Production and Ecological Aspects of Short Rotation Poplars in Sweden

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Contents

Abstract

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Poplars (*Populus sp.*) are widely used in short rotation forestry for production of biomass for bioenergy, fibre and environmental services. Swedish short rotation forestry is based on *Salix sp.*, and little is known about the production potential of poplar plantations and their effects on the environment. This thesis focuses on four aspects of intensive short rotation forestry with poplars: 1) Biomass production and partitioning at several initial densities and a range of latitudes and growing conditions in Sweden, 2) the effects of poplar plantation on floristic diversity in the Swedish agricultural landscape, 3) the pattern of wind damage and its effects on production in poplar plantations in southern Sweden, and 4) ecological characterisation of poplar varieties in short-term experiments with pot-grown plants.

Annual biomass production in poplar plots and plantations over a rotation period of 9-14 years ranges between 3.3 and 9.2 Mg ha^{-1} yr^{-1}. These high production figures are achieved on relatively fertile, non-fertilised and non-irrigated agricultural land. The production assessments for commercial poplar plantations established at lower initial densities (1000 trees ha^{-1}) in southern Sweden indicate a similar production potential as in closely spaced cultures (5000 trees ha^{-1} yr^{-1}), though at 3-5 years longer rotations. Lower initial densities enable higher pulpwood yields along with the production of biomass for bioenergy.

A comparison among 21 poplar plots, 0.1-13 ha large and adjacent arable fields, indicates that small poplar plantations may increase floristic diversity on a landscape scale, mainly by providing a different type of habitat that may favour shade-tolerant and draught-sensitive species. This is reflected by a relatively low number of species shared by both types of habitat. Poplar plantations also show greater floristic heterogeneity compared to arable fields.

Wind damage in two poplar plantations, 15 and 33 ha large, was assessed using wind damage classes based on leaning angle of individual trees on plots established before wind damage occurred. The extent of damage among 23 plots ranged between 0% and 63% damaged trees. The loss of increment on the strongest damaged plots during the two-year period after the storm was 30%, whereas there was no difference in growth between damaged and undamaged plots in the third year after the storm.

A short-term experiment using pot-grown plants revealed differences in clonal growth response in terms of physiological and morphological variables that determined relative growth rate and nutrient productivity, despite that most of clones were of the same species and geographic origin. The importance of different response variables in determining growth also shifted as an effect of irrigation and fertilisation treatment.

Provided that suitable plant material is selected and widely available, commercial SRF with poplars represent a valuable alternative crop for surplus agricultural land with a potential to produce multiple benefits to society through the high production of biomass and fiber and positive effects on the environment.

Keywords: bioenergy, biomass, clone, floral diversity, hybrid aspen, hybrid poplar, *Populus*, relative growth rate, short rotation forestry, wind damage.

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Contents

Preface

Papers I-IV

This thesis is based on following papers, which will be referred to by their Roman numerals:

I Karacic, A., Verwijst, T. & Weih, M. 2003. Above-ground biomass production of short-rotation *Populus* plantations on agricultural land in Sweden. *Scandinavian Journal of Forest Research 18*, 427-437.

II Weih, M., Karacic, A., Munkert, H., Verwijst, T. & Diekmann, M. 2003. Influence of Young poplar stands on floristic diversity in agricultural landscapes (Sweden). *Basic and Applied Ecology 4*, 149-156.

III Karacic, A., Weih, M. & Verwijst, T. Quantifying the effects of wind damage on tree growth in poplar plantations. (Manuscript).

IV Karacic, A. & Weih, M. Variation in growth and resource utilisation among eight poplar clones grown under different irrigation and fertilisation regimes in Sweden. (Manuscript submitted to *Biomass and Bioenergy*)

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Introduction

Background (Setting the stage…)

The profitability of agriculture within EU largely rests on an extensive system of subsidies resulting in an overproduction of food crops and negative effects on food-production sector of underdeveloped countries. Surplus agricultural land could be used for wood production, as demands on European forests are growing, not only as a source of wood and fiber, but also in terms of environmental services, biodiversity and socio-economic development (Eriksson, Hall & Helynen, 2002). These demands are often conflicting, especially when wood and pulpwood industries are expected to expand, and utilisation of forest residuals for bioenergy is larger than ever and is still increasing (Berg, 2003; Parikka, 2004). While depletion of fossil resources and increase of oil prices belongs to an obvious future scenario, the trend of land conversion continues in many European countries where farmers are encouraged to grow non-food crops, often for bioenergy purposes. On a global scale, energy crops from surplus agricultural land were estimated to have largest potential of biomass production (Hoogwijk *et al.*, 2003). In this context, short rotation forestry represents a valuable alternative with possibility to use already existing practical knowledge and machinery from traditional agriculture.

Short rotation forestry (SRF) is usually defined as a silvicultural practice where fast-growing tree species are grown under intensive management and harvested in 2-10 years cycles (Hansen, 1991). Depending on final product, species used and climate, SRF may include coppiced or single-stem cultures with varying initial density and rotation length up to 20 years (Cannell & Smith, 1980; Mitchell *et al.*, 1992; Deraedt & Ceulemans, 1998). The main products of SRF are biofuel and pulpwood, and most widely used species belong to genera *Eucalyptus*, *Populus* and *Salix*. Sweden is one of few countries where willow SRF for energy purposes exceeds poplar growing (Verwijst, 2001), and has gradually developed into an important alternative crop covering more than 16 000 ha of agricultural land (Weih, 2004). However, recent yield estimations render poplars a promising option on set-aside land in Sweden provided that potential growers are eventually offered suitable plant material (Karacic, Verwijst & Weih, 2003). Intensive SRF, established on highly productive land at short distance from industry facilities, may effectively meet future demands for raw wood material. A high production could be concentrated to a smaller area of land that already is intensively managed providing more space for the conservation and careful management of the remote natural forests. Poplars also could be grown as multipurpose plantations serving as biomass producers and carbon sinks, recycling the waste products from the society and buffering against nutrient leaching. Thereby, the land that has carried agricultural crops since it became human habitat can still yield great benefits to the society if partly converted to poplar based SRF.

(… for a) Forest crop on agricultural land

Historical perspective on poplar culture

The watercourses of large European rivers have been increasingly regulated throughout the centuries, and the wide areas of native riparian poplar and willow forests became reduced to a very limited zone between permanent riverbeds (Guzina *et al.* 1986). Similar scenario of human impact was followed in North America during the last 150 years. The dynamics of lateral movement of riverbeds, *e.g.*, erosion and accumulation of alluvial material, was interrupted hampering the process of formation of new natural riparian forests, while the old stands gradually became isolated and degraded (Braatne, Rood & Heilman, 1996). Thus, the natural forest renewal became a sporadic event and native riparian forests were replaced with plantations of selected poplar and willow clones. On the other hand large areas of aspen and white poplar forests of northern hemisphere stayed out of the reach of human impact until the era of industrial forestry. Being an aggressive coloniser of fire-disturbed sites, aspen invaded the large areas of northern America after the extensive fires of the late 19^{th} and early 20^{th} century (Dickman, 2001). During the last 20 years, the utilisation of these forests became the base for an expansive forest industry of the northern Great Lakes region of USA and the boreal region of Canada (Zasada *et al.* 1996). In Europe, and in Sweden particularly, modern forestry preferred conifers and treated aspen as "weed trees", which, at least in Sweden, has led to cleaning practices that, along with effective fire-protection, held aspen off production forests. This attitude has partly changed since the Swedish Forestry Act from 1994 balanced production and biodiversity (Skogsstyrelsen, 1994) recognising the need for an increased share of deciduous tree species in forests, in particular old aspen trees (Hazell, 1999).

Indeed, poplars were grown on the patches of less productive set-aside land along the riverbanks and channels in alluvial areas since historical times, serving as a local source of timber, fuel and forage, but also as windbreaks improving the yield of agricultural fields. While poplars may still have the same function in many agrarian countries, the processing of poplar wood in industrial societies is aimed for bioenergy, paper, lumber, veneer, plywood and engineered wood products such as oriented strand board (Heilman, 1999). Without a doubt, the ease of clonal propagation greatly contributed to the spread of planted poplars allowing people to reproduce genotypes with desired characteristics suitable for their practical use. After that poplar species from North America were introduced in Europe towards the end of eighteenth century, poplar cultivation was revolutionised by appearance of spontaneously occurring hybrids, usually between European black poplar and North American eastern cottonwood (*Populus nigra* L. *x P. deltoides* Marsh. = *P. euramericana*, syn. *P. canadensis*). These "Canadian poplars" had extremely rapid growth and were easy to propagate by cuttings. At the beginning of twentieth century the first industrial poplar plantations appeared in Italy producing wood for mechanical pulp and plywood (FAO, 1979). By 1930, poplars cultivation was widespread in many other countries calling for more scientific approach to breeding and silviculture. After the appearance of first national poplar commissions in 1940's, the initiative was taken to bring them together and in 1947 the International Poplar Commission (IPC) was set up within the framework of Food and Agriculture Organisation (FAO, 1958). Since then, the work of International Poplar Commission has led to important agreements on nomenclature, registration of clones and varietal control, and a progress in research on utilisation and cultivation of poplars (Zsuffa *et al.* 1996). Today, poplars are planted for different purposes on both northern and southern hemisphere. The largest area of planted poplars was reported in China (6 million ha, whereas other six countries (France, Hungary, Turkey, Italy, Spain and USA) reported more than 100 000 ha of poplar plantations (FAO, 2001).

