to the soil at the spruce forest edge was reflected by higher element fluxes through the soil profile as well. The N flux through the soil decreased with distance from the edge over the first 25 m. At the edge, N fluxes were up to 6 times higher than in the interior of the stand. In the interior of the forest, most N was either taken up by trees or immobilised in the soil. In the beech forest, the edge effect was less pronounced in throughfall. This was also reflected by soil solution concentration, which was not correlated with the distance from the forest edge. Pore water chemistry profiles (greater than 2 m depth) were sampled by Kinniburgh & Trafford (1996) in the edge of a *Fagus sylvatica* stand in the southern part of England. Their analyses showed a dramatic increase in solutes close to the forest edge. This increase was seen 50 m into the forest.

Deposition and nitrate leaching in forest ecosystems are normally determined in the interior part of the forest. Thus, the large variations caused by forest edges are not accounted for. Today, a large part of the new forests are established as a mosaic of small, multifunctional plantations, rather than larger coherent forest areas, and leaching will be considerable from these “all-edge” forests. It is therefore recommended to plan and establish larger coherent forest areas in connection to already existing forests.

3.4. Does the selection of tree species influence nitrate leaching?

N deposition to coniferous tree species is higher than to deciduous tree species since conifers are evergreen and have surfaces that catch more deposition. Studies in old forests have shown that this extra input of N will result in larger leaching of nitrate beneath coniferous species. However, some studies contradict these findings, among these the AFFOREST chronosequences, where leaching was higher beneath oak than beneath Norway spruce.

When planting black and red alder and other N fixing trees it may result in additional leaching from afforested soils.

Individual tree species vary in their soil-forming properties. Different effects of tree species can be expected due to variability in litter quality, canopy architecture and canopy interception of atmospheric deposition, root structure, and rates of nutrient uptake and growth (Miles 1985).

N deposition in coniferous stands is approximately two-fold higher than in deciduous stands caused by the more efficient filtering effect of conifers due to their evergreen foliage and higher leaf area (Kristensen et al. 2004). An enrichment of throughfall for N compounds has been shown for paired comparisons of coniferous and deciduous stands (Brown & Iles 1991; van Ek & Draaijers 1994).

These observed differences in N deposition between the two tree types have been shown to create a higher output of nitrate from the soil under conifers when compared to deciduous tree species at the same site (de Vries & Jansen 1994; Rothe et al. 2002). However, observations from the European monitoring sites (level II sites) show that deciduous species have higher nitrate concentrations than conifers at similar input (Kristensen et al. 2004). One reason for the contrasting result from the European sites may be that the deciduous stands often grow on nutrient-rich soils (higher N status) that are more likely to leach.

In AFFOREST, the oak stands in Denmark and the Netherlands leached more nitrate (5-30 kg N ha^{-1} yr^{-1}) than the spruce forests (<5 kg N ha^{-1} yr^{-1} Figure 11.4). At Vestskoven in Denmark, the oak and spruce stands were planted on similar soils. Oak retained less N in biomass due to slower growth rate and less leaf biomass over the year, which left more N available for leaching.

N fixing trees like black and red alder have been used in silviculture as a tool to improve the soil fertility (Tarrant & Trappe 1971) and as an often-used nurse tree species in new plantations. The annual symbiotic N-fixation was estimated to be between 50 and 200 kg N ha^{-1} (Binkley et al. 1992; Bormann & DeBell 1981), which can result in leaching of 30-50 kg N ha^{-1} yr^{-1}. On agricultural soils where the soil N contents are high from the very beginning, afforestation using N-fixing species must be avoided since this further increases the risk of nitrate leaching.

3.5. How will management of afforested sites influence nitrate leaching?

When weeds are removed, the seedlings alone are unable to withhold available nitrate, which might result in increased nutrient losses. The most intensive preparation methods that disturb the soil the most, like deep ploughing, have been *shown to trigger increased leaching. It is a balance between keeping the culture clean enough for the trees to survive and keeping N leaching to a minimum.*

When stands are clear-cut plant uptake is suddenly disrupted and nitrate concentrations in soil water as well as leaching inceases. Within 2-5 years nitrate will return to preharvesting levels. Even thinning has been shown to increase nitrate leaching slightly.

When drainage pipes from former arable land use stop functioning after afforestation, soils revert to the original drainage regime. In case of more wet conditions, denitrification is significantly enhanced leading to a reduction in nitrate leaching.

Storage of N and leaching of nitrate from newly planted forest is dependent on the management practices applied prior to planting as well as practices during and at the end of a rotation.

3.5.1. Site preparation

Site preparation, frequently used when new forest stands are established, is carried out mainly to create a favourable environment that promotes fast and efficient establishment and good survival of seedlings. This is obtained by reducing the competing ground vegetation (e.g. grasses and herbs). Weed control in the beginning of a new culture greatly improves tree growth in a number of species (Chang & Peston 2000; Munson & Timmer 1995; Sutton 1995). Weed control includes a number of removal methods, which are given here in decreasing order of soil disturbance:

- Mechanical removal by patch scarification, trenching, mounding and ploughing (increases minerlaization)
- Chemical removal by the use of herbicides (decreases biological uptake)
- Mulching
- Competitive weed control

Deep ploughing is the preferred preparation for afforestation of former arable land since it suppresses weed establishment more efficiently than the other mechanical site preparation methods. A study by Matthesen & Kudahl (2001) compared the effect of different mechanical preparation methods on the vegetation cover of competing weeds and grasses in the first growing season on 3 afforestation sites in Denmark. Deep ploughing (down to 60 cm) reduced the cover percentage to approximately 50%, whereas trenching in between rows and agricultural ploughing (down to 20 cm) only reduced the cover 2-8%.

Use of herbicides before and after planting of seedlings is the most common way of controlling weeds and by far the most cost-effective method as well. Mulching involves covering the soil around trees with a cover material, which will prevent weeds from germination. Wood chips have been widely used as cover material, but also degradable plastic and cardboard have been used. Competitive weed control involves the use of other vegetation to take over and suppress the weeds, yet allow the seedlings to get enough light and water to grow. Especially, rye is used as competitive vegetation to weeds when planting on former agricultural soils. Also, nursery trees growing faster than the main tree species may help to earlier create a forest climate, hereby suppressing several weeds and preventing frost.

Mechanical weed control methods disturb the soil to some extent. The most intensive mechanical disturbances increase net N minerlaization, nitrification, and nitrate losses to seepage water (Vitousek & Matson 1985; Attiwill & Adams 1993). When weeds are removed, the seedlings alone are unable to withhold available nitrate (decreased uptake), which might result in increased nutrient losses (Ogner 1987a, b; Lundmark 1977; Lundmark 1988). On two Danish afforestation sites, Drastrup and Nørager, different weed control methods were examined (Pedersen et al. 2000; Gundersen et al. 2001). Agricultural ploughing (down to 20 cm) was compared to deep ploughing. At Drastrup, the nitrate concentration increased drastically after both agricultural and deep ploughing. The concentration of nitrate as well as leaching was highest in the deep ploughing treatment (200 mg l^{-1} corresponding to 100 kg N ha^{-1} yr^{-1}) as compared to the agricultural ploughing (100 mg l^{-1} corresponding to 40 kg N ha^{-1} yr^{-1}) (Figure 11.5).

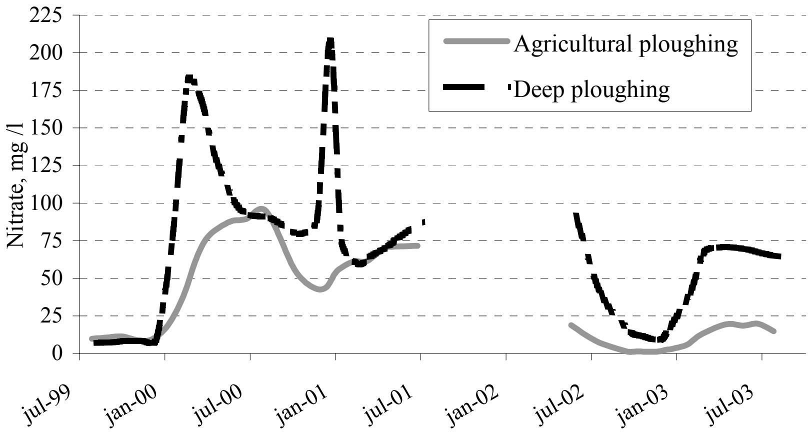

Figure 11.5. *Concentrations of nitrate (mg l^{-1}) in soil water (90 cm) using different site preparation methods on a sandy nutrient-poor soil at Drastrup in Denmark (Gundersen et al. 2001).*

At Nørager, results were comparable to those at Drastrup for the first leaching season (out of two) where 30-40 kg N ha^{-1} yr^{-1} were leached from the agriculturally ploughed plot and 90-130 kg N ha^{-1} yr^{-1} were leached from the deep-ploughed plot. During the second year at Nørager, the nitrate concentration in the deep-ploughed plot fell below the concentration in the agriculturally ploughed plot. In comparison, the average leaching from farmland in Denmark is estimated to be 106 and 55 kg NO_3-N ha^{-1} yr^{-1} from sandy and clayey soils, respectively (Grant et al. 2004).

