Irrigation and nitrogen use efficiency of *Thuja occidentalis* grown on sandy soils

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Irrigation and nitrogen use efficiency of *Thuja occidentalis* grown on sandy soils

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Abstract

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On sandy soils, water and nitrogen (N) use for agricultural production is often limited by governmental regulations. Irrigation is often restricted to prevent a further lowering of the groundwater table. Nitrogen applications are limited to minimize N losses and to protect groundwater from exceeding the limit of 11.3 mg nitrate-N L^{-1}.

Coniferous nursery stock is increasingly grown on sandy soils. Growers and policy makers eagerly need information on techniques and management to improve the effectiveness of irrigation, the N use efficiency and to minimize nitrate (NO_3) leaching. This study was set up to better understand the factors that affect the efficient use of water and N of the field-grown conifer *Thuja occidentalis*. The study involved the development and testing of a model for *Thuja*, using experimental data from field and container trials.

First, a simple method was developed to estimate radiation interception by *Thuja* in which the crop was considered as a row of cuboids. Second, a LINTUL-type model for conifer growth (CONGRO) was calibrated and validated, followed by the establishment of two-dimensional root growth parameters for *Thuja*. Third, CONGRO was coupled with the two-dimensional soil water and N balance model FUSSIM2, which was modified to cylindrical co-ordinates to simulate drip-irrigated systems. The combined model was validated and used to evaluate different irrigation strategies with respect to maximum dry mass production with minimum water losses. Fourth, N dynamics of soil processes and N demand were implemented using site-specific soil mineralization rates and measured N mass fractions in leaf and stem dry mass under well-fertilized conditions. Finally, the model was used to explore three irrigation strategies (non, drip or threshold-irrigated) combined with split-fertilizer applications and N application rates (standard rates or standard rates lowered for the mineral N content in the topsoil at the time of application) using actual weather data of 31 years. These model explorations led to the conclusion that the recommended N fertilizer applications were adequate for N uptake for all three irrigation strategies. To reduce N losses to the groundwater it was imperative to correct recommended application rates for the mineral N content of the topsoil. Average simulated concentrations per scenario ranged from 19 to 26 mg NO_3-N L^{-1} in the year of planting (April-October), from 22 to 114 mg L^{-1} in the subsequent winter period (November-March) and from 19 to 28 mg L^{-1} in the second growing season (April-October).

In conclusion, this study demonstrated that high dry mass production under optimized water and nitrogen applications reduced nitrate concentrations in the percolating soil solution but that the 11.3 mg L^{-1} NO_3-N limit was not met.

Key words: conifer growth model, eastern white cedar, field-grown, irrigation, nursery stock, soil water and nitrogen balance model, two-dimensional, root growth.

Voorwoord

Bij het derde contract op het toenmalige Proefstation voor de Boomkwekerij behoorde het schrijven van een onderzoeksvoorstel voor een promotieonderzoek tot de mogelijkheden. Daarbij werd ik van harte ondersteund door de toenmalige directeur Jan van de Vooren. Het eerste contact met mijn beoogd promotor Hugo Challa was in de zomer van 1996 en het contact met de tweede promotor Oene Oenema volgde al snel daarna. Het schrijven van het onderzoeksvoorstel en het daarna ook nog uitvoeren van het onderzoek heeft enige directeuren, namen en fusies van het Proefstation, onderzoeksposities van mij, en natuurlijk vele jaren gevergd. Maar nu is het proefschrift af. Helaas kan Hugo Challa dit niet meer meemaken. Hij blijft echter in mijn herinnering als een opgewekte, niet gemakkelijke, maar altijd enthousiasmerende persoonlijkheid die mij regelmatig op het 'wetenschappelijke spoor' bracht en hield.
Dit onderzoek is natuurlijk ook mede gerealiseerd door de steun van vele anderen. Graag wil ik iedereen bedanken voor de aandacht, inzet, steun en uithoudingsvermogen. Mijn medeauteurs en Ep Heuvelink, copromotor na het overlijden van Hugo Challa, wil ik met name bedanken voor de discussies en hun geduld, wetende dat ik niet gemakkelijk en snel te overtuigen ben als ik eenmaal een mening heb gevormd. En Paul wil ik toch even apart noemen. De vele weekenden die ik heb doorgebracht achter de computer, hebben zijn geduld aardig op de proef gesteld. Hij heeft mij dan ook vaak achter de computer vandaan gehaald voor de nodige afleiding, in- en ontspanning. Als laatste wil ik de Business Unit AGRO van Plant Research International bedanken voor de steun en de (financiële) ruimte die ik gekregen heb om het proefschrift af te ronden. De laatste loodjes wegen ook in dit geval weer het zwaarst.

Enige opluchting is er wel nu alles af is. Ook grote projecten als promoties verdienen op een gegeven moment een afronding. Zo komt de weg vrij voor andere, spannende en interessante activiteiten. Zo liggen er leuke en uitdagende onderzoeksonderwerpen te wachten. In de privé-sfeer zijn er al plannen voor kleinere en grotere (al dan niet inspannende) ondernemingen, zoals bezoeken aan verre en vreemde (koude) oorden op de fiets of de ski's. Met de afronding van dit proefschrift is de weg vrij voor vernieuwing en een blik op de toekomst.

Contents

CHAPTER 1

General introduction

Background

Importance of nursery stock in the Netherlands

Nursery stock in the Netherlands covers approximately 13,530 ha, including container nurseries (934 ha) and nursery stock in greenhouses (379 ha) (LEI & CBS, 2004). The production value of nursery stock was $570*10^6$ € in 2003 and the total value of exported nursery stock was $425*10^6$ €.