Ecology of Populus

Poplars (*Populus sp.* L.) grow naturally from sub-tropical to the temperate and boreal regions of northern hemisphere occupying a variety of sites (Zsuffa *et al.* 1996). The 29 species of poplars are classified into six sections and many of them are capable of crossbreeding generating a tremendous number of varieties and intermediate forms (Eckenwalder, 1996). This variety is related to adaptive ability to local environments and continued genetic communication over long distances of several important species of the genus (Farmer, 1996). Poplars are dioecious, wind-pollinated, single-stem deciduous trees with extremely light, cottony seeds that can be produced in millions by a single tree and dispersed by wind to long distances. They grow rapidly at juvenile stage, and can reinvade a site by shoots sprouting from root or stump, a characteristic that also fits their ecological role as a major invader of disturbed sites (Dickmann, 2001). On riparian sites, many poplars are adapted to seasonal flooding (*P. nigra* L., *P. deltiodes* Marsh., *P. fremontii* Wats., *P. trichocarpa* T.G., etc.) colonising the fresh material accumulated on sandbanks, whereas aspens (*P. tremula* L. *P. tremuloides* Mich.) are successful pioneers on fire-disturbed upland areas. All poplars are light-demanding and though they can grow on variety of soil types, the best performance is achieved only on deep, fresh soils (FAO, 1958).

There is a great variability in terms of wind firmness, frost, drought, insect and diseases resistance. For example, most of poplars of section *Aigeiros* (black poplars), *Leucoides* (svamp poplars) and *Tacamahaca* (balsam poplars) depend on abundant access to light and water, whereas species of section *Populus* (aspens and white poplars) have larger demands on light than water. Aspens are generally regarded less suitable for windbrakes because of shallow rooting, whereas the rooting depth of black poplars is regarded more flexible and depends on local soil conditions. The ability of poplars to root from cuttings is prerequisite for their cultivation, but this characteristic is not found in all species. Clonal aspens can only be cultivated by rooted plants raised from root suckers, a method much more expensive than propagation by shoot cuttings.

Poplars are typically trees with a high production potential, consistently allocating gathered resources to growth related processes (Mattson, Hart & Volney, 2001). They produce leaves continuously and are able to take advantage of a prolonged growing season or favourable growth conditions. This distinguishes poplars from other species with determinate growth or multiple flushing growth patterns (Dickmann *et al.*, 2001). However, it is necessary to emphasise that fast growth often is achieved at an expense of protective characteristics making poplars susceptible to stress, pathogens, insects and herbivores (Loehle, 1988; Chapin, Autumn & Pugnaire, 1993).

Cultivation practices

Poplar cultivation practices vary worldwide according to different needs, tradition, climate, plant material, available sites, and current economy and legislation in a particular country or region. Typical cultivation issues are selection and production of clone material, site selection and soil preparation, spacing and planting technique, weed and pest control, fertilisation, irrigation, thinning, rotation length and harvest techniques. Most of these issues are closely related to end use of crop. Depending on the major purpose, Zsuffa et al. (1996) distinguish between production plantations, and poplars planted for site protection or landscape.

Most of early industrial plantations in Europe were optimised for the production of sawnwood and pulpwood (FAO, 1979) and while development of technology in recent decades did provide additional possibilities in manufacturing veneers, plywood and various composite products (Lowood, 1997; Balatinecz & Kretschmann, 2001), the silvicultural systems remained basically unchanged or changed very little. In countries with long tradition of poplar cultivation, like France, Hungary, Italy, Romania, and former Yugoslavia, the plantations are usually established on highly fertile sites using intensive agricultural techniques. Euramerican hybrids (crosses between *P. nigra*, *P. deltoids* and *P. trichocarpa*) are still the dominating source of plant material and spacing is between 4 m x 4 m (Italy, Romania, former Yougoslavia) and 7 m x 7 m (Belgium, Netherlands, France). Large plants or cuttings are typically used for planting to the depth of about 1 m or even deeper on sandy soils in order to anchor plants properly and enable roots to develop near the groundwater level. Allowing for variations caused by site (latitude, soil characteristics, availability of water and nutrients) plant material, cultivation intensity and desired product, the usual length of rotation is 11-15 years in southern Europe (4 m x 4 m) and up to 25-40 years (7 m x 7 m) in Belgium, Germany and Netherlands (FAO, 1979; Guzina *et al.*, 1989). In southern Europe, annual crops such as corn, maize, etc. sometimes are cultivated between poplar rows until crown closure (2-4 years) (Zsuffa *et al.*, 1993). This type of tree intercropping system with poplars, usually termed agroforestry, offers a magnitude of possibilities (Jain & Singh, 2000; Tupker, Thomas & Macdonald, 2003; Thevathasan & Gordon, 2004; Rockwood et al., 2004; Puri & Nair, 2004) and is common in India and China (Chaturverdi, 1982; Zsuffa et al., 1996; Newman, 1997; Christersson, 2004).

In North America, poplar cultivation has developed rapidly since the end of 1970s, particularly in the Pacific Northwest (Ranney, Wright & Layton, 1987). The North American model of SRF (short rotation intensive culture, SRIC, or short rotation woody crop, SRWC; not to be confused with Swedish short rotation willow coppice, SRWC), has been very successful receiving a great international attention as a model for multidisciplinary research integrating genetic improvement, tree growth and differentiation, production ecology and practical application and field trials (Hinckley *et al*., 1993; Bradshaw & Stettler, 1995; Hinckley, 1996; Ceulemans & Deraedt, 1999). Breeding has focused on North American poplar species and their hybrids (*P. balsamifera*, *P. deltoids and P. trichocarpa*), and on hybrids between American poplars and *P. nigra* and *P. maximowiczii*. For SRF important traits are sought, like narrow crowns, large upper leaves, indeterminate growth, pest resistance and drought tolerance (Wright & Layton, 1987). The major production goals of these plantations are fiber for fine paper industry and biomass for bioenergy. This is achieved within short rotation periods (3 to 10 years) by means of intensive measures of weed and pest control, and fertilisation and irrigation (Hansen & Netzer, 1985; Ranney, Wright & Layton, 1987; Hansen, 1994; Stanturf *et al*., 2001). During the first ten years of SRF development in North America, the recommended planting densities were between 2500 to 4000 trees ha^{-1} and coppicing was regarded as an appropriate option of regeneration (Ranney, Wright & Layton, 1987). In recent years, spacing recommendations have shifted towards planting densities of 1200-1400 or less stems ha^{-1} and coppice has been eliminated as a regeneration method (Tuskan, 1998; DeBell *et al*., 1997). Instead the land is cleared and replanted using 20-30 cm long woody cuttings of one or two year old shoots (Stanturf *et al*., 2001). Despite the lower establishment costs of coppice regeneration (Perlack & Geyer 1987;), the shift to single-stem, non-coppice systems offers the advantage of more frequent implementation of new, genetically improved, plant material with higher production rates and better pest and disease resistance. The higher increment of dense coppice regenerations compared to planted single-stem cultures (Cristopherson *et al*., 1989; Herve & Ceulemans, 1996; McDonald, A.J.S. & Pereira, J.S., 1996; Hofmann-Schielle *et al*., 1999; Mitchell, Stevens & Waters, 1999) are usually lost over longer rotations of 6-10 years (DeBell, Clenden & Zasada, 1993; Armstrong, Johns & Tubby, 1999; Proe *et al*., 1999). Moreover, the harvest costs per unit of produced biomass are reduced at wider planting densities. Today, harvest operations relay on traditional technological systems with felling, skidding and chipping at the landing with immediate transport to industrial facilities (Tuskan, 1998).

During the 1980s Sweden has led the development of willow coppice systems (Sirén, Sennerby-Forsse & Ledin, 1987; Christersson, Sennerby-Forsse & Zsuffa, 1993; Christersson & Sennerby-Forsse, 1994; Rosenqvist *et al*., 2000), while poplar coppice has been of interest in Belgium, France, Germany, Italy, the UK and North America (Mitchell, 1995; Ceulemans & Deraedt, 1999; Mitchell, Stevens & Watters, 1999; Makeschin, 1999; Kauter, Lewandowski & Claupein, 2003). The coppice regime is a cultural treatment aimed to take advantage of simple and cheap regeneration and more conventional agricultural harvest techniques (Pontailler, Ceulemans & Guittet, 1999). As in other SRF systems, rotation age is determined by initial plant density and growth rate (Mitchell, Stevens & Waters, 1999). Generally, the best results with poplar coppice in the UK and the USA are achieved at spacing between 5000 and 7000 trees ha^{-1} and harvest cycles of 3-4 years (Mitchell, 1995). Harvest is always performed during the dormant winter period in order to reduce plant stress caused by soil compaction and nutrient removal from the site, and minimise moisture content of harvested wood (Mitchell, Stevens & Waters, 1999). The two most broadly used harvesting techniques are “single pass cut and chip” and “whole stem” system. Whole stem harvesting is recommended when harvested biomass is to be stored for longer period before processing (Makeschin, 1999).

Yield

Rapid early growth enables poplars to fully utilise the resources released after a disturbance. This characteristic is exploited to achieve high biomass production on fertile agricultural land or in irrigated and fertilised cultivations where yields of ca 18 Mg ha^{-1} yr^{-1} have been reported (Stanturf *et al.*, 2001). These production figures are similar to those reported for the improved genetic material on large monoclonal plots (DeBell, 1996), but less than previously reported yields from small experimental plots (Heilman & Stettler, 1985; Heilman & Fu-Guang, X, 1993; Scarascia-Mugnozza *et al.*, 1997). In Europe, mean annual production in both single-stem and coppice poplar and hybrid aspen plots was reported to range between 2 and 13.5 Mg ha^{-1} (Mitchell, 1995; Liesebach, M. Wuehlisch & Muhs, 1999; Makeschin, 1999; Kauter, Lewandowski & Claupein, 2003; Laureysens *et al.*, 2003). Pontailler, Ceulemans & Guittet (1999) reported yields of between 20 and 30 Mg ha^{-1} yr^{-1} in subsequent 2-year coppice rotations on irrigated and fertilised plots in France, but such high figures should not be expected from plantations on operational scale.