At Drastrup, trees were also planted with large distance (2.5 x 2.5 m) and mulching with wood chips was performed. Here, the grass and weed cover was kept intact when planting, and it did not influence the concentration of nitrate (Gundersen et al. 2001), which was low already from the beginning because of a grass cover.

Mellert *et al.* (1998) found a close negative correlation between total vegetation cover and nitrate concentrations in soil solution (r^2=0.7). This is explained both by a higher total plant biomass (weeds and trees) on weedy areas and a higher N-accumulation in weeds compared to the tree (Smethurst & Nambiar 1989).

3.5.2. Thinning and harvesting

Canopy removal by thinning temporarily increases the amount of precipitation and sunlight reaching the forest floor, influencing the forest floor microclimate and thus the decomposition and minerlaization conditions. An increase in soil nitrate concentrations was visible in a thinning experiment in lodgepole pine where 60% of the trees were removed. Up to two years after thinning nitrate leaching was apparent but small and far from the 10-40 times increase in nitrate concentration found in the clear-cut stand (Knight et al. 1991). Bäumler & Zech (1999) also observed a small increase in nitrate concentrations after a 40% thinning. The concentrations were back to pre-cutting conditions after one year.

Like for thinning, removal of the whole canopy when harvesting increased the amount of precipitation reaching the forest floor and the light available for tree growth, leading to more favourable soil moisture and temperature conditions for decay microorganisms. (Piene & van Cleve 1978; Binkley 1984). However, for a clear-cut the disturbance is more severe since plant uptake is disrupted at the same time as minerlaization and nitrification increase. Furthermore, the outflow of run-off and seepage water is larger due to lower evapotranspiration (Knights et al. 1991; Qualls et al. 2000).

The effect of clear-cutting on nitrate leaching was followed in numerous old-forest studies. In general, the concentration of nitrate in soil and stream water increased after clear-cutting with peak nitrate concentrations the first three years after clear-felling. The nitrate concentrations will return to pre-cutting levels within relatively short time, normally 2-5 years. The effect of clear-cutting on leaching from originally afforested arable soils has not been examined yet. As these arable soils were N-saturated prior to afforestation it is hypothesised that nitrate leaching may be high after crown closure, at least in high deposition areas. A management strategy to prevent N leaching could be frequent thinnings, e.g. of whole trees for bioenergy purposes, to keep a high N sink at these sites. In this case, the removal of other nutrients with biomass must be balanced by the supply of other nutrients from soil and atmosphere or the loss of nutrients should be compensated by fertilization. Continuous cover forestry will also be a relevant option to avoid the disturbances connected with clear cutting that disrupts the N cycle.

3.5.3. Drainage

The drainage regime has large impact on soil N dynamics. Reduced drainage enhances the loss of nitrate through denitrification. Arable soils are often drained to ditches, and the natural drainage regime is usually more wet. Bad drainage can be due to slow infiltration of precipitation as in clay-rich soils or due to high groundwater tables. When drainage pipes from the former arable land use stop functioning after afforestation, soils revert to the original drainage regime. In case of more wet conditions, the availability of oxygen decreases and denitrification is significantly enhanced, which leads to a reduction in nitrate leaching.

3.6. Concluding guidelines concerning nitrate leaching

From existing knowledge about the N cycle in forests and afforested former arable land we have the following recommendations for afforestation where low nitrate leaching is a goal:

- Afforestation should preferably be performed as larger coherent forest areas in connection to already existing forest in order to decrease deposition caused by edge effects.
- The best place to afforest is far away from local emission sources.
- The new forests should preferably consist of deciduous tree species (e.g. beech and oak) since they have a lower deposition of N and a higher water recharge (see chapter 2) which mostly leads to lower nitrate concentrations in leaching water.
- N-fixing tree species like black and red alder should be avoided when afforesting former arable land.
- A fast establishment of both trees and weeds will cause the lowest nitrate leaching.
- As little site preparation and weed control as possible (accept some weeds) to avoid nitrate leaching or selection of weed control methods that will only disturb the system leniently.
- The crown cover should not be too closed. A relatively open forest established by medium thinning intensity is preferable since the deposition will be slightly decreased with decreased crown cover.
- Frequent thinnings for bioenergy can be evaluated in order to remove N from an area with high N status as for example former arable land. In this case, the removal of biomass must be balanced with the contribution of other nutrients from soil and atmosphere or the loss of other nutrients than N should be compensated by fertilization.
- Continuous cover forestry will be preferable at afforested sites as an alternative to clear cutting and the resulting disruption of the N cycle.

4. CARBON SEQUESTRATION

The land-use change from agriculture to forestry implies a shift from a landscape of low C density to one of higher C density. Carbon is stored in afforested systems as a result of the assimilation of CO_2 during photosynthesis and the subsequent accumulation of woody biomass. A certain amount of C is transferred each year to the soil with litterfall, sloughing of dead roots and C leaching from roots. The amount of C stored in soils after afforestation reflects the balance between input from the vegetation and the ongoing mineralization of organic C.

4.1. What is the potential of afforestation for carbon sequestration?

Afforestation of arable previously tilled land leads to constant or increasing soil C stocks. Studies show average rates of soil C sequestration between 0.3 and 0.8 t C ha^{-1} yr^{-1}. Carbon stocks were found to increase by in average 18% over a variable number of years.

The C storage in biomass depends on the growth rate of trees. Trees growing on former arable land have growth rates that are higher than expected from the parent material. Biomass C sequestration rates from 0-50 years are reported to range from 1.5-4.3 t C ha^{-1} yr^{-1}. Biomass C sequestration rates of the entire forest rotation (about 100 years) are more likely in the range of 1.5-2.0 t C ha^{-1} yr^{-1}.

Evidently, C storage mainly takes place in the above- and belowground biomass. Approximately 70% of the C stored in the new forest is sequestered here. The remaining is sequestered in soils.

There is substantial variation among studies regarding the relative contribution of soils and vegetation to total ecosystem C sequestration following afforestation. While there is always some sequestration in the biomass of growing forest trees, soils may gain C, experience no change in C or even loose C following afforestation (Guo & Gifford 2002; Vesterdal et al. 2002).

A recent review of many studies (Post & Kwon 2000) found that the average rate of soil C sequestration was 0.3 t C ha^{-1} yr^{-1} (range 0-3 t C ha^{-1} yr^{-1}) across different climatic zones. An analysis of 29 studies on afforestation of arable cropland showed that C stocks increase by in average 18% over a variable number of years (Guo & Gifford 2002). In the AFFOREST chronosequence studies on former cropland soils sequestered C at a rate ranging from 0 (no change) to 1.3 t C ha^{-1} yr^{-1} for the Dutch oak chronosequence (Table 11.1). The average rate of soil C sequestration was 0.8 t C ha^{-1} yr^{-1} across all sites.

Table 11.1. *Rates of soil C sequestration (t C ha^{-1} yr^{-1}) over 30-90 years in the AFFOREST chronosequences.*

Country	Soil type	Tree species	C sequestration
Denmark	Sandy clay	Oak, Spruce	~0
Denmark	Sand	Spruce	1.1
Sweden	Sand	Spruce	0.6
The Netherlands	Sand	Oak	1.3

Within the soil, C storage may occur because of the development of a forest floor – the organic layer consisting of dead leaves twigs etc. which blankets the mineral soil. However, additional C can be stored in the mineral soil, where it is more protected towards forest management and other environmental changes. In general, it takes longer (>30 years) for C sequestration to occur in the mineral soil (Paul et al., 2002). Such differences in allocation of sequestered soil C may be attributed to tree species, i.e. with oak accumulating less C than spruce in forest floors, and to the humus forms characteristic of different soil types.

The development in biomass C storage is basically the same as in any stand regenerating after disturbances like wind throw or clear-cutting. The storage depends on the growth rate of trees and possible understory species. Former arable soils differ from most forest soils in the fact that they are rich in nutrients, at least in the first decade following abandonment of agriculture. This is a legacy of frequent fertilization and liming. The nutritional demands of forest trees may therefore be more than met, and growth rates higher than expected from the parent material. In the literature, biomass C sequestration rates from 0-50 years are reported to range from 1.5-4.3 t C ha^{-1} yr^{-1} in boreal, cool temperate and subtropical climates (Vesterdal et al. 2002).