Despite the limited surface area covered by ornamental nurseries, a great deal of diversity exists in crops, cropping systems and agronomic practice. In line with agro-economical developments in the agricultural sector in the Netherlands, the average size of nurseries has increased during the last decade. The number of small nurseries (<0.5 ha) of field-grown crops has decreased from 1002 in 1999 to 797 in 2003, whereas the number of large nurseries (>10 ha) has increased from 195 to 237 during the same period. Among the main crops grown in nurseries are ornamental conifers with a total area 2,547 ha, commonly found on well-drained sandy soils in the provinces of Noord-Brabant and Limburg (1,425 ha). The cultivated area of these crops has increased during the past five years (LEI & CBS, 2004).

Conifer growing in the Netherlands

Conifers are commonly grown in nurseries for two or three years. Distinct activities during this period include planting, fertilization, irrigation, mechanical and chemical weed control, chemical and biological control of pests and diseases, leaf and root pruning, and finally harvesting. Growers have to take good care of soil fertility because of the limited nutrient content in sandy soils. In addition to the limited natural capacity of the soil to sustain crop production, part of the topsoil is removed during the bi-annual harvest of plants with root balls, further reducing the organic matter content of the soil. The removal of soil material is estimated at 240 m^3 ha^{-1} on average every other year (≈ 8 tons of soil organic matter) for harvested conifers with root balls. Assuming a bulk density of 1.4 kg L^{-1} and a topsoil of 0.30 m, the annual removal of 120 m^3 yr^{-1} is equivalent to 4% of the total organic matter pool of the upper 0.30 m. This of course stresses the need for compensation measures to replenish the soil organic matter content. Large amounts of manure and compost are traditionally applied to achieve

this goal. However, due to recent changes in governmental regulations, large applications of animal manure and compost are restricted, stressing the need for other measures to compensate for the loss of organic matter. One of the practical solutions includes the use of cover crops to improve soil fertility, which is now practiced more frequently.
In addition to the application of animal manure, inorganic fertilizers are applied especially during the second and third growing season. The combination of manure and fertilizer application, however, easily leads to excess fertilization (Alt *et al.,* 1989). In combination with the hydrological properties that prevail on sandy soils, *i.e.* a limited capacity of the soil to store rain and/or irrigation water, the use of fertilizers and manure leads to unacceptable losses of nitrogen (N) through leaching, thus affecting the quality of the upper groundwater in these systems.

In short, major environmental problems related to nursery stock on sandy soils in the Netherlands are:

- a loss of soil material due to the harvesting techniques involved, leading to
- a loss of soil organic matter (and nutrients) in the topsoil, which requires
- the use of large amounts of manure and inorganic fertilizers, which in combination with irrigation (required on sandy soils) leads to:
- large losses of N leaching to the groundwater.

To reduce the loss of N leaching to the groundwater, it is essential to either reduce the input of nutrients, to regulate the water supply, or a combination of both. In this thesis several measures are evaluated, based on both field studies and model simulations to assess the possibilities to reduce N leaching losses.

System Description

Interactions between climate, plant and soil

The plant-soil 'system' considered in this study consists of two main sub-systems: the ‘crop system' and the ‘soil system' (Fig. 1). This crop-soil system is exposed to local meteorological conditions such as radiation, air temperature, wind speed, and precipitation. Meteorological conditions affect crop growth, which can be 'divided' into specific crop-physiological processes including photosynthesis, morphology, leaf elongation, transpiration and rooting depth. In the crop-soil system the plant dry matter increases due to interception of radiation and uptake of carbon dioxide by leaves, and uptake of water and nutrients by the roots from the soil. The roots are part of the sub-system crop but physically grow within the sub-system soil.