The productivity of cultivated poplars is affected by climate, nutrient and water availability, plant material, type and intensity of silvicultural system and the efficiency of pest and disease control. Provided that water and nutrients are readily available, the production potential of cultivated poplars is higher in temperate than in boreal regions due to a longer growing season. Addition of nutrients usually increases biomass production of hybrid poplars mainly through an increased leaf mass and leaf area (Heilman & Xie, 1994). For instance, Heilman & Xie, (1993) reported the addition rate of 137 kg nitrogen ha^{-1} yr^{-1} to increase yield by 21% after 4-year period, whereas Van Veen et al. (1981) estimated that short-rotation poplar forest producing 14.4 Mg ha^{-1} yr^{-1} needed an annual input of 122 kg N during a 5-year growing period. However, the nutrient management depends on site characteristics and overall management strategy, which is also related to the functional aim with a particular poplar plantation. A practical approximation of an optimal nutrient regime for North American SRF is a rate of 50-100 kg N ha^{-1} yr^{-1} beginning at the time of canopy closure when weeds are outcompeted and foliar biomass is expanding most rapidly (Hansen, 1994; Stanturf *et al.*, 2001). In many cases, good fertility of agricultural soils would allow an entire first rotation cycle to be fulfilled without fertilisation. This is enabled by a rapid recycling of nutrients through the litterfall (Berthelot, Ranger & Gelhaye, 2000) and relatively low nutrient content in poplar stemwood, especially at larger stem dimensions (Rytter, 2002). Heilman & Xie (1993) concluded that strong competition among the trees might limit the positive response to fertiliser and recommend wider spacing (ca 1000 trees ha^{-1}) to allow for longer duration of nitrogen response and shortening the time needed to reach maximum periodical annual increment. Heilman & Norby (1998) found two main approaches to fertility management in SRF plantations evident in the literature. The more common is a conservative approach that restricts the application of fertilisers only to the plantations with deficiency symptoms. In contrast to this approach is the fertility management that seeks to maintain a constant high level of site fertility in order to assure optimal nutritional status of the crop. In the case of a more conservative approach, a maximum yield and profit is not assured, especially with high value crops, whereas the second approach is costly and substantially increases the potential for leaching and denitrification losses.

The most effective yield increase is achieved by a combination of irrigation and addition of fertiliser, but response is highly clone-specific and related to plants ability to use the whole length of growing season (Dickmann, Nguyen & Pregitzer, 1996). Highly productive clones like Beaupré were reported to transpire 6±0.5 mm water day^{-1} (Hall et al., 1998) and 5±1.8 mm day^{-1} (Allen, Hall & Rosier, 1999) during the most intensive period of growth in June and July when soil water was plentiful, whereas much lower rates (1 mm day^{-1}) were recorded later in the season during a drought period. In absolute terms, the yield gain through the positive effect of irrigation is most striking when highly productive clones like Beaupré are used (Souch & Stephens, 1998). Kranjcec, Mahoney and Rood (1998) reported large variations across cottonwood genotypes in the tolerance to water table decline with the clones of *P. balsamifera* being the most vigorous in the conditions of sudden decrease in water availability. Also in boreal climate, current annual increment and total productivity of willows and poplars vary with water availability during the vegetation period and is regarded to be critical for profitability of SRF (Lindroth & Båth, 1999; Karacic, Verwijst & Weih, 2003).

The maximum mean annual growth is reached within a shorter period of time when using the best plant material and closer spacings (Armstrong, Johns, & Tubby, 1999). At longer rotations, however, basically the same yields can be achieved at wider spacing given that a spacing is close enough so that the canopy is allowed to close at a reasonably early stage (DeBell, Clendenen & Zasada, 1993; DeBell *et al*. 1996, 1997). Thus, the gain in an early high production achieved at high density should be evaluated against the higher costs of establishment and harvest (single-stem systems) or the higher costs related to frequent harvest in coppice systems. If the final product is pulpwood, the wider spacing (3 m x 3 m or 4 m x 4 m) is preferable. On the other hand, wider spacings require more intensive weed control during the establishment period to secure a good survival and avoid unnecessary prolonged rotations. Weed control is most effectively achieved through the application of appropriate herbicides, before and after planting, proper timing of planting, and weed control in previous crops (Hansen & Netzer, 1985; Buhler *et al*. 1998).

In recent years, considerable increase in yields reported from commercial poplar plantations in the Pacific North West and large monoclonal plots are related to improved plant material (DeBell *et al*. 1997). Beside yield, plant improvement and breeding has produced large number of clones with improved drought tolerance and pest resistance (Heilman & Stettler, 1985, 1990; Robinson & Raffa, 1998; Benetka, Bartáková & Mottl, 2002). Due to differences between clones in growth response through time it was recommended to defer the choice of individual clones for production purposes until a full rotation is completed (Stanton, 2001; Ares, 2002). Yields of cultivated poplars are usually not affected by clone deployment within the pure and mixed cultures (DeBell & Harrington, 1993, 1997; Benbrahim, Gavaland & Gauvin, 2000). The presence of clones resistant to some disease may reduce damage in SRF (Verwijst, 1989), but deployment in monoclonal blocks may facilitate pest and disease control, as well as the replacement of damaged clones (DeBell & Harrington, 1993). As a general rule it applies that "in polyclonal plantations the good clones tend to get better and the poor clones get poorer" (DeBell & Harrington, 1997).

Biodiversity and environmental issues

The introduction of SRF on agricultural land represents a considerable change to the landscape. People, in general, dislike changes and prefer some degree of continuity in the landscape near their settlement, which may result in a negative public perception of poplar plantations. However, the attitude towards plantation forestry and landscape varies among different regions and countries as much as the physical character of the landscape itself. Bell (1994) outlined some basic recommendations for designing coppice plantations in Britain starting from the main shapes and patterns of landscape. In Sweden, landscape perspective on SRWC was studied in a view of aesthetic and visual character (Skärbäck & Becht, 2005). It was concluded that *Salix* introduces new colours and special and textural variation into the rural landscape. The general rule is that in a small-scale landscape, plantation should be small, whereas an open landscape allows establishment of larger connected areas of SRF cultures, preferably of shifting age and shape.

Regardless of the perception of landscape that may differ between rural and urban public and shift quickly, the positive effects of SRF on the environment and biodiversity are relatively well documented. In this contecst, poplars and other short rotation crops are very often, unjustly and unconditionally, compared with natural or only extensively used ecosystems. Instead, SRF should be considered in landscape context (Weih *et al*., 2003) and compared with the cropping systems it substitutes (Christian *et al*., 1994). Research on wildlife in SRF has focused on birds as they rapidly colonise new areas and are easy to survey (Sage, 1998). Hanowski, Niemi and Christian (1997) found that poplar plantations probably would not support bird communities that are comparable to natural or semi-natural forests regarding either species composition or species diversity. However, as a habitat to many bird and mammal species, SRF plantations have been found to be at least as favourable as agricultural crops (Christian *et al*., 1998). Many authors report an increase of faunal diversity relating it to an improved structural diversity of agricultural landscape after the introduction of SRWC (Göranson & Boel, 1989; Twedt *et al*., 1999; Bergström, 2001; Berg, 2002). Some positive effects may also emerge from the variability of crop height and density or clonal deployment (Berg, 2002; Dhondt *et al*., 2004). In addition, willow coppice is regarded to contain a richer avian fauna than poplar plantations, probably due to larger populations of insects (Sage, 1998). Similarly to the diversity of fauna, young and relatively dense poplar and willow plantations were found to increase floristic diversity compared to managed coniferous forest and farmland in Sweden (Gustafsson, 1987; Weih *et al*., 2003).

The competitive ability of young poplars planted with unrooted cuttings is low and the use of herbicides during the plantation establishment is necessary. Compared to conventional agricultural crops the frequency of chemical weeding and pest control is low, and the risk for pollution of groundwater also decreases. Nutrient leaching from SRF may occur if an intensive fertility management is wrongly applied at the beginning of rotation period when the soil is not completely explored by the root system. Makeschin (1994) reported a 50% reduction of nitrate in percolation water from both fertilised and unfertilised SRF in Germany compared to the control field with an intensive agricultural management. It was also shown for series of fertilisation intensities in SRWC on sandy soils in Sweden that intensively fertilised plots have not increased N-leaching to the groundwater (Aronsson, Bergström & Elowson, 2000). Deeply rooted poplars are able to immobilise nutrients applied annually at low rates (50-150 kg N) sustaining both high production and avoiding the nutrient leaching to the groundwater (Stanturf *et al*., 2001). Up to 60% of nutrients can be recycled through the litterfall annually, stored in the organic matter of topsoil and subsequently released to the soil solution. These processes have also positive effects on soil fauna increasing the microbial activity and improving the structure of the soil (Makeschin, 1994). Establishment of poplar plantations on agricultural land is likely to decrease soil reaction (pH), which is thought to be an effect of a surplus production of mobile anions and leaching of base cations like Ca (Jug *et al*., 1999). However, the acidifying effect is even larger under conifer forests (Canell, 1999).