In the AFFOREST chronosequence studies rates of C sequestration of both oak and spruce across sites were quite similar for the first 40 years after afforestation with an average rate of 3.7 t C ha^{-1} yr^{-1}. The current growth rate of forest stands decreases with age, so biomass C sequestration rates of the entire forest rotation (about 100 years) is more likely in the range of 1.5-2.0 t C ha^{-1} yr^{-1}. Therefore, roughly 30% of the total stored C is sequestered in soils and the remaining 70% is sequestered in above- and belowground biomass (Figure 11.6).

In general, high short-term rates of biomass C sequestration is achieved in early succession tree species on nutrient-rich soils and in a climate with a long growth season in combination with ample amounts of moisture. In the longer term, however, more slow-starting late-succession tree species may provide higher rates of C sequestration. Also, other factors than growth rates matter for biomass C sequestration in a long-term perspective including several rotations of forest, e.g. effects of inherent soil properties, tree species and management practices must be expected to show up later.

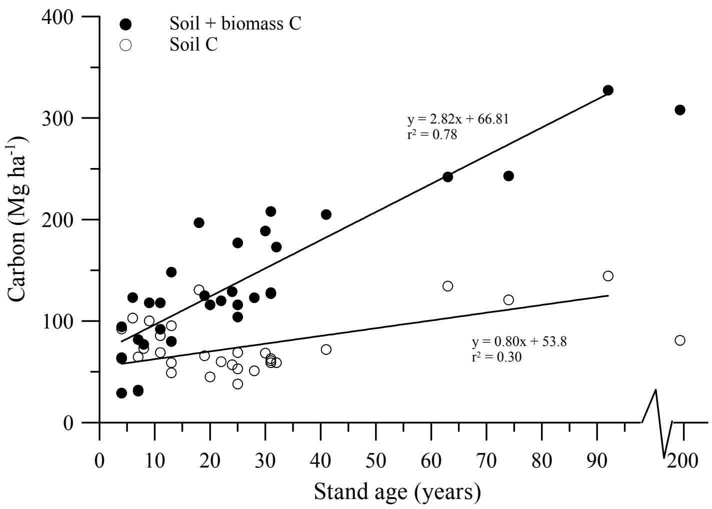

Figure 11.6. *Changes in total ecosystem C storage with time since afforestation in Denmark, southern Sweden and the Netherlands. The difference between the plotted lines indicates the relative contribution of biomass C sequestration.*

4.2. Does the selection of afforestation site influence the potential for carbon sequestration?

Storage of C in the forest floor is highest on nutrient-poor sandy soils. The effect of soil type on the storage of C in the mineral soil is not clear.
In the long-term, biomass C sequestration is expected to be highest at rich sites due to the higher increment rates. Afforestation of nutrient-rich soil types would therefore be the best option for biomass C sequestration.
Biomass growth appears to be the main sink for CO_2 following afforestation. This suggests that afforestation of rich soils is the optimal choice.

An important issue when planning afforestation projects is the selection of site, i.e. the effect on the mitigation potential of selecting marginal, nutrient-poor land versus more nutrient-rich arable land. In most cases land is available for afforestation because it is marginal for crop production. The soil type of the chosen land area influences the mitigation potential of an afforestation project, and the question is therefore which soil type will provide most C sequestration in soil and biomass?

There is good evidence that forest floors store more C when soils are poor, i.e. have sandy texture, low nutrient availability and low pH, and when soils are wet. This is because decomposition of litter proceeds very slowly in such soil types resulting in a thick humus layer, which blankets the mineral soil. It is less certain how C sequestration in the mineral soil is affected by soil type. In some cases, nutrient- and clay-rich soils have been suggested to store more C, because production of litter is high and because clay protects organic matter from decomposition. In other cases, poor soils seem to store more C than rich soils, which was explained by slow decomposition and complexation between C compounds and iron and aluminium in poor sandy soils. In the AFFOREST project there was an indication that sandy soils accumulated more soil C (including forest floor C) over 30-40 years than loamy soils.

Biomass production is known to vary considerably between sites for the same tree species due to soil nutrient status and climate. Accordingly, potential C sequestration in biomass is highly variable. However, biomass C sequestration at afforested sites will not differ that much over the first decades because abandoned arable soils are fertile for forest trees. Thus the influence of "native" soil type (parent material) may be masked by fertilization and liming during the previous land use and even sites with poor subsoil may have relatively high site index for trees. It is debated how long this fertilization effect will last, but in the long-term biomass C sequestration is expected to be highest at rich sites due to the higher increment rates. Afforestation of nutrient-rich soil types would therefore be the best option for biomass C sequestration in case this type of arable land is available.

The question is then, what soil type to afforest in order to maximise the C sequestration of the whole ecosystem? It is not possible to give a general answer to this question, as there seem to be different mechanisms controlling soil C sequestration. As mentioned before, biomass growth appears to be the main sink for CO_2 following afforestation. This suggests that afforestation of rich soils is the optimal choice. It is possible, however, that the soil contributes more when afforesting podsolized poor forest soils. It is thus recommended to select sites based on regional or local knowledge of the soil type and C stocks in such soil types under forest and crop production.

4.3. Does the selection of tree species influence the magnitude of carbon sequestration?

Tree species influence soil properties, but the influence of tree species on soil C sequestration is not well known. Some studies have indicated tree species differences, and others not.

Different tree species will affect C sequestration in biomass according to the relative growth potentials of the species. The longer-lasting and more continuous growth of oak and beech makes these species a good option on rich, loamy soil types.

In order to optimise C sequestration in afforestation areas, tree species with high rates of increment over a long life cycle should be selected.

Tree species can influence C sequestration because of different accumulation of living biomass and dead organic matter.

Tree species planted at the same soil type accumulate very different amounts of dead organic matter in the forest floor, i.e. some tree species also sequester more C than others in this part of the soil. For instance oak in Denmark sequesters less C (0.03 t C ha^{-1} yr^{-1}) in forest floors than Norway spruce (0.3 t C ha^{-1} yr^{-1}) over 30 years, and pine species have higher C sequestration rates (0.6 t C ha^{-1} yr^{-1}) than spruce. Other broadleaved tree species like ash and lime (*Tilia*) may sequester even less C in forest floors than oak.

There is little support for generalizations regarding tree species differences in mineral soil C sequestration. Some studies have indicated tree species differences, and others not. Based on experiences in the AFFOREST project we conclude that after about 30 years tree species like oak and Norway spruce do not influence the C stock in mineral soils differently. But in the long term this may not be the case.

The selection of tree species will affect C sequestration in biomass according to the relative growth potentials of the species. Thus, conifers may at sandy soils be superior to broadleaves in growth rate. However, the longer-lasting and more continuous growth of oak and beech makes these species a better option on rich, loamy soil types. Here spruce has high initial increment rates but a short-lasting life cycle, as it becomes unstable after less than 50 years.

The total ecosystem C changes in soil and biomass will be larger in conifers than broadleaved tree species in the short-term (<30 years since afforestation) because of higher rates of increment of the conifers within this age range and development of larger forest floors (Figure 11.7). It is difficult to compare tree species without taking the different management into account. For instance, rotation lengths are shorter for conifers, so biomass accumulation stops earlier and must start all over again. In the long-term, tree species selection should therefore be based on species that maintain high C stocks for a long period and continuously sequester C. In this case, stable, long-lived broadleaved species may provide the best alternative in spite of their lower rates of increment and forest floor accumulation.

In order to optimise C sequestration in afforestation areas, it is recommended to select tree species with high rates of increment over a long life cycle. Relevant tree species should also accumulate C in the soil. The specific selection of tree species must eventually be based on regional knowledge of tree species ecology at a given soil type.

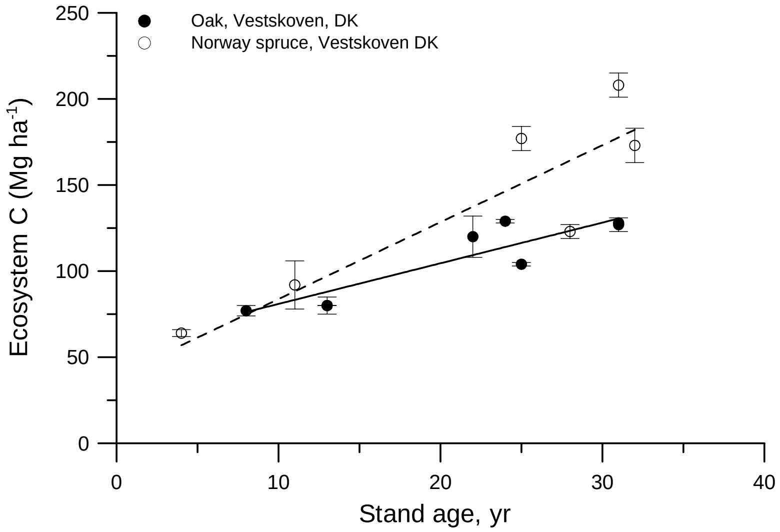

Figure 11.7. *Example of ecosystem C change in Norway spruce and oak at Vestskoven, Denmark.*

4.4. How will management of afforested sites influence carbon storage?

Continuous cover forestry using natural regeneration will have a higher average biomass C stock per ha and possibly also preserves more C in soils compared to traditional clear-cut/replanting systems.