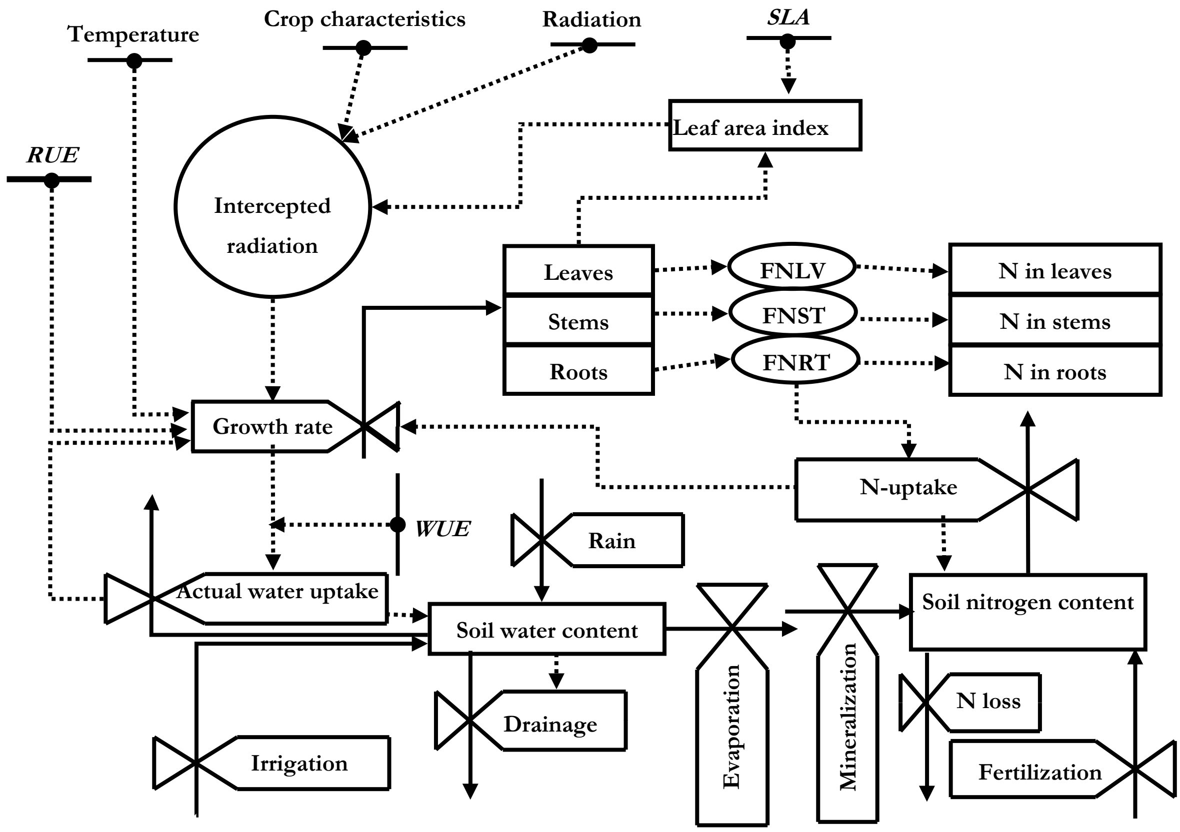

Figure 1. Simplified relational diagram of a crop-soil system where water and nitrogen are limiting crop growth. WUE is the water use efficiency; RUE the radiation use efficiency; SLA is the specific leaf area and FNLV, FNST and FNRT are the fractions of nitrogen of the newly formed biomass of leaves, stems and roots, respectively. (After Van Keulen & Seligman (1987) and Spitters (1990)).

The *demand* for water and nutrients originates from the sub-system crop but is (usually) limited by the *supply* from the sub-system soil. The actual soil conditions in combination with the capacity of the crop to actually retain the nutrients supplied by the soil determine whether or not these demands can be met.
In general, physical soil conditions result in a series of plant physiological responses. For example, when the demand for water is not met, the crop transpiration rate is reduced resulting in a reduced uptake of carbon dioxide. Ultimately, this results in a reduction of the dry matter production. Another important series of processes is related to the availability of N in soil. When the demand for N uptake is not met, it results in reduced N concentrations in the leaves which in turn result in reduced growth. Both shortages in water and the availability of N occur when the physico-chemical conditions in the sub-system soil become less favorable for the uptake of water and nutrients.

The N uptake by nursery stock is relatively low compared to that of many other agronomic crops. Measured nutrient uptake rates by nursery stock range from 20 to 160 kg N ha^{-1} yr^{-1} (Oele, 1994). Despite the limited crop demand, actual average N application rates often exceed 250 kg N ha^{-1} yr^{-1}. Current N fertilizer recommendations for field-grown nursery stock aim to achieve maximum growth and dry matter production which sometimes results in recommended application levels that exceed actual N uptake rates by a factor of 2 to 4 (De Beuze *et al.,* 2004).

Governmental policy and measures related to irrigation and nutrient use in nursery stock

In contrast to parameters like radiation and temperature, which (in field-grown crops) are beyond the grower's control, growers can optimize inputs of irrigation water and nutrients according to the crop's requirements. However, the use of those inputs is becoming increasingly restricted by governmental regulations and actual application rates of both water and nutrients have to meet the demands of both crop physiology and regulations.

The European Union (EU) Nitrate Directive 91/676 states that all members have to reduce water pollution caused or induced by nitrate from agricultural sources and prevent further such pollution (Anonymous, 1991). Therefore, the Dutch Government increasingly regulates N inputs in agriculture and horticulture (Anonymous, 2002; LNV, 2004; Ondersteijn *et al.,* 2002). In response, new N fertilizer recommendations have been developed for nursery stock, but it is still unclear whether or not the EU nitrate-N limit for groundwater will be met.

Local governments impose another constraint on crop production on sandy soils. Groundwater withdrawal for irrigation of grassland, arable and horticultural crop production is restricted (VenW, 1989) in order to prevent the drastic lowering of the groundwater level. Growers situated in these areas need to use an irrigation support tool and a certified water meter to keep track on the water taken from groundwater wells in order to receive tax relief on groundwater extraction.

Development of Decision Support Tools to improve water and nutrient efficiency

The governmental policies and measures increasingly limit both water use and fertilizer applications in nursery stock. This stresses the need for tools that allow the farmer to assess when (if at all) to irrigate, and when and how much fertilizer to apply, within the boundaries of current and future legislative boundaries.

Various approaches to optimize water and nutrient applications are being currently explored. For instance, information on the reference transpiration (Penman) to estimate actual water loss is passed on (through internet) to vegetable growers in those areas where irrigation is restricted. This information is then used to determine the appropriate time of irrigation. Another example is the use of a threshold value of the soil pressure head below which irrigation is required (Evenhuis *et al.,* 2000). More advanced irrigation scheduling techniques involve individual support of vegetable and fruit growers by private companies. For example, private companies use complex simulation models to determine both the time and appropriate amount of irrigation for apple trees (Opticrop, Boshuizen & Van Der Maas, 1999). Irrigation strategies for field-grown nursery stock have been investigated for *Gardenia jasminoides* and *Ilex crenata* (Ponder *et al*,. 1984), *Forsythia* (Curtius & Bohne, 1996) and avenue trees (Averdieck & Bohne, 1994), but these studies are mainly focused on the *potential* dry matter production instead of improving the effectiveness of irrigation. Despite these developments, no decision support systems are currently available for nursery stock growers of field-grown conifers to increase the effectiveness of the irrigation. Instead, current irrigation application 'rules' are still based on the individual experience of growers or on irrigation guidelines for vegetable crops. Not surprisingly, this often still leads to excess irrigation, and hence losses of N to groundwater.