Phytoremediation and vegetation filters are the most commonly used terms for an emerging set of technologies that use plants for cleaning contaminated soils and water or as an alternative to conventional treatment of wastewater and landfill leachate (Isebrands & Karnosky, 2001; Aronsson & Perttu, 2001). In order to maintain rapid growth poplars consume large amounts of water and nutrients simultaneously degrading, extracting and immobilising pollutants, and decreasing mobility of contaminated sediments towards watercourses and lakes (Isebrands & Karnosky, 2001). There are many opportunities for the application of different phytoremediation systems. Bioenergy and solid wood production may be combined with streamside and riparian buffers, wastewater treatment, riverbed landfill buffers, carbon sequestration management, soil erosion control, protection and urban plantings and socio-economic benefits through diversified production from the farmlands and healthier air, water and wildlife (Licht & Isebrands, 2005). The interactions between plant, soil and contaminant are very specific and remediating effects will often depend on the choice of an adequate species or clone. Phytoextraction potential differs among poplar clones and is primarily determined by nutrient (metal) concentration and by biomass growth (Laureysens *et al*., 2005). Thus, clones that accumulate large amounts of one metal may be less suitable for extraction of some other metal or for recycling of N, P and K from municipal wastewater. In addition, willows were found to be more effective than poplars in remediating metal-contaminated land (Robinson *et al*., 2000; Moffat, Armstrong & Ockleston, 2001), but substantial differences among willow clones exist in this respect (Perttu, 1993). Also a high potential of poplars in remediating some types of organic pollutants was detected in several studies (Palmroth, Pichtel & Puhakka, 2002; Rubin & Ramaswami, 2001). In Sweden, willows are currently used as vegetation filter buffering against nitrogen leaching from farmland in southern Sweden, and for the treatment of municipal wastewater, landfill leachates and the runoff water from wood industry (Mirck *et al*., 2005).

Risks and limitations

“Disease resistance and vigour appear to be associated with the male sex.” This statement of Pauley (1949) cited by Newcombe (1996) regarding the hypothesis that disease resistance may be related with sex in dioecious poplars has been neither confirmed nor refused (Newcombe, 1996), but reveals the wishful thinking of breeders to find a single trait controlling the great variety of host – pathogen interactions. However, the only effective way to reduce disease-related loss in production is to plant clones inherently resistant to pathogens, which has made disease resistance one of the major selection criteria in breeding programs (Newcombe *et al*., 2001). However, the probability of selecting clones with desirable growth characteristics and resistance to diseases is low, partly due to biological trade-offs between high growth rate and pest and disease resistance (Chapin, Autumn & Pugnaire, 1993; Weih, 2003). Moreover, extensively planted poplar clones may become susceptible to newly evolving pathogen races despite the initial resistance to the particular pathogen species (Newcombe, 1996). An extensive literature witnesses about great numbers of insect and fungi species found on native and cultivated poplars in Europe and North America (FAO, 1958; FAO, 1979; Ostry et al., 1989; Peterson & Peterson, 1992; Delplanque et al., 1998; Mattson, Hart & Volney, 2001; Newcombe *at al*., 2001). The major insect damages are related to defoliating insects from the *Chrisomelidae* family, *Melasoma populi* in Europe and *Chrisomelida scripta* in North America, whereas fungi species of the genus *Melampsora spp.* are by far the commonest, most widely distributed and most serious disease of poplars worldwide. Fungal stem canker caused by *Septoria musiva* is a particularly serious pathogen on fast growing hybrid poplars in North America, while it causes no serious damage to the native poplar species. Another stem canker disease, caused by *Hypoxylon mammatum*, appears on *Populus tremuloides*, but is also recorded in *P. tremula* in Europe (FAO, 1979).

The large game mammals like red deer, roe deer and moose can cause serious damage in poplar and hybrid aspen cultures by feeding on young shoots and bark of young trees (FAO, 1979). Fencing of plantations is probably the most effective measure against browsing damages of large mammals, but is less effective in protecting the plantations against small rodents like voles and rabbits. Due to high pressure of browsing animals in Sweden, establishment of almost any deciduous species without appropriate, and often very expensive, protection measures appears to be a rather risky enterprise. This is particularly true for hybrid aspen in the areas with high population of moose. In such regions, it is recommended that fence protection should be kept intact for the entire first rotation period, whereas the risk of damage in subsequent rotations is relatively low due to very dense regeneration by root suckers (Almgren, 1990; Rytter, Stener & Werner, 2002, 2003).

In boreal regions, the risk of frost damage on deciduous poplars is relatively low during the winter period (von Fircks, 1992; Weih, 2004), whereas the risk of frost injury is particularly high during the transition periods between the dormant and growing seasons. The photoperiodicity of latitudinal ecotypes is closely related to growth cessation and hibernation of poplars (Howe *et al.*, 1995), and planting outside their latitudinal range is often associated with risks for frost damage. Therefore, the origin of plant material is crucial for the survival and growth performance in boreal SRF (Verwijst *et al.*, 1996; Christersson, 1996; Ilstedt, 1996). Despite the fact that moderate frosts may occur during the growing season without causing serious damage, they represent a stress factor that may interact with biotic damaging agents (Kozlowski, Kramer & Pallardy, 1991).

Poplars in Sweden

Aspen (*Populus tremula* L.) is the only poplar species native to Sweden. It occurs in the entire country, except for the alpine region of Sweden (Hultén, 1971), usually mixed with conifers, in small clonal groups or along forest edges (Hazell, 1999). Aspen is of minor importance to Swedish forestry with a standing volume of 41.8 million m^3, which represent 1.5% of the total standing volume for the period 1998-2002 (National Board of Forestry, 2004), but locally it may reach up to 8% (Sterner, 1998). Regarded as a strong competitors to coniferous species, aspen has been cleaned from conifer stands on most forestland until the recent decade when the demand for hardwood pulp increased along with the awareness of the importance of aspen and other pioneer tree species for providing habitat to many endangered species (Hazell, 1999). Practical management recommends rotations of 45-60 years with heavy cleaning and thinning leaving ca 400 standing trees ha^{-1} towards the end of rotation (Almgren, 1990). Self-thinning dynamics in aspen stands and ability of the largest trees to dominate and develop large crowns despite the high initial density allow for the management commonly applied in North American aspen forests, in which vegetatively regenerated stands are not cleaned or thinned prior the harvest age (Zasada *et al.*, 2001). Almgren (1990) suggests that on productive sites in Sweden (agricultural land), the first treatments may be postponed until trees have reached considerable height without negative effects on continued development of the stand. The mean annual production of pure aspen plots on fertile land was estimated to 7-10 m^3 ha^{-1} yr^{-1} (Eriksson, 1984; Almgren, 1990).

Hybrid aspen, the crosses of European and American aspen (*P.tremula* L. x *P.tremuloides* Michx.) produced in Sweden in 1939, was superior to both parents in terms of biomass growth, but also in terms of some resistance to *Melampsora* and *Polaccia* patogens (Almgren, 1990). Swedish match industry initiated a number of trials established in Sweden between 1940 and 1965, and also the poplar breeding institute in Geraardsbergen, Belgium (Christersson, 1996). These plots were recovered and measured at several occasions during the 1970s and 1980s when the interest for hybrid aspen was renewed, now as an alternative crop on agricultural land (Persson, 1973; Eriksson, 1984; Elfving, 1986). Very few clones of other hybrid poplars were tested at Mykinge trial station, mostly well known, old varieties like ‘Gerlica’, ‘Marilandica’, ‘Serotina’, ‘Robusta’ and some pure *P. nigra* clones (Persson, 1973). In the end of 1980s some of the clones bred in Geraardsbergen were transferred to Sweden and studied for a number of traits (Ilstedt, 1994, 1996). It was concluded that tested genotypes had poor budset and hibernation because of their origin that is more than 10 degrees south of the test areas. Thus, the autumn frost damage appears to be the main limitation when plant material originating mostly from Oregon and Washington, USA is used (Christersson, 1996), even though some clones of southern origin, like ‘Beaupre’ and ‘Boelare’ have grown quite well in southern Sweden (Telenius, 1999; Karacic, Verwijst & Weih, 2003). On the best sites, the production of conventionally managed, early thinned, hybrid aspen and hybrid poplars is 16-20 m^3 ha^{-1} yr^{-1} on a basis of a 26-30 years long rotation (Eriksson, 1984; Elvfing, 1986; Almgren, 1990). Recent studies of 17 hybrid aspen stands grown under different management regimes suggest that yields above 20 m^3 ha^{-1} yr^{-1} are achievable during a 20-25 year rotation periods (Rytter, Stener & Werner, 2003). Moreover, the vegetatively regenerated stands have a more rapid initial growth compared to planted crop and do not require fence protection which in a long run improves the economy of hybrid aspen cultivation (Rytter, Stener & Werner, 2002).

Objectives

The main objective of the work included in this thesis was to evaluate the performance of hybrid poplar and hybrid aspen in trials and commercial plantations established at the end of 1980s and beginning of 1990s in Sweden. The specific objectives related to the issues important for the success of poplar and hybrid aspen SRF on agricultural land were:

1. Survival and stand development of hybrid poplar and hybrid aspen plots established at high initial density;
2. Establishment of clone- and age-specific equations for the assessment of biomass production;
3. Assessment of biomass production and its suitability for the specific product (pulpwood or bioenergy) in relation to initial density and age of the stand;
4. Assessment of the effect of small-scale poplar plantations on the floristic diversity in agricultural landscape across Sweden;
5. Quantification of wind damage, its relation to the dimensional parameters of individual trees and the stand, and the effect of damage on future growth of individual trees and area-based productivity of commercial poplar plantations;
6. Characterisation of poplar clones in terms of growth and nutrient use efficiency under different levels of water and nutrient availability using pot-grown plants;

7. Evaluation of different physiological and morphological variables as predictors of clone performance by means of short-term experiments with pot-grown plants.

Materials and Methods

Locations

The study of poplar and hybrid aspen biomass production (Paper I) was carried out in three experimental fields (Innertavle, Bodarna and Bullstofta) and two commercial poplar plantations (Sångletorp and Rydsgård, Fig. 1). The study of wind damage effects on growth and production of poplar plantations (Paper III) was accomplished on 23 plots originally established for yield studies at Sångletorp and Rydsgård.