The influence of thinning intensity on soil C storage is small. Reduced thinning intensity increases the biomass in the forest, thereby maintaining higher C stocks. High stocking levels (stems per ha) obtain maximum assimilation of CO_2 per area faster than when using lower stocking levels. Furthermore, harvest of excess biomass for bioenergy purposes in early thinnings will contribute to CO_2 mitigation.

When drainage pipes from the former arable land use stop functioning after afforestation, soils revert to the original drainage regime. In case of more wet conditions, C storage is significantly enhanced.

The answer to this question is basically the same for new and old forests. Management practices known to increase C stocks of the vegetation and/or the soil in existing forests would most probably also be relevant in afforestation management. Relevant management practices are, e.g. silvicultural system, thinning intensity, drainage regime and fertilization. Here we only address C stocks on afforested sites – C storage in wood products is not considered.
Traditionally, afforested stands are plantation forests where the silvicultural system is characterized by rotations initiated by planting and terminated by clear-cut harvesting. During recent years, continuous cover forestry (CCF) or nature-based

forestry has come into focus. These systems aim at introducing the small-scale mosaic patterns found in natural forest in order to avoid costly large-scale clear-cuts and artificial reforestation efforts. The idea is that forest management should mimic the natural forest structure and dynamics where single trees die and create space for new trees. An important characteristic is the continuous cover or at least the smaller and less long-lasting openings in the forest canopy. This means that over time there is a higher average biomass C stock per ha in such forests compared to traditional clear-cut/replanting systems where 10-20 years per rotation is characterized by very low biomass C stocks. CCF possibly also preserves more C in soils as the input to soil is not interrupted by clear-cutting and replanting. As natural regeneration is the preferred method of regeneration, negative impact on soil C stocks by site preparation is also avoided. It is a challenge to develop first-generation afforested stands into more complex multi-aged stands. This issue was outside the scope of AFFOREST and is addressed elsewhere (Pommerening & Murphy 2004). However, for optimizing C stocks it is recommended to establish species-diverse forest stands that are able to perform natural regeneration or function as shelter for other tree species.

Reduced thinning intensity increases the biomass in the forest, thereby also maintaining higher C stocks. In the short term following afforestation, it would also be possible to use high stocking levels (stems per ha), i.e. obtain canopy closure and thus maximum assimilation of CO_2 per area faster than when using lower stocking levels. The influence of thinning intensity on soils was also explored in thinning trials in the AFFOREST project. There was no general evidence of different soil C storage. This is in line with other studies (de Wit & Kvindesland 1999). As strong thinning regimes are preferred in order to reduce N deposition and increase water recharge, reduced thinning intensity is not recommended for C sequestration in afforestation areas where water management is prioritized. Strong thinning regimes and use of wood for bioenergy purposes may consequently be a better option which contributes to CO_2 mitigation by substituting consumption of fossil fuel.

The drainage regime has large impact on soil C dynamics and tree growth. Reduced drainage is probably the main management parameter which may influence soil C stocks. Arable soils are often drained to ditches, and the natural drainage regime is usually more wet. Bad drainage can be due to slow infiltration of precipitation as in clay-rich soils or due to high groundwater tables. Wet conditions decrease the availability of oxygen, which hampers decomposition of soil organic matter. Wet soils therefore have significantly higher C stocks than well-drained soils. Up to five times more C may be found to a depth of 1 meter. Following afforestation, drains stop functioning over time, and soils revert to more wet conditions. It is therefore necessary to include these possible changes in the planning of afforestation projects in order to select suitable tree species for more wet soil conditions. For instance, oak is very tolerant with respect to drainage regime. In case suitable tree species are planted, the more wet conditions enhance C storage in the soil compartment significantly, thus increasing the CO_2 mitigation potential of afforestation. However, emissions of other greenhouse gases like N_2O and methane (CH_4) are enhanced in wet soils, and this possible negative effect on mitigation of greenhouse gases must be considered too.

4.5. Concluding guidelines concerning carbon sequestration

From existing knowledge of carbon stocks in biomass and soils in forests planted on former arable land we have the following recommendations for sequestration of C after afforestation:

- Forest trees sequester carbon faster than soils after afforestation. High short-term rates of biomass C sequestration are achieved in early succession tree species. In the longer term more slow-starting late-succession tree species may provide higher rates of C sequestration.
- Forest floors sequester C most rapidly after afforestation. However, in terms of permanency it is wiser to manage for sequestration of C in the mineral soil, where it is more protected toward forest management and other environmental changes. It takes longer (>30 years) for C sequestration to occur in the mineral soil.
- Tree species with high rates of increment over a long life cycle should be selected. Relevant tree species should also accumulate C in the soil, e.g. conifers. The specific selection of tree species must ideally be based on regional knowledge of tree species ecology at a given soil type.
- Afforestation of nutrient-rich soil types is preferable for biomass C sequestration. It is not possible to generalize regarding the potential of poor and rich soils for soil C sequestration. Local knowledge of C stocks in different soil types under forest and crop production can be consulted for decision support.
- Management of afforested stands should focus on use of biomass from thinnings for substitution of fossil fuels, increased rotation periods and the principles of nature-based management and continuous cover forestry. A change in drainage regime towards more natural, wet conditions when drains are impaired may significantly increase the C stock of the mineral soil.

5. DIVERSITY OF UNDERSTORY VEGETATION

In North-Western Europe, forest areas often serve a multitude of functions. Besides environmental and production purposes, nature development and recreation are objectives of afforestation. For both nature and recreation a diverse and abundant understory, consisting of valuable and typical forest species, is important.

As the tree layer is often planted and therefore quite artificial and the understory is left to spontaneous development, the question arises if it is feasible to expect the development of such a valuable understory to occur in a relatively short time span (if ever). Also, the differences in environmental conditions of the new forest areas due to anthropogenic influences as compared to ancient forests, will probably affect the development of a natural forest understory. However, some extra attention for the understory and active interference can stimulate and speed up the developments.

5.1. How diverse is the flora of current forests in North-Western Europe relative to arable land?

Arable land and recently planted forests are both not recognized for their high diversity in vascular plant species. However, diversity is not the only criterion in the determination of the value of an ecosystem. Due to the high amount of endangered species that occur on the forest floor of old forests, the rarity of well-developed understory systems in the north-western part of Europe and the vulnerability of the system, the new forest and its understory are potentially very valuable.

The exact value of the forest (understory) ecosystem compared to the current land use, but also compared to other possible land use types, depends on a combination of biological, recreational, landscape and economical factors and can be evaluated in a local, regional or larger context. Within the AFFOREST project, this consideration has not been addressed. The AFFOREST project focussed on the possibilities to steer the newly planted forests on arable land towards the highest system-specific diversity. Since the system-specific diversity is related to a certain combination of balanced environmental factors, most suitable for the species group of interest, the AFFOREST project focussed on the relation between plant performance of forest species and non-forest species and the environment. Recommendations for the afforestation of former agricultural land from a biodiversity point of view are based on that approach. So, it is not a high diversity for itself that is important, but the system-specific diversity that counts.

5.2. How is diversity of understory vegetation affected when arable land is afforested? How long does it take for the understory of afforested stands to be comparable to old forest sites?

In new forests planted on former agricultural soil, the vegetation is often characterized by a large proportion of nitrophilic, highly competitive species. The ancient forest species generally appear slowly in the understory vegetation. This slow development of a typical forest understory is ascribed to seed availability and environmental conditions.

The seeds of most forest species are short-lived. The chances of seeds reaching the new forest, depend on the distance between the forest and the seed sources in the neighbourhood, that is old-growth forest.

The most important environmental factors affecting the development of the forest understory are light and nutrients (especially N). Higher N availability in the soil, often found on former arable land, favour the early succession forest species while ancient forest species seem to respond more indifferently to the N supply.

A period of 50-100 years or even more before typical understory vegetation starts to build up after afforestation is not an unrealistic estimate. However, active intervention in the seed availability can speed up this process.

In Denmark, the understory vegetation of new forests planted on former arable land differing in age was characterized by use of a Forest Flora Index (Riis-Nielsen, unpublished data). This index describes the ecological habitat preference of species occurring in the vegetation records of the different forests, ranging from “not present in forests” to “confined to forest”. The Forest Flora Index for each species was determined based on habitat descriptions (Hansen 1976). The mean Forest Flora Index determined in the AFFOREST chronosequences showed an increase with the age of the forest (Figure 11.8), however, a very slow increase. In literature, this slow development of a typical forest understory is ascribed to seed availability and environmental conditions (Verheyen & Hermy 2001; Honnay et al. 1999).