Methods to improve the efficiency of nitrogen use and the effectiveness of irrigation

During the past decade, several techniques have been developed to improve the efficiencies of both irrigation and N applications, as briefly discussed below.

Split application of nitrogen fertilizer

One fertilizer N application per season, *i.e.*, before planting and another at the start of each subsequent growing season involves a high risk of N leaching. One fertilizer N application also increases the risks on N shortages in the second half of the growing season, because all N may have been leached at that time.

Efficient use of fertilizer N can be improved by split applications. When the total N application is spread out in time over the growing season, the risk of N leaching and/or N deficiency in plants might be reduced. Current recommendations for a split fertilizer application for field-grown nursery stocks include one N application in mid-May and another at the end of June (Aendekerk *et al.*, 2000). When organic materials are incorporated into the soil prior to planting, or when planting is late in spring, the mid-May application is usually skipped.

Correcting fertilizer N applications for soil mineral N

To further improve the efficiency of N use, the amount of soil mineral N is measured in the topsoil (0-0.3 m) and subtracted from the recommended fertilizer N application rate. The recommended application rate is corrected for the mineral N content measured in the topsoil at each time of application. This technique is also recommended when the application is not split (Aendekerk *et al.*, 2000).

Irrigation and fertigation

The effectiveness of irrigation can be improved when 1) water is applied only to the rooted area, and 2) water is applied only when dry matter is likely to be reduced by drought stress (Clark, 1992). Nursery stock is planted at low plant densities. This suggests that water and nutrient use efficiency can be increased when water and nutrients are applied at the stem base compared to a broad application. When irrigation is applied frequently throughout the growing season it is only a small step to include soluble fertilizers in the irrigation water, a practice called fertigation. There are advanced techniques available to do this. In field trials, the effectiveness of drip irrigation and fertigation was compared with non-irrigated treatments. Drip irrigation and drip fertigation increased dry matter production of several nursery stock crops in field trials compared to non-irrigated and standard fertilized crops (Pronk & Ravesloot, 1998).

Currently, daily water applications are common in drip-irrigated systems, whereas the frequency in the case of overhead sprinkler systems is usually determined by the grower's experience. At times of high precipitation, daily drip irrigation is likely to increase leaching. When irrigation events are threshold based, initiated at a certain soil pressure head threshold level, irrigation only takes place when dry matter might be reduced by drought stress. The soil pressure head threshold level depends on the crop involved, the developmental stage of the crop and on soil type (Dekkers, 2000; Feddes, 1969). However, the understanding of the relationship between irrigation and dry matter production of field-grown conifers on sandy soils is poor and has to be increased to be able to improve the efficiency of irrigation applications via time dependent irrigation strategies.

Integrated production of nursery stock

Integrated cropping systems aim at integrating objectives with all available measures and techniques, in order to optimize production and minimize emissions to the environment (Dolmans, 1992; Vereijken, 1990). Therefore, the split application of N fertilizers is combined with a correction for the mineral N content of the topsoil to improve the efficiency of N use in the integrated nursery stock system. For field-grown ornamental shrubs and conifers on sandy soil it was shown that this method can greatly reduce N application rates compared to the recommended rate (Table 1).
In the first year of the cultivation of *Mahonia aquifolium* 'Apollo', the measured soil mineral N content was 62 and 196 kg N ha^{-1} in May and June, respectively (Table 1). In the second growing season the measured soil mineral N content was 18 and 244 kg N ha^{-1} (May and June, respectively). An application of 50 kg N ha^{-1} of N fertilizer was only needed in the second growing season to maintain optimal levels for crop production, and was indeed found for *Thuja occidentalis* 'Brabant'.

The split application system combined with the correction for the measured mineral N content in the topsoil resulted in a considerable decrease in the total N dose, without changing dry matter production. This indicates that the efficiency of fertilizer N use was improved by the combination of split applications and the correction for the mineral N content in the topsoil.

Table 1. *Split application system combined with measuring mineral nitrogen content of the topsoil (0-0.3 m) for nitrogen fertilizer applications in the integrated nursery stock production system in Horst. After Pronk & Challa (2000).*

	Tagetes patula[1]		*Mahonia aquifolium* 'Apollo'				*Thuja occidentalis* 'Brabant'			
	1991		1992		1993		1994		1995	
	May	June	May	June	May	June	May	June	May	June
(kg N ha^{-1})			1st year		2nd year		1st year		2nd year	
Application rate[2]		100	75		100		75		100	
Split application rate	- [1]	100	50	50	75	50	50	50	75	50
Mineral N (0-0.3 m)	-	131	62	196	18	244	64	71	8	109
Actual application rate	-	0	0	0	50	0	0	0	50	0
Savings [3]		100	75		50		75		50	

[1] *Tagetes patula was sown in June. No soil sample was taken in May*

[2] *Standard application rates after (Aendekerk et al., 2000)*

[3] *Savings are calculated as the difference between the standard application rate minus actual application rate and no actual application is applied when smaller than the measured mineral N content*

Though various techniques in practice have proven to be effective in increasing the N fertilizer use efficiency, (e.g. Table 1) and the effectiveness of irrigation gaps in our fundamental knowledge on the relationship between inputs (water and N supply) and outputs (dry matter production, water and N leaching) still remain. Our current understanding of the relationship between irrigation and dry matter production of field-grown conifers growing on sandy soils is insufficient to improve the effectiveness of irrigation via time dependent irrigation strategies. The relationship between N supply and dry matter production has not yet been fully explored and it is unclear which fertilization strategies can meet both the minimum crop N demand and the maximum EU nitrate-N limit for groundwater.