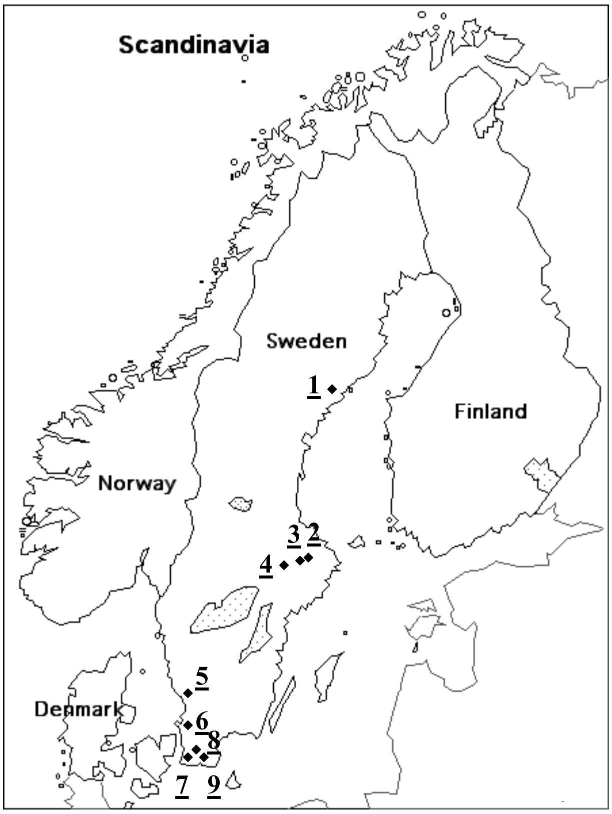

Figure 1. The locations of sites included in this thesis. 1) Innertavle; 2) Bodarna; 3) Ultuna; 4) Malmön; 5) Långaveka; 6) Bullstofta; 7) Sturup; 8) Sångletorp; 9) Rydsgård

The assessments of floristic diversity (Paper II) were performed at all the locations from Papers I and III, and on two additional experimental stations

(Malmön and Långaveka) and one commercial hybrid aspen plantation in Sturup. Finally, a study with pot-grown plants (Paper IV) was performed in Ultuna. Details about site characteristics and cultivation practices on each location were presented in the respective paper.

The sites differed with respect to soil type, ranging from sand (Långaveka, 95% sand) to clay (Bodarna, 65% clay). Very few differences were found between soil characteristics in 10-15-year old poplar plantations (only untreated sites) and adjacent agricultural fields, the largest differences being found in phosphorus and magnesium content (Fig. 2).

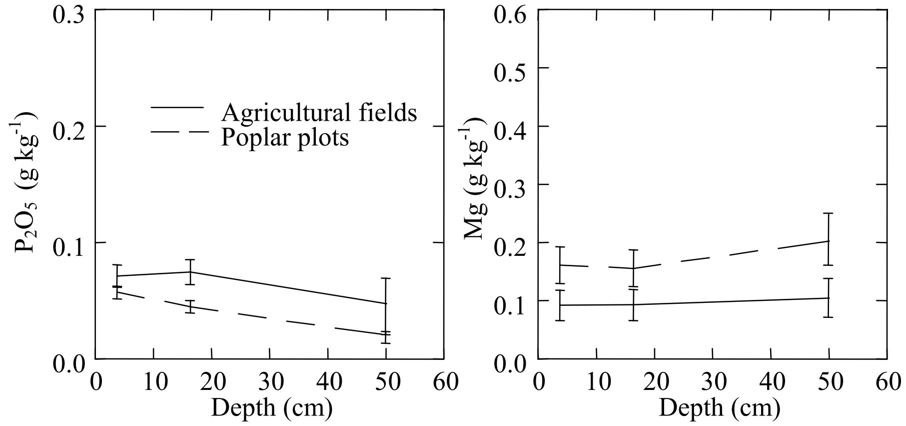

Figure 2. The available soil phosphorus and magnesium in 10-15-year old poplar and hybrid aspen plantations and adjacent agricultural fields cultivated with annual crops or converted to grassland or fallow. The values are means of 17 poplar and hybrid aspen plots and 10 adjacent agricultural from northern to southern Sweden and including a range of soil textures, from clay to sand

Estimation of yield and wind damage (Papers I and III)

All biomass estimations were based on destructive sampling of individual trees belonging to a range of diameter strata. Thus the fresh biomass of each tree was measured in the field and dry weight calculated from the fresh weight/dry weight relationship for at least five samples per tree. The relationship between total dry weight of a tree and its diameter at breast height (DBH) was used for the assessment of dry biomass in all the trees on each plot (Paper I). The functions used to express the relationships between total dry weight, stem volume, pulpwood weight percentage and pulpwood stem volume percentage and DBH are presented in table 1. In all regression procedures 'Boelare' and 'Beaupré' were pooled together, as well as clones '910' and '51', whereas 'OP42' and clone mixture 'Ekebo' were processed separately (Paper I). Total standing biomass and annual increments on one-hectare area basis were calculated after upscaling of respective figures for all the living trees on net-plots on each site.

On December 4th 1999, a storm passed the southwest parts of Sweden and caused extensive forest damages. The damage in 9-year old commercial poplar plantations at Rydsgård and Sångletorp were surveyed directly after the storm event on 11 and

12 plots per respective site established and measured earlier in the autumn 1999 for the purpose of yield estimation (Paper III). The size of the plots was 30 m x 30 m with ca 100 trees per plot. A wind damage class 0-4 (not damaged - windfall) was assigned to each tree based on stem inclination from the vertical and discernable damages on root system. Measurements of DBH were repeated in 2001 and 2002 so that tree growth of trees belonging to different wind damage categories could be studied. The spacing was close to regular, which allowed for studies of wind damage and subsequent growth increment in the light of dimensional relationships and degree of wind damage among neighbour trees.

Table 1. *Function parameters used in equations for calculating total dry weight, stem volume and pulpwood weight and volume percentage as a function of diameter at breast height*

Clone	Age (year)	Parameters					R^2 corrected
		a	b	c	d	f	
Boelare, Beaupré[a]	4		0.10634	2.17336			0.97
	5		0.090436	2.294451			0.98
	6-8		0.151527	2.063844			0.97
	9		0.101811	2.258561			0.99
Hybrid aspen[a]	4 and 5		0.121844	2.081332			0.92
	5-7		0.064766	2.387294			0.95
	7-9		0.031873	2.707311			0.97
	9-11		0.106179	2.257852			0.96
OP42[a]	9-11		0.085431	2.390766			0.997
910, 51[a]	14		0.147958	2.10326			0.97
Boelare, Beaupré[b]	4-9	-12	93.8714	6.159421	-0.95148	1.881695	0.94
H. aspen[b]	4-11	-12	84.1844	3.823489	-0.97403	0.368863	0.92
OP42[b]	9-11	-12	86.9887	0.6343	-1.3273	0.001191	0.99
910,51[b]	14	-12	92.2343	-4.50983	-0.87831	0.000146	0.94
Boelare, Beaupré[c]	4-9	-5.46410	0.367779	2.158033			0.98
H. aspen[c]	4-11	-0.35114	0.14442	2.449045			0.99
OP42[c]	9-11	1.315563	0.172386	2.431559			0.99
910;51[c]	14	-1.80065	0.025735	2.246894			0.99
Boelare, Beaupré, H. aspen[d]	7	97.1374	-11006.1	-2.9474			0.89
Boelare, Beaupré, H. aspen[e]	7	96.7951	-17346.0	-2.9473			0.73

a) $TDW = b \times DBH^c$, where TDW is total dry weight of individual trees (kg) and DBH is their diameter at breast height (cm); b) $PP = a + b \times (1 + e^{(c + d \times DBH)})^{(-1/f)}$, where PP is pulpwood percentage of the total dry weight of individual trees and e is the base of natural logarithm; c) $V_E = a + b \times DBH^c$, where V_E is the stem volume (dm^3) calculated using the equation of Eriksson (1973, see Paper I) in which both height and DBH of a tree were included; d) $PV = a + b \times DBH^c$, where PV is the pulpwood fraction (%) of the whole stem volume, and e) the same as previous, but PV denotes the pulpwood fraction harvestable as 3 m long stocks.

Effects of wind damage on basal area increment of individual trees were estimated using covariance analysis where other variables denoted basal area of individual trees before the storm and its variation among the sites and plots within each site, and two indices describing the level of damage on neighbour trees. The same covariance analysis was performed without the two latter indices. Total basal area increment per plot and mean basal area increment of individual trees per plot were related to mean wind damage class per plot in order to estimate the effects of wind damage on increment on area basis.

Measuring biodiversity in young poplar plantations (Paper II)

A survey was carried out during July 2000 in order to compare floristic diversity in Swedish poplar plantations and nearby agricultural fields. The vegetation was recorded using nested quadrates (Fig. 3) located along 4-5 transects running perpendicularly from the boundary into the central part of a field or plantation (Hodgson *et al*. 1994). The quadrates were positioned at five points along each transect beginning from 2, 8, 16, 32 and 64 m from the field or plantation edge. Species were recorded sequentially in a series of cells as it is described in figure 3.