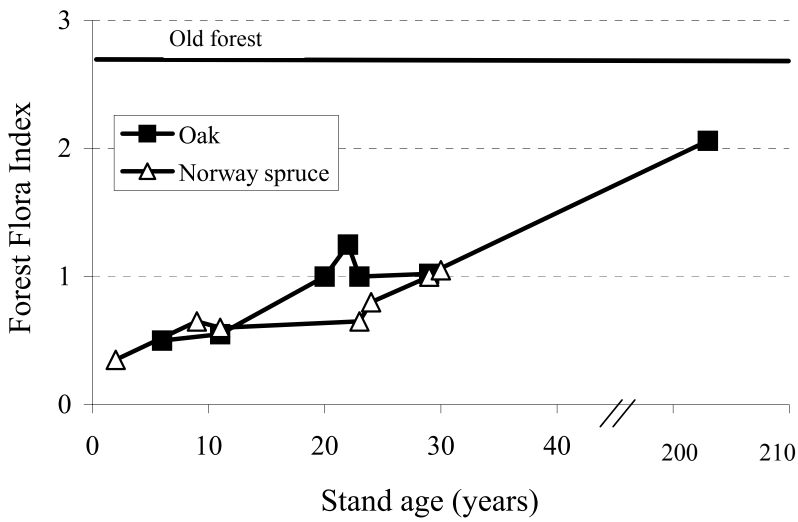

Figure 11.8. *Forest Flora Index (FFI) determined on the AFFOREST chronosequences in oak and Norway spruce at Vestskoven, Denmark. FFI was calculated based on habitat descriptions for each species (Hansen 1976). 0 = not present in forest, 1 = predominately outside forest, 2 = often present in forest, and 3 = confined to forest (Riis-Nielsen unpublished data).*

The seeds of most of the forest species are short-lived and the agricultural land-use often has a negative effect on the viability of the seed bank. Thus, the development of a valuable forest understory from seeds that have been stored in the ground since the disappearance of former forest can be ruled out. Therefore, the new forests are dependent on dispersal of seeds from seed sources outside the forest. The chances of seeds reaching the forest depend on the distance between the forest and the seed sources in the neighbourhood. Because the dispersal mechanism of many forest species is specialized in short-distance dispersal and because forest species tend to produce only few viable seeds, the development of the forest understory is often hampered by the availability of seeds.

The most important environmental factors affecting the development of the forest understory are light and nutrients (especially N). In a greenhouse experiment conducted within the AFFOREST project, the response of shade-tolerant forest species and species typical for younger or disturbed forests to different combinations of light and nutrients was tested. It is concluded that higher N availability in the soil, often found on former arable land, favoured the early successional forest species while ancient forest species seemed to respond more indifferently to the N supply. The effect of enlarged N availability was strongest at the higher light intensities. At very low light intensity, light was the most limiting growth factor and none of the species could take advantage of the high nutrient supply. Comparable results are found in other studies (Corré 1983). Ancient forest species are more adapted to low light and low N availability conditions, while early succession species are more adapted to high light and high N availability conditions.

It is difficult to give an indication of the time it takes for the understory of afforested stands to become comparable to old forest sites. If no special measures are taken to improve understory development, a period of 50-100 years or more (Brunet & von Oheimb 1998; Harmer et al. 2001) before a typical understory vegetation starts to build up is not an unrealistic estimate. However, by taking the appropriate measures, this process can be accelerated.

The development of the forest understory is dependent on the local situation and the design of the new forest. Indications of development time are often based on seed limitation and the time it takes for seeds to reach the forest. Active intervention in the seed availability can speed up this process. However, a slow development and a lengthy succession characterize the forest system. A natural forest goes through different developmental phases, each phase having its own characteristics and value and its own contribution to the construction of a balanced a-biotic and biotic system. Restoration defines a goal and a time frame for management measures, and at this point any threshold in the system becomes important (Heil 2004). The environmental factors of light and N availability determine the abiotic constraints, and seed availability determines the chance of assembling the system specific diversity.

5.3. Does the selection of afforestation site influence diversity of understory vegetation?

Selection of afforestation site does play an important role in the development of the forest understory. The site should preferably be planted directly bordering or in the vicinity of existing old-growth forest where the goal-vegetation is present. Sites with low N availability are preferable since N favours early successional species and increases their competitive strength.

The selection of afforestation site can affect both seed availability and environmental conditions (mainly N availability), which have been recognized as important determinants of the forest understory diversity.

To improve seed availability, the site should be in the vicinity of old-growth forest where the target vegetation is present and reproductive. In the most ideal situation, the new forest should be planted directly bordering the ancient forest. In other cases, suitable habitats between the forests, like hedges and shrubbery, can increase the colonization success (Butaye et al. 2001).

The stronger effect of N availability on non-forest species than on ancient forest species was already described in 5.2. The importance of competition was shown in the AFFOREST-field-experiment in a chronosequence of deciduous forests. In forests where no competition occurred, ancient forest plants performed well. In the younger forests where competition was severe due to higher light and nutrient levels, indications were found that the performance of the ancient forest species lagged behind. Also, in literature the suggestion is often put forward that N availability can favour early successional species in competitive situations. Most of the studies working with this hypothesis are aimed at unravelling the effect of N deposition on existing (ancient) forest systems. These studies clearly show that the performance of ancient forest species declines when the species are competing with fast-growing ruderals (Falkengren-Grerup 1993). The actual disappearance of ancient forest plants, and thus a decrease in biodiversity and value of the understory, is dependent on the duration and intensity of the competition and on the vitality of the ancient forest species.

In conclusion, preference should be given to sites that border existing old growth forests and sites with low N availability. If such sites cannot be found management measures will be necessary to increase seed availability and suppress competitive weed domination (see 5.5).

5.4. Does the selection of tree species influence diversity of understory vegetation?

The tree species sets the light environment of the understory vegetation and thus indirectly affects understory diversity. In addition, tree species influence diversity via their litter quality. Therefore, the selection of tree species is important for the development of the understory vegetation. Forest species are, in contrast to more competitive ruderal species, able to survive an environment with little light, which calls for selecting tree species with denser crowns.

In a natural situation, the occurrence of tree species is determined by the environmental conditions of the site (soil type, soil moisture etcetera); the understory composition, in turn, is associated with both the environment and the tree species. To develop a (semi-) natural forest, selection of the naturally occurring tree species is a prerequisite.

Different tree species are known to differ in the density of their crowns and thus in the relative amount of light that penetrates through their canopy (Leuschner & Rode 1999). The AFFOREST field experiment showed that forest species could survive rather low light levels. The results of the greenhouse experiment support this conclusion. The same experiments showed that non-forest species are more sensitive to light conditions. Growth rates, and thus competitive strength, decreased strongly with decreasing light.

Thus, to steer the development of the forest understory in the direction of the target vegetation, tree species with a relatively dense crown are preferred. However, light intensity on the forest floor can also be manipulated by the density of the trees, i.e. thinning intensity.

Another aspect that plays a role in the selection of tree species is important in the determination of the target vegetation type and the accompanying system specific diversity and species composition. Vegetation science of forest systems revealed a rigid combination of soil type, tree species and vegetation type (Stortelder et al. 1999). When selecting the tree species or, preferably, species combination, it is of importance to have a clear picture of the possible and desired target vegetation.

5.5. How will management of afforested sites influence diversity of understory vegetation?

Management can strongly affect the development of the species composition in the forest understory and can thus be used to steer the succession on the forest floor.

Seed availability could be improved by sowing the desired understory species. Also, flowering and seed production of existing plant populations in the new forest or in old forests in the surroundings could be stimulated.

The competition between ancient forest species and nitrophilic species can be controlled by active removal of competitive species, by grazing or by intervention in the light climate.

Management should aim at seed availability and at competition control. Two possibilities exist to increase seed availability. Firstly, sowing can provide an artificial supply of seed. Though strictly speaking not a management measure but more a measure of eco-engineering, but on condition that it is executed at the correct time, when environmental conditions are suitable for the species sown, a very effective measure. Secondly, flowering and seed production of existing plant populations in the new forest or in forests in the surroundings could be stimulated, for instance by thinning. Here, light is again an important factor. More light results in more flowering and higher seed production. Permanent deep shade leads to a stronger investment in survival of the existing population rather than expansion (Willems & Boessenkool 1999).