Knowledge gaps

The demand for water and N for several horticultural and agricultural crops can be estimated by dynamic crop simulation models (c.f. Van Ittersum *et al.*, 2003). Some of these models include the subsystem soil and are able to predict effects of limited water and N availability on crop growth (e.g. Fig. 1). In general, the leaf area of agricultural and horticultural crops develops rapidly after sowing or planting into a homogeneous closed canopy. Radiation interception is therefore estimated with standard radiation interception equations (Monsi & Saeki, 1953). Dry matter increase is proportional to the intercepted radiation using the concept of the radiation use efficiency (Monteith,

1977; Sinclair & Muchow, 1999). Transpiration can be then calculated from the known dry matter increase using the concept of water use efficiency (Loomis, 1983), which is assumed to be constant during the cultivation period. Thus the water demand can be estimated (Van Keulen & Van Laar, 1986). Root growth, distribution and rooting intensity in the soil profile contribute to the uptake of water. In models which contain the sub-system soil, most often only the rooting depth is considered because roots are assumed to be distributed evenly over the horizontal gradient of the soil (Van Keulen, 1986). The N demand is often simulated through dry matter increase and N concentrations in the different plant tissues (Godwin & Jones, 1991; Van Ittersum *et al.*, 2003). Most soil water balance models are one-dimensional, meaning that water transport is only simulated over the vertical gradient.
The modeling approach for agricultural crops outlined above is satisfactory, but crops in ornamental nurseries grown at low plant density in rows differ on several points from this general concept. Radiation interception of row crops differs considerably from the interception of a homogeneous closed canopy (Goudriaan, 1977). Some horticultural crops like leeks, are also planted in rows and radiation interception is estimated with modified interception equations which account for the open area between the rows (Baumann *et al.*, 2002). However, the row distance of many conifers in nurseries, as for example transplanted *Thuja occidentalis,* is only slightly larger than the intra-row planting distance (0.5 m row distance, 0.4 m intra-row distance) providing an open area between plants in the row. As a consequence, improved radiation interception methods of individual trees are needed.

Just after transplanting conifers, roots explore the soil in both a vertical and horizontal direction. It takes time before the topsoil is uniformly rooted, as has also been suggested for other nursery stock crops (Ledin, 1986). Furthermore, many ornamental conifers are irrigated through drip irrigation. To simulate the water dynamics in such drip-irrigated systems, two-dimensional or even three-dimensional soil-water balance models are necessary to include the horizontal transport of water (Ahuja & Nielsen 1949). Although such advanced models (partly) exist for various agricultural (Van Keulen, 1986; Van Keulen & Van Laar, 1986) and vegetable crops (Heinen, 1997), no such model is available for field-grown conifers. Evidently, established model structures need to be parameterized for such crops, or new model structures need to be developed.

Aim and outline of this thesis

Aim of the study

Currently there is a lack of understanding of the quantitative effects of irrigation and N fertilizer applications on dry matter production of ornamental conifers and on N leaching. This study aims at a better understanding of the relationships between irrigation (method, amount, time) and N fertilizer applications (method, rate) on the one hand, and dry matter production of ornamental confiners and losses of N and water to the environment on the other hand. It is focused on the relationship between inputs (of irrigation water and N fertilizer supply) and outputs (dry matter production, water and N leaching) in the crop-soil system. The specific output of this study is a field-based model to explore the effects of irrigation and fertilizer strategies on dry matter production and on N leaching. The model will be subsequently used to evaluate time dependent irrigation strategies aimed to increase the effectiveness of irrigation. Also the impact of fertilizer application methods and application levels on N (leaching) losses within the framework of the EU nitrate-N limit will be assessed.

The ornamental conifer western cedar (*Thuja occidentalis*) was chosen as a model crop in this study. Generally, *Thuja* are grown from cuttings and transplanted into the field at low plant densities (5 plants m^{-1}), as most conifers are, and may be considered as the model crop for ornamental conifers. Most conifers have comparable growing features when it comes to physiological processes like bud burst and leaf area. The trees are planted in rows in the spring and grown for two growing seasons on nurseries. When irrigated, irrigation is applied through drip irrigation, placing one emitter at the stem base. The demands for water and N of *Thuja* are not yet well known.

Outline of this thesis

Following the general introduction with the problem definition and objectives (this chapter), Chapter 2 presents a simple quantitative method to estimate light interception by small, transplanted field-grown white cedar (*Thuja occidentalis*). The concept of the radiation use efficiency was calibrated and validated in Chapter 3. In addition, the leaf area development and partitioning of dry matter to the various plant organs is discussed. The dry matter partitioned to the below ground biomass is used to obtain root diffusion parameters for a model based on the concept of the convective-diffusion model of two-dimensional root growth and proliferation (Chapter 4). In Chapter 5 the crop growth model is combined with a two-dimensional soil water balance model and used to describe the movement of water in a crop-soil system. An evaluation of the effects of three irrigation strategies is given in Chapter 6 and is combined with effects of two fertilizer application methods and two fertilizer application rates on N use efficiency, N losses and N concentration in the percolating soil water solution.