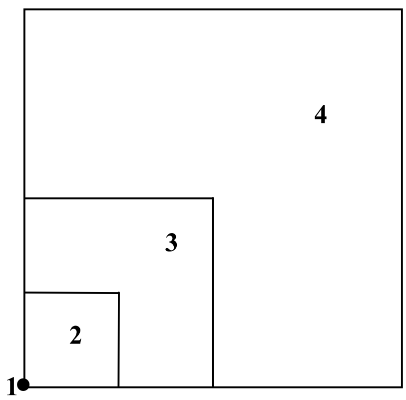

Figure 3. The species immediately below pin-hit position was assigned a score of 1. Additional species found within each subsequent quadrate received a score of 2 (12.5 cm x 12.5 cm), 3 (25 cm x 25 cm) or 4 (50 cm x 50 cm)

This method was developed to increase efficiency and decrease observer variation in estimations of species abundance and floristic heterogeneity in grasslands (Hodgson *et al*., 1994). The small plots size on several experimental sites allowed for only four transect and three nested quadrates to be surveyed and these plots were excluded from statistical analysis. Species numbers on arable fields and poplar plots were compared using t-test, and nested ANOVA analysis was performed to estimate effects of site, habitat type (arable field or forest), transect and quadrate position on mean species number per quadrate. To obtain a general impression of species composition in poplar plots and arable fields, multivariate analyses were performed on the third quadrate of third transect across all the poplar plots and arable fields. The data was classified by a polythetic, divisive clustering method TWINSPAN (Hill, 1979a) and by detrended correspondence analysis (Hill, 1979b).

Study of pot-grown plants: a method for fast evaluation of clone material (Paper IV)

The study of physiological and morphological characteristics of eight poplar clones was performed by means of classical growth studies (Paper IV). Pot-grown plants, raised from dormant cuttings were fertilised (three levels) and irrigated (two levels) for 10 weeks. The replicates were arranged in a full-factorial experimental design with 24 plots and two irrigation blocks. During rainy periods, the plants assigned to low irrigation treatment were isolated from rainfall water by transparent plastic cover. Plants were harvested prior the treatment application (12 plants per clone), after the 10 weeks of treatment application (12 plants per clone and treatment) and after leaf shedding (four plants per treatment in four clones). Fresh and dry weights of different plant parts were measured, and also leaf area of newly harvested leaves. N and P contents were determined photometrically using flow injection analysis. In harvest 1, leaves and shoots were analysed separately from cuttings. Roots, shoots and cuttings of second harvest were analysed separately from leaves, whereas in the third harvest only abscised leaves were analysed. Relative growth rate (*RGR*) of plants was studied in relationship to its components, unit leaf area (*ULR*) and leaf area ratio (*LAR*), and also in terms of N economy. The following relationships were studied:

$RGR = ULR \times LAR$

$ULR = LNCa \times LNP$

$RGR = PNC \times PNP$,

where *LNCa* is the leaf N concentration on leaf area basis, *LNP* is leaf N productivity, *PNC* is plant N concentration and *PNP* is plant N productivity.

Results and discussion

The ability of poplars to grow well at high latitudes was demonstrated on a plot in Innertavle, northern Sweden (63º48'N), where two balsam poplar clones were planted at spacing 2 m x 3 m (table 3, Paper I). The mean annual increment (MAI) of this 14 years old plot was 8.5 m^3 ha^{-1} yr^{-1}, which may be compared to the best stands of traditionally managed spruce and birch forest of the same region with maximum MAI of 6.5 m^3 ha^{-1} yr^{-1} over a 75-year rotation period (Eriksson, 1976) and 4.5 m^3 ha^{-1} yr^{-1} over a 50-year rotation period respectively (Fries, 1964). It should be mentioned that high production figures (8-8.6 m^3 ha^{-1} yr^{-1}), similar to those in poplars, were recorded at extremely high densities (16 000 - 42 000 trees ha^{-1}) in young, naturally regenerated, birch and grey alder stands in northern Sweden (Johansson, 1999, 2000, table 4, Paper I). The biomass from these stands can only be harvested for bioenergy provided that a cost-effective harvest technique is developed. Assessing the potential of poplars to produce biomass for bioenergy was also the aim with densely planted experimental plots (5000 trees ha^{-1}) in Bodarna and Bullstofta. In Bullstofta, 'Beaupré' and 'Boelare' produced 8-9 Mg ha^{-1} yr^{-1} within only 9 years (table 3, Paper I), whereas in Bodarna, these two clones were completely eliminated by frost only two years after planting. Also in Bullstofta, the growth of 'Beaupré' and 'Boelare' was impeded by late frosts, at least in some years. For comparison, 'Beaupré' is one of the most productive clones tested in Britain with a maximum MAI in non-irrigated and non-fertilised plots reaching 4.3 to 14 Mg ha^{-1} yr^{-1} over rotation periods of 4-10 years and at spacing 1 m x 1 m to 3 m x 3 m (Tabush, & Beaton, 1998; Armstrong, Johns & Tubby, 1999). At operational scale, maximum annual production of poplars in Europe is in a range between 2.8 and 9 Mg ha^{-1} yr^{-1} with a perspective to achieve 8-12 Mg ha^{-1} yr^{-1} by means of improved clonal material and management strategies (Mitchell, Stevens & Watters, 1999).

The final product is usually the most important determinant of initial planting density in poplar cultures. Generally, a high planting density is expected to result in a high biomass production within a relatively short rotation period, but also cause higher costs of establishment and harvest, and an early competition resulting in density dependent mortality and small stem dimensions. Production figures from two commercial plantations in southern Sweden suggest that equally high annual yields can be achieved at wider spacing, though at a slightly prolonged rotation (Figure 4, Paper I). For instance, the experiences from North American poplar SRF are that a number of poplar products require a minimum growing space of 6.2 m^2 per tree (DeBell, Clendenen & Zasada, 1993; DeBell *et al*., 1996, 1997; Tuskan, 1998). However, we found that pulpwood could be produced even at relatively high densities, like in Bodarna and in Bullstofta, because the percentage of pulpwood in the total biomass production of 9-year old stand was quite high (65%-75%), despite that the mean diameter at breast height (DBH) was only 9 cm (Fig. 5b, Paper I). Moreover, the percentage of pulpwood seems to reach its maximum about the age of 9-10 years and is not likely to increase significantly even in wider spaced plantations. However, considering the common harvest practice in Swedish forestry that requires a 3-meter minimum length of pulpwood logs, and that a relatively high percentage of bark is contained in small stems, the actual pulp yield will increase significantly with DBH>10 cm (Fig. 3, Paper I).

The high biomass yields of poplars presented here suggest that poplar based SRF has the potential of becoming a valuable enterprise on agricultural land in Sweden. At present, however, Swedish farmers feel more comfortable with traditional choice of forest tree species and production systems, and rely on a well-established conifer-wood market. According to a survey of Swedish poplar growers (Karacic & Christersson, unpublished), this reserved attitude toward poplars is related to the insufficient knowledge about production systems, the lack of available plant material, high costs of planting stock and fencing, an uncertain wood market, changing land-use legislation, and damages caused by voles, hare, fallow deer and storm damage. Despite these limitations, all the interviewed farmers agreed that poplar plantations are more profitable than conventional forestry. At present, only 200-300 ha poplar plantations exist in Sweden and damage caused by diseases like leaf rusts and bacterial stem canker are still of minor importance, but judging from the experience from short rotation willow coppice, drawbacks related to insects and various pathogens are likely to appear along with a further commercialisation of poplar culture.

Damage caused by catastrophic winds is one of the potential limitations to poplar culture, particularly in southern Sweden, where extensive and relatively frequent damages were recorded in coniferous forests during the 20^{th} century (Nilsson *et al*., 2004). The storm that occurred in December 1999 caused damage to poplar trees previously measured for the purpose of yield studies in the two commercial plantations in Rydsgård and Sångletorp. Also spruce stands, both those established on agricultural and forestland, were seriously damaged, and a debate was raised whether an alternative to spruce is necessary in southern Sweden. A large proportion of damaged spruce trees had snapped stems, whereas in poplar plantations trees were fallen or leaning at different angles. Whether this qualitative difference between damage in spruce and poplar can be generalised is difficult to say, as the information about wind damage in poplar plantations is fairly limited. It is though clear that snapped stems limit the possibility to produce pulpwood or timber.

The extent of wind damage is most often defined by wind speed, topography, edaphic factors, species and stand characteristics and recent stand management (Booth, 1977; Cramer *et al*., 1982; Lohmander & Helles, 1987; Blenow & Sallnäs, 2000). Older stands are more prone to wind damage mostly because of a higher top height (Cramer et al., 1982) and changes in stand structure caused by thinning (Lohmander & Helles, 1987; Foster, 1988). At the time when damage occurred, the poplar plantations in Rydsgård and Sångletorp were 9-year old, had a top height of 17 m and mean DBH of 16 cm and 15 cm respectively. Large variation in the amount of damage between plots was recorded (0%-63% of trees with leaning angle larger than 10º). An index was defined (mean wind damage class) to express the total damage on each plot and related to relative and absolute measures of basal area increment (BAI) per area and individual trees (Fig 3, Paper III). By the end of third growing season after the storm, the BAI of individual trees on strongly damaged plots increased almost 200% compared to undamaged plots (Fig. 3f, Paper III). This increase in BAI, related to the release of additional growing space, resulted in levelling off BAI ha^{-1} on strongly damaged and undamaged plots (Fig. 3c, Paper III). During the two first seasons after the storm, the total loss of increment in strongly damaged plots compared to undamaged plots was 2.5 m^2 or ca 30%.

The short rotation length of poplar SRF compared to traditional forest crops on agricultural land is probably the strongest single factor that minimises the risk of economic loss caused by catastrophic winds. For rotations up to 15 years, a single plantation is exposed to the potential wind damage for less than 10 years because a stand can be considered to be wind-firm before canopy closure, and at 3.3 m x 3.3 m spacing, the canopy closure could be expected to occur at age 6 or 7 years. Another opportunity to decrease the risk of wind damage in poplar SRF is in clone-selection for traits that define wind-firmness. For instance, the susceptibility of different poplar clones to wind damage may be related to the amount of aboveground biomass per unit of cross-sectional root area (Harrington & DeBell, 1996). Appropriate cultivation measures can also contribute to decrease the risk of wind damage, like deep planting of long cuttings, choice of spacing and soil preparation. The implication of strong damage on a large area will be processing and harvest of parts or the entire plantation, whereas the creation of damaged patches, as at Rydsgård and Sångletorp, will not require additional management steps, and the losses of growth increment in subsequent years will be relatively low.