There are different options available to control competition and guard ancient forest species against exclusion by nitrophilic species. Firstly, active anthropogenic removal of competitive species is possible. Though effective, it is labour-intensive, environmentally unfit and produces a severe disturbance of a potentially stabile system and is therefore not very suitable. Secondly, several studies propose grazing as a measure for weed control, and interesting results have been reported (Papanastasis et al. 1995). Thirdly, an intervention in the light climate of the forest could be performed e.g. by applying a weak thinning regime, which allows fast canopy closure. The highly competitive non-forest species are, in contrast to forest species, not capable of surviving or competing in dense shade. However, permanent deep shade will also affect survival and, especially, expansion of ancient forest species (Willems & Boessenkool 1999). It can be concluded that seeding at a proper time, if the environmental conditions are favourable for ancient forest species, will be the most successful management measure to enhance the system specific diversity.

5.6. Concluding guidelines concerning understory vegetation

Based on existing knowledge we have the following recommendations in order to accelerate and steer the development of the understory vegetation in recently afforested arable land:

- Improve the seed availability of ancient forest species by:
  - selecting sites for the new forests adjacent to old-growth forests where the target species are present and reproductive
  - sowing the target species in the new forest
- Reduce the competition by non-forest species weeds by:
  - reduction of N availability to limit the competitive strength of weedy species
  - reduction of light availability to a level where the fast-growing species cease to grow but where ancient forest species can still survive
  - removal of fast-growing species by weeding or grazing.

6. COMPLEX QUESTIONS

Afforestation efforts are location specific and multi-objective. They are location specific since the benefits of the new forest in terms of e.g. biomass production, environmental services, and recreation strongly depend on the local site quality and its spatial organization in relation to its surroundings. They are multi-objective because they are based on decisions driven by multiple functions, with their respective claims to produce goods and services in a maximal way. Maximizing a single objective will often cause trade-offs for another objective. Addressing more than one forest function is therefore always a complex multi-objective optimization challenge, which implies insight in the complex interactions between the performance response of objectives to different site and management characteristics. In other words, the creation of a multipurpose forest should be a well thought compromise to meet the goals set by managers and stakeholders in an optimal way.

In the preceding sections, generalized and mono-objective guidelines were derived from field observations, literature review and expert knowledge. In this section, guidelines to questions with a higher level of complexity are given. Some questions are site specific but most questions are location specific and can be solved by linking the METAFORE model outputs to a spatial database. This is done in the AFFOREST-sDSS, the spatial Decision Support System of AFFOREST, which is designed as a user friendly tool that allows a flexible treatment of numerous afforestation questions. Also multi-objective questions setting weights or thresholds on the environmental impact categories C sequestration, nitrate leaching, and water recharge can be solved by the AFFOREST-sDSS.

Based on contacts with end users (national and local policy makers, land use planners, environmentalists, foresters) a range of policy relevant end-user questions were formulated (Table 2). Some of these questions are analyzed and solved in the following guidelines using the AFFOREST-sDSS. The selected questions illustrate the functionality of the sDSS and the possible guidance this tool offers. The selected questions and their solutions were saved as predefined cases in the AFFOREST-sDSS, which means that the solution can be followed step by step by running the predefined cases in the AFFOREST-sDSS software.

Table 11.2. *End user questions to the AFFOREST-sDSS. C= carbon sequestration; N= nitrate leaching; W= water recharge.*

Question	Country and Scale	Environ-mental impact category	Extra data need
Where are the best places in northwestern Europe to establish 100,000 hectares of new forest with maximum carbon sequestration as a goal?	NW EU 1 km^2	C	No
Where is the best place to afforest in order to reach the best possible environmental performance after 50 years given that the potential afforestation areas are situated adjacent to existing forest?	B (Flanders) 1ha	C+N+W	Forest map of Flanders
What is the difference in environmental performance (C, N, and H2O, respectively) after 100 years between high intensity and low intensity management for a planned afforestation area?	B (Flanders) 1ha	C+ N+W	Map of planned afforestation
The policy on afforestation in the Netherlands suggests planting 30,000 ha of oak forest. Where is the best place to afforest if carbon sequestration should be maximized, while at the same time nitrate leaching should not exceed the ground water standard of 50 mg/l?	NL 1ha	C+N+W	
Which tree species and which management strategies should Sweden use in each location of the territory to maximize C sequestration?	S 1ha	C	
For implementation of the EU Water Framework Directive, arable land in Denmark, assigned as groundwater protection area, is afforested with broadleaved forest	DK 1ha	C+N+W	Map of ground-water protection

mainly for recreational purposes. What is the environmental performance after 100 years?			areas
The government of Denmark decides to double the forested area by afforestation (intensive site preparation, medium stand tending) with oak over 100 years. After how many years is nitrate leaching below 5 kg N/ha/year on sandy soil? On clayey soil?	DK 1ha	N	Forest map of Denmark
A municipality has an objective to afforest an area with sandy soils in a way that produces as much clean drinking water as possible and as a second priority sequesters as much carbon as possible over 15 years. How should this be done in the best possible way?	DK 1ha	C+H+W	Map of area
A forest district has purchased marginal arable land (sandy soil) adjacent to existing forest. The aim is to obtain maximum wood production over 70 years using spruce and a low management intensity. What is the environmental performance?	DK 1ha	C+H+W	Map of purchased arable land

6.1. Where are the best places to afforest in north-western Europe in order to establish 100,000 hectares of new forest with maximum carbon sequestration as a goal?

This is a 'where' question with the afforestation strategy not being defined. It is wise to define a time horizon for evaluation, e.g. 50 years. It is solved in the AFFOREST-sDSS with the multicriteria option putting maximum weight on carbon. The solution was stored in the AFFOREST-sDSS as a predefined case named 'WHEREARmaxC'. The final result, showing the best places to afforest in order to reach the highest C sequestration, is seen in Figure 11.9.

This question needs to be solved in two steps. First the AFFOREST-sDSS selects the afforestation strategy resulting in maximum carbon sequestration for all available pixels (1 km^2) in the AFFOREST region (Sweden, Denmark, the Netherlands, and Flanders, Belgium). Available pixels are pixels with present agricultural land use. We look at the cumulative amount of carbon sequestered after 50 years. The result is a table with the best afforestation strategy per pixel. Since this output table is not sorted by C sequestration but by the pixel class value, a second step is needed in order to find the best 1000 km^2 (100,000 ha). In the second step, the output table is sorted by C and the first 1000 km^2 are selected. Based on this selection a new grid is created after converting to the 'grid' command of ArcView. The final result (Figure 11.9) is a map of the AFFOREST region highlighting the 100,000 ha where the cumulative C sequestration is the highest. A fair amount of these successful pixels are situated in the south of Flanders, Belgium (Color Plate 8). A mild climate with sufficient rainfall (800 mm), very fertile loamy soils but low initial soil carbon content under the current arable land use characterize this area. As a consequence, a high carbon sequestration potential in living biomass and in soil could be expected.

6.2. Where should we afforest in order to reach the best possible environmental performance after 50 years given that the potential afforestation areas are situated adjacent to existing forest?

This 'where' question was solved for Flanders, Belgium. An evaluation time of 50 years must be selected. Since the environmental performance is not specified, it is a multi-objective query with equal weight for the three environmental categories C sequestration, nitrate leaching, and water recharge. For the condition "adjacent to existing forest" an input map with the present forests in Flanders is needed. The solution is saved in the AFFOREST-sDSS as a predefined case named 'WHEREFlbestEP'. The final result, showing the best places to afforest in order to reach the best environmental performance, is seen in Color Plate 9 and Figure 11.9.

Similar to Question 18 we select a regional/national assessment but now for Flanders, Belgium (pixels 1ha). We also select a multi-criteria analysis but with equal weight for the three environmental categories C sequestration, nitrate leaching, and water recharge, because no specifications concerning environmental category was made. The environmental impact is calculated cumulatively for a period of 50 years, while no afforestation strategies are specified. For the condition "adjacent to existing forest" an additional GIS operation is needed before running the AFFOREST-sDSS, where the maximum distance to existing forest must be defined. We chose zones with a maximum width of 500m. These zones are entered as an ARCview shapefile in the AFFOREST-sDSS. The result is a map showing the best locations and the afforestation strategies there to obtain best possible environmental performance (Color Plate 9). In Figure 11.9 a detail of the result is shown with the existing forests (in grey), surrounded by a contour line at 500 m distance, indicating the potential afforestation zones. Within these zones, colored pixels are available for afforestation. The color indicates the afforestation strategy to follow in order to obtain the best environmental performance. In the area, we see pixels with afforestation strategy 21 and 12, being pine and beech afforestation respectively, both with high stand preparation intensity and low thinning intensity.

It is typical for optimizations where C sequestration plays a role that high intensity site preparation combined with low intensity thinning management give the best result, because it leads to higher biomass accumulation. However, in areas where spruce afforestation has the best environmental performance it goes in combination with a high thinning intensity. The reason is that for un-thinned spruce the trade-off in terms of decreased water recharge and increased nitrate leaching due to increased interception becomes too important.