Chapter 7 contains an overall discussion of the findings and discusses the necessary changes in field-grown nursery stock in order to meet the prevailing constraints *i.e.* irrigation and nitrate leaching.

CHAPTER 2

A simple method to estimate radiation interception by nursery stock conifers: a case study of eastern white cedar

Co-authors: J. Goudriaan, E. Stilma & H. Challa†
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Abstract

A simple method was developed to estimate the fraction radiation intercepted by small eastern white cedar plants (*Thuja occidentalis* 'Brabant'). The method, which describes the crop canopy as rows of cuboids, was compared with methods used for estimating radiation interception by crops with homogeneous canopies and crops grown in rows. The extinction coefficient k was determined at different plant arrangements and an average k value of 0.48 ± 0.03 (R^2 = 0.89) was used in the calculations. Effects of changing plant characteristics and inter-row and intra-row plant distances were explored. The fraction radiation intercepted that was estimated with the method for rows of cuboids was up to 20% and for row crops up to 8% lower than estimated with the method for homogeneous canopies at low plant densities and a *LAI* of 1. The fraction radiation intercepted by small plants of *Thuja occidentalis* 'Brabant' was best estimated by the simple method described in this paper.

Keywords: clustering factor, extinction coefficient, *Thuja occidentalis* 'Brabant', row crops, rows of cuboids.

† Deceased

Introduction

The amount of radiation intercepted by plants depends on the plant canopy structure. The estimation of the amount of intercepted radiation becomes increasingly complicated for stronger heterogeneity of the plant canopy structure. To estimate radiation interception, several methods are available, each of which is suitable for the specific representation of the canopy involved (Miller, 1967; Miller, 1965; Monsi & Saeki, 1953; Ross & Nilson, 1966; Wit, 1965). However, these methods generally require a homogeneous distribution of leaves within the crop canopy and interception of radiation is by the photosynthetic active surface, the leaves only. Such conditions are not met by field-grown nursery stock planted at low densities where foliage is clustered into individual plant crowns and where stems may contribute to radiation interception. In systems with discontinuous canopies and clustered foliage a more detailed description of radiation interception by the leaves is needed as more radiation reaches the ground and is lost for dry matter production compared with the situation where leaves are homogeneously distributed.

Norman & Welles (1983) and Bartelink (1996) developed detailed and complex methods to estimate radiation interception of discontinuous canopies with grouped foliage, mainly for individual tree crowns or for forests. However, conditions of individual trees and of forests differ considerably from those of conifers in production nurseries. For example: *Thuja occidentalis* 'Brabant' (eastern white cedar) is planted in rows with a low leaf area index (*LAI*). This allows a more simple approach to estimate the fraction of radiation interception: the row crop approach (Goudriaan, 1977), a method successfully used for other row crops (Heuvelink, 1996; Palmer, 1989; Wagenmakers, 1995). However, the row crop approach assumes continuous rows, a condition not always met after planting of field-grown nursery stock. For instance, during the first year of the two-year growing period of transplanted conifers, the intra-row bare area interrupts the row in a similar way as the bare area between rows (Fig. 1). The reduction of intercepted radiation due to the intra-row bare area may be included in the row crop approach. To estimate this reduction in row crops the bare intra-row area can be treated in the same way as the bare area inter-row area. In other words, the plant row can be considered as an array of cuboids.

The objective of this study was to use this approach and develop a simple method to estimate radiation interception in crops consisting of rows of cuboids. In this study the conifer eastern white cedar (*Thuja occidentalis* 'Brabant') was used because this crop is planted in the field in rows with bare inter-row areas during much of the two-year cropping period. The extinction coefficient k was determined experimentally and used to investigate effects of increasing *LAI*, plant height and width on the fraction of intercepted radiation calculated for a homogeneous canopy, a row crop and a row of cuboids.