Public perception of plantations and their effect on landscape often is negative. The attributes ‘clonal’ or ‘monoclonal’ might additionally burden the reputation of poplar plantations alluding to something opposite to diversity. However, the ability of poplar plantations to produce multiple environmental benefits as well as energy and fibre is well documented (Makeschin, 1994; Thornton et al., 1998; Tolbert & Wright, 1998; Isebrands & Karnosky, 2001; Licht & Isebrands, 2005), as is their positive effect on diversity of wildlife (Wesley Perkins & Sullivan, 1981; Christian *et al*., 1998; Sage, 1998; Twedt *et al*., 1999). Willow plantations in Sweden were found to increase floristic diversity compared to annual crop farmland (Gustafsson, 1987) and similar positive effects were hypothesized for small-scale poplar plantations (Paper II). Indeed, a greater floristic heterogeneity within poplar stands compared to arable fields was reflected by greater increase in species number per quadrate with increasing quadrate size (table 4, Paper II) and greater variation in species number between quadrates along transects. On 10 out of 16 sites the cumulative number of species in poplar plantations was larger than in adjacent arable fields (Fig. 1, Paper II). The difference was particularly high when widely spaced plantations in southern Sweden were compared to nearby annual agricultural crops. The classification and ordination analysis showed some separation between species occurring in poplar plantations and arable fields suggesting that poplar plantations could increase diversity on a landscape scale.

Evaluation of species richness patterns in poplar plantations, agricultural land and natural forest has to take into consideration the variation at the landscape scale and regional aspects of biodiversity (Paper II). Moreover, biodiversity of poplar plantations should be compared to the biodiversity of crops it substitutes (Christian *et al*., 1994). Because poplars in Sweden should be considered only on agricultural land, the effects on biodiversity should be evaluated for cases where agricultural annual crops or coniferous forest on agricultural land are converted to poplar SRF. Annually cultivated agricultural land is more frequently disturbed compared to poplar SRF, and more frequently treated with herbicides and pesticides that keep down the number of floral and insect species, affect negatively avian community and threaten human environment. Shade tolerant and drought sensitive species or species that need different temporal continuity of habitat from that on annually cropped agricultural land may thrive in poplar plantations. There is little evidence that the monoclonal character of poplar plantations would negatively affect floral diversity or that polyclonal plantations would significantly improve diversity. In addition, many improvements can be done through biodiversity considerations taken by applying specific principles in management of poplar plantations (Trinkaus, 1998; Hartley, 2002).

Given a relatively large area of agricultural land under transition and the constantly increasing demands on forests as a source of providing both wood raw material and social and environmental services, poplar SRF may have an important role for future forest industry in Sweden as well as in other parts of Europe and the World. At present, Swedish poplar plantations are scarce and suitable plant material is not available on commercial scale. Therefore, a future breeding program will need to take into consideration a wide range of latitudes and growing conditions associated with potential poplar sites in Sweden. Thus, a broad approach is necessary with regard to both desirable traits and the origin of plant material. In fact, clones widely used in Europe like 'Beaupré' and 'Boelare', may also grow well in southernmost Sweden (Paper I), whereas the plant material aimed for planting at higher latitudes has to be much better adapted to local temperature and day-length regimes (Christersson, 1996; Ilstedt, 1996, Weih, 2004). Different purposes (*e.g.* production of pulpwood or phytoremediation, or both) will emphasise different traits, but irrespective of their purpose, poplar cultures have to be effective in terms of resource utilisation both with regard to production and environmental goals. Thus, genetic variation needs to be studied through the interaction with relevant environmental conditions since productivity and resource utilisation are determined by both heritage and environmental factors. This could be done by means of short-term, semi-controlled experiments using pot-grown plants and applying the treatments that will simulate various environmental conditions (Weih, 2001; Weih & Nordh, 2002).

In paper IV, plant growth and resource use efficiency of pot-grown poplar plants was evaluated in terms of a number of physiological and morphological variables. Determinants of clone performance in response to two irrigation and three fertilisation regimes were sought in relative growth rate (RGR) and its morphological and physiological components, biomass production and partitioning, and nitrogen productivity, accumulation and losses. We found that RGR increased as a result of an increase in unit leaf area (ULR, net assimilation rate) and plant nitrogen concentration, and that ULR increased with increasing leaf nitrogen productivity and leaf nitrogen concentration per unit leaf area (Fig. 2, Paper IV). A substantial literature has been produced (see Paper IV) that relates increase in RGR either to leaf area ratio (LAR) and its components or to ULR. Such contradicting results are result of differences in various experimental conditions (irradiance, temperature and nutritional regimes) as well as in plant material used. RGR has a tendency to remain relatively constant under changing environmental conditions, which explains trade-offs between ULR and LAR in determining RGR. In this context, it is interesting that conclusions could be different if only parts of plant material or, for instance, only one irrigation treatment was observed. Thus, for the clones PG3-23, PG1-25, PG2-23 and PG2-26 in low irrigation treatment, RGR is positively related to LAR rather than ULR (Fig. 2a and 2b, Paper IV), whereas the opposite is true for the same clones grown under high irrigation treatment. When all six clones were considered, RGR appeared to be positively related with ULR in both irrigation treatments. Hence, the variables that determinate high RGR in dry conditions may vary with clonal material tested. We also found strong correlations between total plant and shoot dry weight, and RGR and leaf nitrogen productivity, whereas RGR was most strongly correlated to total plant nitrogen concentration in case when data from the two irrigation treatment were viewed separately (Fig. 2f, table 3, Paper IV). It is unclear whether results from the pot study represent poplar growth in the field. However, there is evidence from *Salix* that plant traits such as total leaf area and N pool of plants grown in pot experiments are good predictors of biomass production in the field after 3 years of growth (Weih & Nordh, 2005).

The aboveground woody biomass is the most important variable when the primary goal of poplar culture is biomass production. If plant material is evaluated for multipurpose plantations (*e.g.* phytoremediation and biomass production), also characteristics such as low nutrient productivity and low nutrient concentrations in senescent leaves are desirable as they indicate plant's ability to conserve nutrients. As high nutrient conservation and high growth performance usually are traits inherited in diametrically opposed environmental conditions, the choice of clone needs to be evaluated against the overall effect on an area basis. Thus, it was suggested that in many cases the choice of the production system (e.g., single stem or coppice, spacing, harvest season, rotation length) is more important or, at least, that clone selection should focus on the highest biomass or stem-wood production for the chosen production system.

Conclusions

Intensive culture of hybrid poplar and hybrid aspen for bioenergy, fibre and environmental services is a cropping system that expands in many regions of the world. In Sweden, short rotation forestry is based on Salix sp. and little is known about production potential and ecology of short rotation poplar crops. The following points are suggested as conclusions of this thesis and also as suggestions for future research:

- Poplars have high biomass production, not only in southern, but also in northern parts of Sweden. Plantations established at relatively high densities (5000 trees ha^{-1} yr^{-1}) reach maximum mean annual growth within shorter rotation lengths compared to lower densities (1000 trees ha^{-1} yr^{-1}), but are less suitable when pulpwood is one of the desired final products. On annual basis, about the same biomass production should be expected within the above density range. Hybrid aspen grows almost equally well in southern and central Sweden despite large differences in climate and soil conditions of experimental sites.
- Hybrid poplar clones of southern origin, similar to that of 'Beaupré' and 'Boelare', are not suitable for growth in central and northern Sweden. Varieties that are better adapted to photoperiodic and temperature conditions of these regions should be bred and selected. This task deserves priority if poplar based short rotation forestry is to be further commercialised.
- Introduction of poplar plantations in agricultural landscapes may increase floristic diversity at landscape level. Effects of poplar plantations on ground flora should be evaluated regionally and compared to the effects of the cropping system that is substituted by the poplars. It is also of great importance to develop field assessment methods that capture equally diversity of poplar plantations and arable fields. The method of nested

quadrates used in our study was developed for assessment of floral diversity in grasslands and is less adequate for application in poplar plantations due to the larger spatial heterogeneity of ground flora.

- Wind damage occurs frequently in southern Sweden and may cause damage in poplar plantations. Despite of a clearly negative effect of wind damage on increment of individual trees, the loss of increment for the entire range of mean wind damage class per plot was relatively low and limited to the period of two years after the storm. Thus, it is suggested that poplar plantations imply decreased risk for production loss compared to conventional spruce forests that are frequently damaged by storm, particularly in southern Sweden. Wind-firmness may be improved by appropriate management strategies, but also through the research and selection of varieties with specific characteristics that may decrease the risk of wind damage.
- The characterisation of poplar clones with respect to their growth response under a range of important ecological parameters, like water and nutrient availability, comprises a number of possibilities to improve and shorten the process of clone selection. For instance, information about biomass partitioning or nutrient economy of plants in dry conditions is of great practical importance as it can provide specific information about varieties that is not available in traditional selection trials.
- Provided that suitable plant material is selected and widely available, commercial SRF with poplars represent a valuable alternative crop for surplus agricultural land with a potential to produce multiple benefits to society through the high production of biomass and fiber and positive effects on the environment.