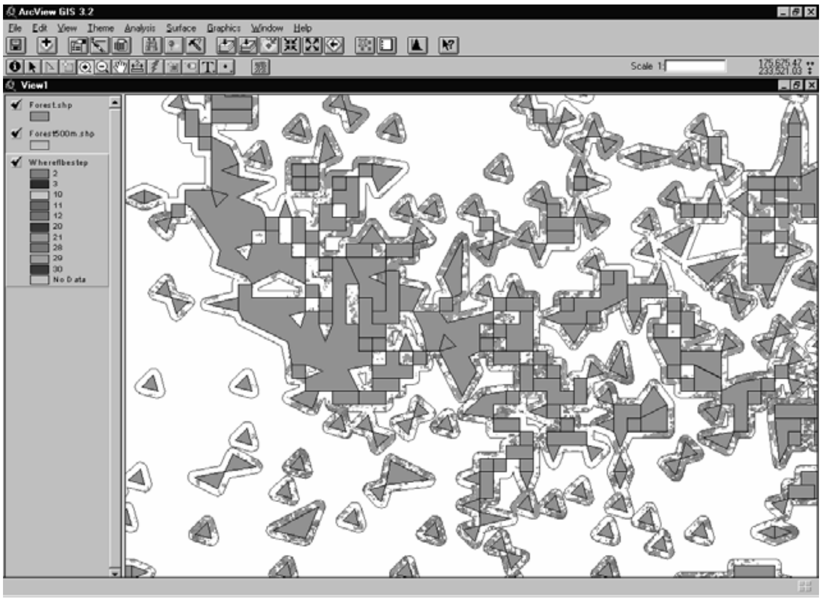

Figure 11.9. *Map of afforestation zones with best possible environmental performance adjacent to existing forests in Flanders (after zooming of Color Plate 8). Contour lines at 500 m distance, indicate the potential afforestation zones*

6.3. The policy on afforestation in the Netherlands suggests planting 30,000 ha of oak forest. Where is the best place to afforest if carbon sequestration should be maximized, while at the same time nitrate leaching should not exceed the ground water standard of 50 mg/l?

This is a typical 'where' question solved in the AFFOREST-sDSS by using the 'Locate Afforestation Area' query with multicriteria option. In order to get a focused answer it is wise to specify a time horizon and the used afforestation strategy. The result was saved as a predefined case named WHERENLmaxCdrinkingnorm.

To solve this question we choose a time horizon of 50 years and an afforestation strategy of planting oak with intensive site preparation and low thinning intensity. There are two ways to approach this question.

The first one is similar to the case in question 18: a multicriteria approach with all weight on carbon. The result is an area with highest possible carbon sequestration but without information on nitrate leaching and water. This result must be saved as a shape file and brought in again in the sDSS for a second query. In this query the environmental performance of the area is addressed based on the given management strategy. After running the sDSS the end user must check in the output table which areas do not exceed the ground water standard. The output of nitrate leaching is not in concentrations but in absolute quantities (kg/ha). Concentrations can be obtained by dividing the N column by the W column and adjusting the units. Then the pixels that meet the requirement of 50 mg/l NO_3-N are selected. The table of this selection is then sorted by C, the first 30,000 ha are selected and a map is created.

The second approach is to select a multicriteria approach for the three Environmental Impact Categories (EIC). It must be ensured that carbon is maximized but that meanwhile the drinking water norm for nitrate is not exceeded. Putting large weight on carbon and little weight on nitrate and water recharge can do this. Instead of 30,000 ha we select 50,000 ha as a minimum in order to make sure that we obtain at least 30,000 ha in the end. The intermediate result is a map of the best pixels; approximately 70,000 ha were found (Figure 11.10). These pixels for sure have high carbon sequestration and low nitrate leaching. But do they meet the drinking water norm? To know this, the end user must check the output table in the same way as described in option A. The result is presented in Figure 11.11.

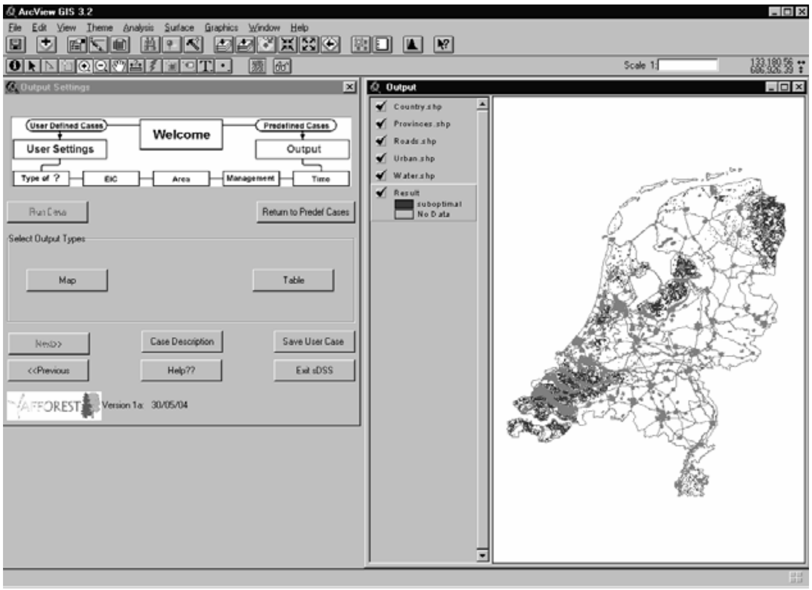

Figure 11.10. *Selection of minimum 50,000 ha afforestation area with oak obtaining the maximum carbon sequestration, minimum nitrate leaching, and maximum water recharge.*

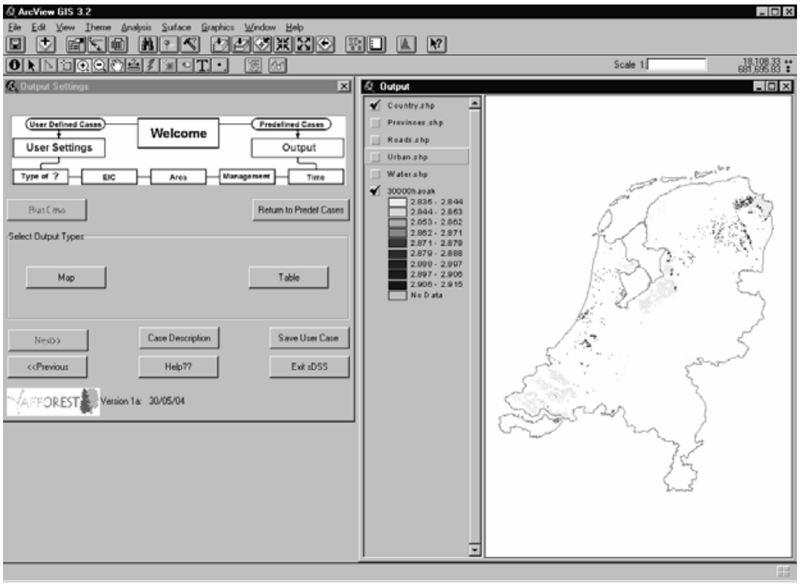

Figure 11.11. *Map of the 30,000 ha of oak afforestation in the Netherlands with the highest carbon sequestration and nitrate leaching below the drinking water norm.*

6.4. The government of Denmark decides to double the forested area by afforestation with oak over the next 100 years. After how many years is nitrate leaching below 5 kg N/ha/year on sandy soil? And on clayey soil?

This is a question on when a given environmental effect will be reached. The solution is calculated with the AFFOREST-sDSS and saved as a predefined case named WHENDKNleachsand for sandy soils and WHENDKNleachclay for clayey soils.

In the AFFOREST-sDSS the question is solved using the ‘Find out when a given objective is met’ option. The area is restricted by site characteristics. A query is built to select the soil type of interest. Nitrate leaching is selected as the objective to minimize with a threshold value set at 5 kg/ha/yr. Finally, the management strategy is selected. The results are presented in a time map (Figure 11.12 for sandy soils and Figure 11.13 for clay soils). The results for sandy soils show that the objective is never reached. The results for clay soils show that the objective is reached after a period between 1 and 32 years. Why it takes much longer at some places than at others is hard to interpret but it is mainly influenced by the local N deposition level.