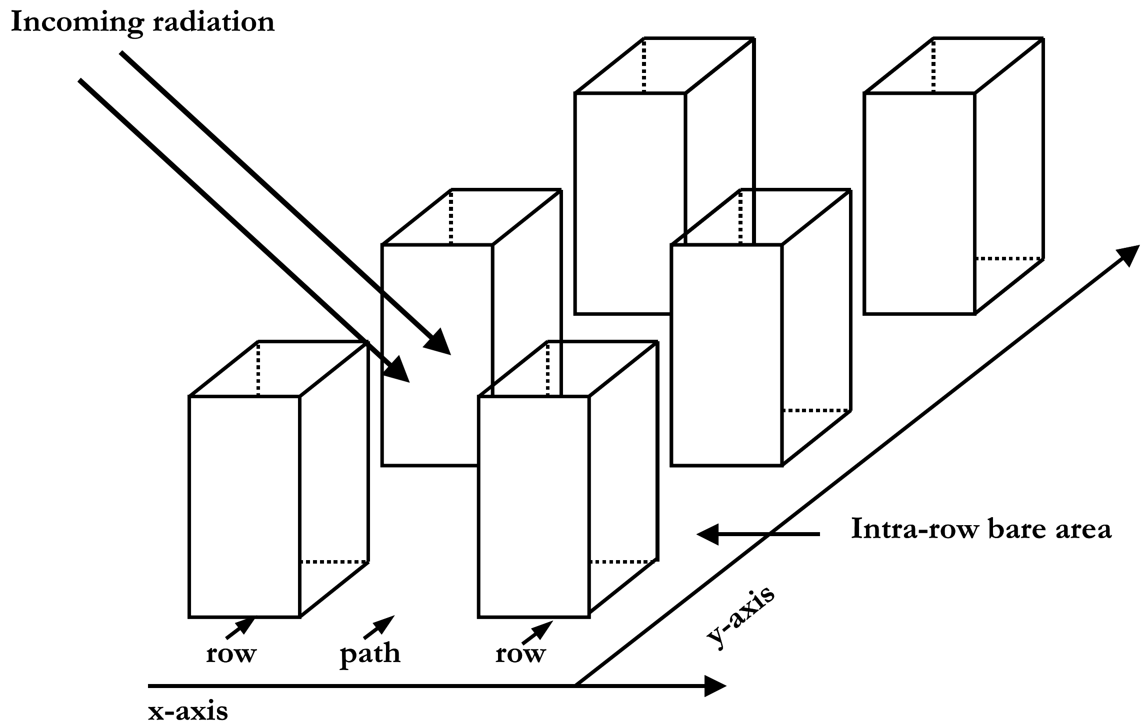


Figure 1. *Radiation interception by a crop consisting of rows of cuboids. Y-axis is in the direction of the row; x-axis is perpendicular to the row.*

Theory of radiation interception by crop canopies

Homogeneous canopy versus row crop

In a homogeneous crop canopy the fraction of radiation intercepted (F_{int}) is described as an exponential extinction function of *LAI* (Monsi & Saeki, 1953):

$$I = I_0 * \mathrm{e}^{-k*LAI} \tag{1}$$

where I is the radiation intensity below the plant canopy, I_0 the radiation intensity above the plant canopy, k is the radiation extinction coefficient and *LAI* the leaf area index. So F_{int} by the canopy is (ignoring reflection by the canopy):

$$F_{int} = 1 - \mathrm{e}^{-k*LAI} \tag{2}$$

In Eq. 2, F_{int} is the complement (1-e^{-k*LAI}) of the fraction transmitted to the soil surface, assuming that the leaf area is homogeneously distributed over the entire area.
In a row crop, paths and rows alternate. The total leaf area being the same, the leaves are then concentrated in the plant rows and absent between the rows: the paths.

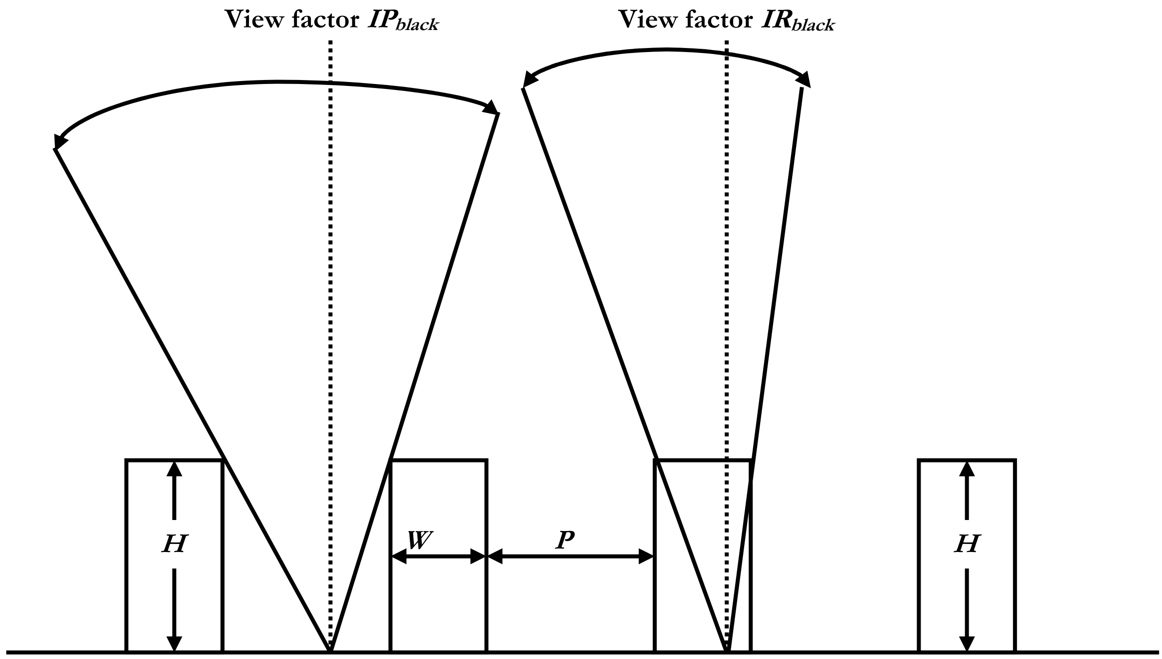


Figure 2. *Boundaries of part of the sky seen from a point at the bottom of the path between two rows (view factor IP_{black}) and from a point in the crop row (view factor IR_{black}) with infinitive LAI (after Goudriaan, 1977). H is the plant height, W is the crop width and P is the bare path width.*

This heterogeneity of the crop canopy normally tends to reduce the canopy radiation interception because the leaves shade each other more strongly. Most of the radiation in the path will fall onto the soil surface. The description of this heterogeneity could be simplified by considering a crop to consist of two parts: a homogeneous part with the 'compressed' leaf area and a bare, leafless part. If all rows were pushed together, the compressed leaf area index (LAI_{comp}) is given by the following equation:

$$LAI_{comp} = LAI * \frac{(W + P)}{W} \tag{3}$$

where W is the width of the plant row and P is the width of the bare path (Fig. 1). The radiation level transmitted to the soil (I_{comp}) below the LAI_{comp} then becomes:

$$I_{comp} = I_0 * \mathrm{e}^{-k*LAI_{comp}} \tag{4}$$

In such a compressed canopy the fraction of soil area covered by the crop is $W/(W+P)$. Consequently, the fraction of radiation intercepted, $F_{int,comp}$, averaged over the whole area, becomes:

$$F_{int,comp} = \frac{W}{(W + P)} * (1 - \mathrm{e}^{-k*LAI_{comp}}) \tag{5}$$

and the fraction of soil area that is bare and receives full radiation becomes $P/(W+P)$.