Sammanfattning (Swedish summary)

Poppelodling (*Populus sp.*) för energi, träfiber och miljöändamål är vitt utbrett i världen. I odlingssystem för motsvarande ändamål i Sverige används *Salix sp.* medan kunskapen saknas om produktion och miljöeffekter av intensiv poppelodling. Den här avhandlingen fokuserar på fyra aspekter av intensiv poppelodling med korta omloppstider: 1) Biomassaproduktion och tillväxtfördelning vid olika planteringsförband inom ett brett geografiskt område med varierande tillväxtförhållanden i Sverige, 2) Effekter av poppelodling på floristisk diversitet i det svenska jordbrukslandskapet, 3) Karaktär av vindskador och deras tillväxtbegränsande effekt i kommersiella poppelodlingar i södra Sverige, och 4) Ekologisk karaktärisering av poppelkloner i krukförsök.

Den årliga tillväxten uppmätt i försöksytor och kommersiella poppelodlingar vid en 9-14 år lång omloppstid var 3.3-9.2 Mg ha^{-1} $år^{-1}$. Denna produktionsnivå har uppnåtts på relativ bördig jordbruksmark och utan gödsling och bevattning. Produktionsuppskattningar i kommersiella poppelodlingar i södra Sverige, etablerade i ett glesare förband (1000 träd ha^{-1}) visar en liknande produktionspotential som odlingar med tätare förband (5000 träd ha^{-1}), även om omloppstiden förlängs 3-5 år.

En jämförelse mellan 21 poppelparceller med en areal varierande mellan 0.1-13 ha, och närbelägna jordbruksfält visar att småskalig poppelodling kan öka floristisk diversitet på landskapsnivå, huvudsakligen genom att skapa en gynnsam miljö för skuggföredragande växter och växter känsliga för torka.

Vindskador i två 15 och 33 ha stora kommersiella odlingar uppskattades med hjälp av skadekategorier baserade på trädens lutningsvinkel. Mellan 0% och 63% av träd var vindskadade inom 23 ytor etablerade och uppmätta innan stormtillfället. Tillväxtförlusten i de värst skadade ytorna under de två första åren efter stormen var 30%, medan det, inte fanns någon skillnad i tillväxt mellan skadade och oskadade ytor under den tredje växtsäsongen.

Ett korttidskrukförsök med olika poppelkloner visade skillnader i olika kloners respons i termer av fysiologiska och morfologiska variabler bestämmande relativ tillväxthastighet och näringsproduktivitet, trots att de flesta kloner var av samma art och proveniens. Graden till vilken de olika variablerna bestämmer tillväxten ändras med nivån av närings- och vattentillförsel.

Rezime (Bosnian summary)

Kulture topola (*Populus sp.*) sa kratkim ophodnjama namijenjene proizvodnji drvne biomase za toplotnu i električnu energiju, proizvodnji drvnih vlakana i unapredjenju životne sredine široko su rasprostranjene u svijetu. U Švedskoj se u istu svrhu koristi *Salix sp.* dok se vrlo malo zna o prirastu i prinosu topola i njihovom uticaju na okoliš. Ova disertacija dodiruje četiri aspekta intenzivnog uzgoja topola u kratkim ophodnjama: 1) Prirast i prinos u odnosu na nekoliko inicijalnih razmaka sadjenja, i relativno veliki raspon geografskih širina i stanišnih uslova u Švedskoj, 2) Uticaj kultura topole na raznolikost prizemne flore agrarnog područja Švedske, 3) Karakterstike povreda uzrokovanih olujnim vjetrom i njihiv uticaj na prirast u plantažama topole u južnoj Švedskoj, i 4) Ekološku karakterizaciju klonova topole putem kratkih eksperimenata sa kontejnerskim sadnicama.

Prosječni godišnji prirast topola na eksperimentalnim parcelama i plantažama 9-14 godina starosti iznosio je 3.3-9.2 Mg ha^{-1}. Ovako visok prirast postignut je na relativno produktivnim agrarnim zemljištima bez upotrebe dodatnog hraniva i navodnjavanja. Procjene prirasta topola na plantažama u južnoj Švedskoj zasnovanih na većim razmacima sadjenja (1000 stabala ha^{-1}) ukazuju na gotovo identičan produkcioni potencijal kao i u kulturama sa 5000 stabala ha^{-1}. Treba reći da veći razmaci sadjenja produzuju ophodnju za 3-5 godina, ali i istovremeno omogućuju veći prinos drvnih vlakana za proizvonju celuloze uz paralelnu proizvodnju drvne mase za toplotnu i električnu energiju. Veći razmaci sadjenja takodje zahtijevaju intenzivnije i dugotrajnije mjere odstranjivanja nepoželjne prizemne vegetacije.

Poredjenjem 21 parcele topola, veličine 0.1-13 ha, sa agrarnim poljima u njihovoj neposrednoj blizini ukazano je da kulture topola manjeg areala imaju pozitivan uticaj na raznovrsnost prizemne flore na nivou odredjenog agrarnog područja. Kulture topola mogu pružiti povoljne stanišne uslove mezofilnim i fotofobnim vrstama što se očituje u relativno malom broju vrsta zajedničkih za kulture topola i agrarnih polja. U parcelama topola zabilježena je i veća heterogenost flore u poredjenju sa strukturom flore na agrarnim poljima.

Oštecenja stabala uzrokovana olujnim vjetrom na dvjema plantazama sa arealom od 15 i 33 ha su procijenjena pomoću kategorija zasnovanih na uglu naginjanja stabala. Ove procjene su provedene na parcelama mjerenim prije nastajanja povreda. Procenat oštećenih stabala na 23 parcele kretao se izmedju 0% i 63%. U periodu od dvije godine nakon nastajanja povreda, gubitak prirasta na najoštećenijim parcelama iznosio je 30% dok se u trećoj godini tekući godišnji prirast na oštećenim i neoštećenim parcelama nije razlikovao.

Kartki eksperiment sa klonskim sadnicama je pokazao razlike u pogledu fizioloških i morfoloških variabli koje odredjuju stopu relativnog prirasta i produktivitet u odnosu na apsorpciju hraniva, iako većina upotrijebljenih genotipova pripada jednoj vrsti topola identične provenijencije. Značaj izučavanih variabli u odredjivanju prirasta se mijenja u zavisnosti od promjene nivoa dodavanja hraniva i vodenog rezima. Naročito je značajna interakcija izmedju genotipa i vodenog rezima sobzirom na nekoliko važnijih varijabli prirasta.

Kokkuvõte (Estonian summary)

Lühikese raieringiga paplikultuure (*Populus sp.*) rajatakse rohelise energia ja puidukiu saamiseks, samuti keskkonnakaitselistel eesmärkidel. Rootsis on pikka aega kasvatatud lühikese raieringiga istandustes peamiselt paju liike (*Salix sp.*). Vähe on aga teada, milline on paplikultuuride produktsioonivõime ja nende mõju kasvukeskkonnale Rootsi tingimustes. Käesolev doktoritöö käsitleb nelja aspekti paplite kasvatamisel Rootsis: 1) biomassi produktsiooni ja allokatsiooni erineva tihedusega istandustes, erinevatel geograafilistel laiuskraadidel ja erinevates kasvutingimustes, 2) paplikultuuride mõju soontaimeliikide mitmekesisusele põllumajandusmaastikul, 3) tuulekahjustuste sagedust ja nende mõju papliistanduste produktsioonile, ning 4) erinevate papliklоonide ökofüsioloogilisi omadusi lühiajalises potikatses sõltuvalt väetamis- ja kastmisrežiimist.

Biomassi produktsioon paplikultuurides ja katseruutudel 9 kuni 14 aastat pärast rajamist ulatus 3,3 t ha^{-1} a^{-1} kuni 9,2 t ha^{-1} a^{-1}. Sedavõrd kõrge produktsioon esines suhteliselt viljakatel, väetamata ja kastmata endistel põllumaadel. Madala istutustihedusega kultuuride (1000 puud hektaril) produktsioonivõime oli sama suur kui kõrge istutustihedusega kultuurides (5000 puud hektaril) vaid 3 kuni 5 aastat pikema raieringi korral. Madala istutustihedusega kultuurides on paberipuiduks sobiva biomassi osakaal suurem võrreldes kõrge istutustihedusega kultuuridega, *kuid istanduse rajamise käigus on vajalik ka väga hoolikas umbrohutõrje*.

Võrreldes 21 paplikultuuri (mille pindala varieerus 0,1 kuni 13 hektarini) vahetus läheduses asuva põllumaaga, ilmnes, et väiksed paplikultuurid võivad taimeliikide mitmekesisust põllumajandusmaastikul suurendada, luues kasvukohti, mis sobivad varjutaluvatele ja kuivustundlikele taimeliikidele. Võrreldes põllumaaga on ka floristiline heterogeensus paplikultuurides suurem.

Tormikahjustuste mõju kahe Lõuna-Rootsis asuva suureskaalalise (15 ha ja 33 ha) istanduse produktsioonile hinnati jaotades puud nelja erinevasse gruppi sõltuvalt puu kaldenurga suurusest. Tuulest kaldu vajunud puude osakaal 23 katseruudul varieerus 0% kuni 63%ni. Kaks aastat pärast tormi oli biomassi juurdekasv kõige suurema kaldenurgaga puude grupis vähenenud 30%. Kolmandal tormijärgsel aastal aga aastane juurdekasv tuulest kahjustada saanud katseruutudel ei erinenud ruutudest, kus tormikahjustusi ei esinenud.

Lühiajalises potikatses erinesid uuritud paplikloonid üksteisest füsioloogiliste ja morfoloogiliste näitajate poolest, mille tõttu ka kloonide suhteline kasvukiirus (g g^{-1} nädal^{-1}) ja toitainete produktiivsus (g g^{-1}N a^{-1}) erines. Erinevate füsioloogiliste ja morfoloogiliste näitajate mõju suurus suhtelise kasvukiiruse määramisel muutus sõltuvalt väetamis- ja kastmisrežiimist.

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