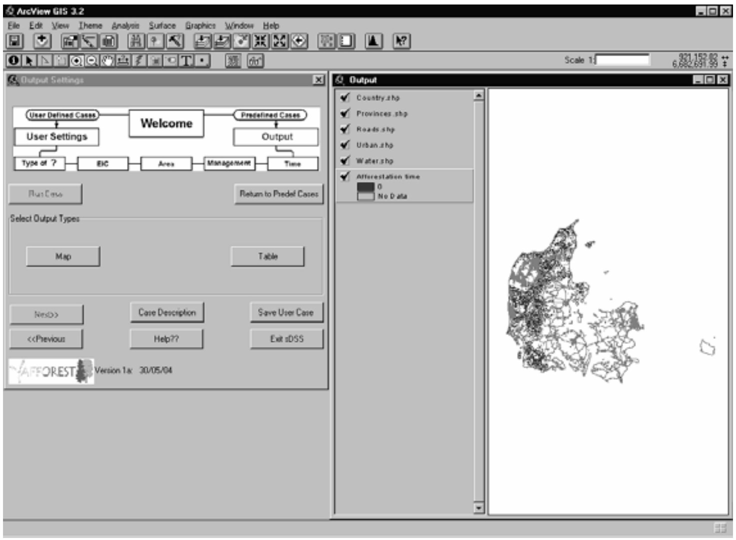

Figure 11.12. Map indicating when nitrate leaching is below 5kg/ha/yr for afforestation with oak on sandy soils. All agricultural land on sandy soils is in class0, which is without result. This means that the threshold value is never reached and nitrate leaching is always higher.

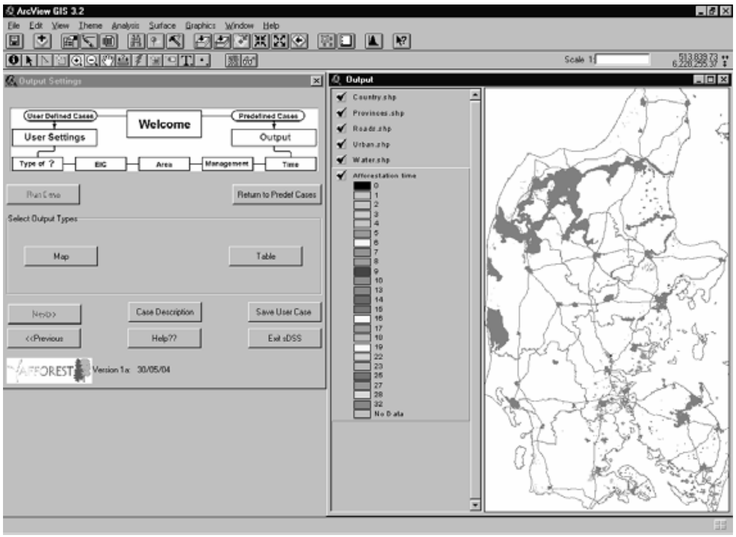

Figure 11.13. Map showing the time needed before nitrate leaching is below 5 kg/ha/year for afforestation with oak on clay soils.

6.5. A municipality has an objective to afforest an area with sandy soils in a way that produces as much clean drinking water as possible and as a second priority sequesters as much carbon as possible over 15 years. How should this be done in the best possible way?

This is a question on the afforestation strategy meeting the multiple objective of maximizing water recharge and carbon and minimizing nitrate leaching. The solution (Figure 16) calculated using AFFOREST-sDSS is stored in a predefined case called 'AFFSTRATDKdrinkingwater'.

The first step is to add a shapefile with the boundaries of the municipality. In this example, we answered the question for the whole of Denmark. The question is solved with the 'Find management strategy' option of the AFFOREST-sDSS. The area is restricted by site characteristics building a query with selection of sandy soils. Hereafter, the multicriteria option is selected with a weight of 0.4 on water and nitrate and a weight of 0.2 on carbon. Calculations are asked cumulatively for a period of 15 years. The result is a map indicating the best management strategy. From the map (Color Plate 9) it can be read that afforestation with oak using high intensity site preparation and high intensity thinning (afforestation strategy 1) is by far the most successful. By comparing this guideline with earlier ones, it becomes clear that by putting less emphasis on carbon sequestration and more weight on nitrate leaching and water recharge, the optimal thinning intensity moves from low to high.

7. CONCLUSIONS

If only one objective is set for an afforestation project, planning is less complicated. In such a case, a single-objective question has to be answered. Table 11.3 summarises the best possible choices regarding site and management for new forests in order to maximise water recharge, and C sequestration, to minimise nitrate leaching, and to encourage colonization of understory species characteristic for ancient woodlands.

It is evident that afforestation largely improves environmental performance compared to arable land use (Table 11.3). Carbon is sequestered, nitrate leaching decreases, and forest species characteristic of old forests will slowly appear. The exception is that water recharge will be reduced because of higher evapotranspiration in forests.

It is then a question of where and how to afforest to optimise all environmental effects at the same time. Table 11.3 shows us that nitrate leaching decreases and seed availability is highest if the new forest is located adjacent to an old forest, but this does not matter for C sequestration and water recharge. When old drainage pipes from former arable use are impaired or removed, it is positive for water recharge, nitrate leaching, and C sequestration. Selection of deciduous species is also favourable for the environmental impact categories being considered. In combination with intensive thinning it will significantly reduce interception evaporation. However, there may be a trade-off in the short term for carbon storage due to the slower initial growth rates of deciduous trees. But in the long-term, the greater stability towards disturbances such as windstorms and the possibility to perform continuous cover forestry can compensate this.

Afforestation is often based on decisions driven by multiple objectives. When multi-purpose demands are involved, it is difficult and involves many pitfalls to plan the new forests in a proper way while meeting the array of natural, political, and socio-economic conditions. Maximising a single objective will often cause trade-offs for another objective. It is therefore a complex optimisation challenge to address more than one objective. It is necessary to know the interactions between the performance of individual services provided by afforestation and different site and management characteristics.

A range of possible complex questions concerning environmental effects of afforestation have been posed (Table 11.2) and the solution to part of them, solved using the AFFOREST-sDSS, have been shown here. The questions are relevant examples formulated based on contacts with end users (national and local policy makers, land use planners, environmentalists, and foresters). Two general conclusions can be made based on the use of the AFFOREST-sDSS. Initially in the planning process, the ‘where’ question is more important than the ‘how’ question, which means that the environmental performance in terms of carbon sequestration, nitrate leaching, and groundwater recharge is more influenced by the site of afforestation than by afforestation management. In other words, climate, soil and N deposition level play a more important role than the tree species and the management strategy chosen when afforestation is performed.

Once an afforestation area is selected, the ‘how’ question becomes of major importance. When the management strategy is optimised there seems to be a trade-off between carbon sequestration on the one hand and groundwater recharge on the other. Measures leading to high carbon sequestration (i.e. fast growing tree species, intensive stand preparation, and low thinning intensity) at the same time lead to low groundwater recharge. This relation is rather obvious, and different authors have demonstrated the relationship between net primary production and evapotranspiration. The relationship between these two environmental impact categories and nitrate leaching is less obvious, but in general, high nitrate concentrations in groundwater often accompanies low recharge and high carbon sequestration. Such situations will be typical for fertilised and unthinned spruce stands. Reversely, older heavily thinned broadleaved stands will have lower nitrate concentrations in the groundwater due to lower N deposition and lower interception evaporation, while recharge is higher and carbon sequestration lower in such old stands.

Table 11.3. *Overview of afforestation strategies in order to optimise the environmental impacts.*

	Water recharge	Nitrate leaching	Carbon sequestration	Characteristic forest understory species
What happens after afforestation compared to arable land?	• Decreases during first 10-20 years • Thereafter constant	• Fast reduction during first five years • Increases again after canopy closure (~20 years)	• Average rates of C sequestration range from 0.3-0.8 t C ha^{-1} yr^{-1} in soils and from 1.5-4.3 t C ha^{-1} yr^{-1} in biomass	• It takes 50-100 years or more before typical characteristic forest understory species start to develop • Seed availability, light and nutrients determine the time scale
Which afforestation sites should be selected?	• Sandy soils	• Nutrient-poor sandy soils • Low N deposition areas away from local sources • Larger forest fragments connected to former forest	• Nutrient-rich soils • Moist soil conditions	• Bordering or in vicinity of old-growth forest = seed availability • Low N availability
Which tree species should be selected?	• Deciduous species preferable to conifers	• Deciduous species or mixtures of species • No use of N fixing species	• Tree species with high increment rates over a long life cycle • Species with slowly decomposing litter	• Deciduous trees with high density of overstory = low light levels
Which manage-ment practices will optimise?	• Low density of overstory • No artificial drainage • Low density of understory = bare soils	• Little site preparation • No mechanical weed control • Fast establishment • Weak thinning regime and no clear-cutting • No artificial drainage	• Continuous cover forestry • Weak thinning regime • No artificial drainage • Stronger thinning regimes in productive sites where wood products can substitute fossil fuels	• Seed availability improved by sowing • Anthropogenic removal of competitive species • Grazing

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