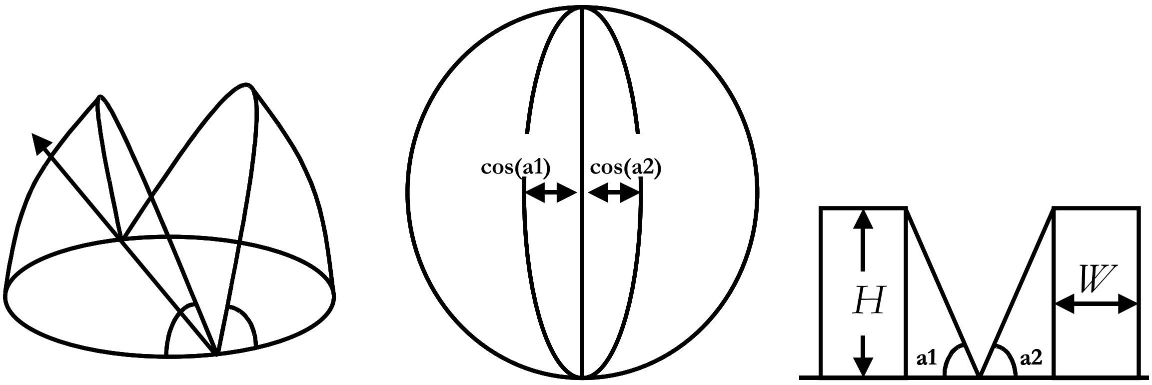


Figure 3. *The vertical projection of the view factor of the path. H is the plant height, W is the crop width and a1 and a2 are the inclinations of the incident rays in the normal polar co-ordinate system. The arrow points out the row direction.*

Direct and diffuse radiation

In this study it was assumed that on a daily basis direct of diffuse radiation does not affect the average fraction radiation intercepted (Goudriaan, 1977; 1988). The simplest description for diffuse radiation is that of isotropy, *i.e.* homogeneous radiance from the entire sky. This assumption enables easy spatial integration over all directions without the need to consider time of day or the day of year.

Transmission for row systems with 'black' and 'non-infinite' LAI

Rows with non-infinite leaf area index transmit radiation either to the soil surface or to the adjacent plant row. To calculate the fraction of transmitted radiation, the theoretical case of a 'black' row (infinite *LAI*) not transmitting any radiation, is considered first. The only radiation reaching the soil is then passing through the space of the paths. If can be calculated for a known path width, plant row width and plant row height. This fraction (radiation level at a horizontal surface element of the path divided by the radiation level above the canopy) is called the *view factor* of the sky. The *view factor* for any horizontal surface is identical to the vertical projection of the unobstructed portions of the sky dome, relative to the total vertical projection of the sky dome (Fig. 2).

Since the radiation from the sky dome is assumed to be homogeneous, the contribution of any element of the sky to radiation that reaches the soil surface is proportional to the sine of the angle of incidence of the radiation coming from that sky element. The vertical projection of the sky view of the path is given by the difference of the cosines (Fig. 3).

If spatially integrated over the path the relative radiation on the path, IP_{black}, is (Goudriaan, 1977):

$$IP_{black} = \frac{\sqrt{H^2 + P^2} - H}{P} \tag{6}$$

where H is the plant height and P the bare path width between the rows.
At non-infinite LAI, however, the row transmits radiation, increasing the level of IP_{black}. Depending n the angle of incidence, radiation from lateral directions will have passed through one or more adjacent rows before reaching the path. The number of rows through which radiation passes can be estimated according to Gijzen & Goudriaan (1989), but here a simplifying approach is followed. On average the radiation transmitted by the row equals I/I_0 (Eq. 1), as in a homogeneous canopy.
Its *view factor* is the complement of that for the path, IP_{black}, and so the resulting expression for radiation levels in the path at soil level with non-infinite LAI, SP_{ni}, is:

$$SP_{ni} = IP_{black} + (1 - IP_{black}) * \mathrm{e}^{-k*LAI} \tag{7}$$

For the radiation level at the soil surface below the row, SR_{ni}, a similar geometrical approach is followed. First the *view factor* of the row itself is determined, IR_{black}, in the same way as IP_{black} (Eq. 6 but with P replaced by W). In analogy to the equations for SP_{ni}, SR_{ni} would be given by IR_{black} + (1- IR_{black})* I/I_0. However, this would result in an overestimation as in the first term with the *view factor* IR_{black} one still needs to account for the radiation extinction in the overhead row itself. The best approximation for this *view factor* is the transmission value in case the rows were pushed together, termed I_{comp}/I_0 (Eq. 4). So the final expression for SR_{ni} will be:

$$SR_{ni} = IR_{black} * \frac{I_{comp}}{I_0} + (1 - IR_{black}) * \mathrm{e}^{-k*LAI} \tag{8}$$

Fraction of radiation interception by the plant canopy

For a plant canopy with a given total leaf area index and a given plant height, the degree of heterogeneity varies with row and path widths, relative to canopy height. For row and path widths that are much smaller than canopy height, the canopy will be indistinguishable from a homogeneous canopy and Eq. 1 can be used. On the other hand, if path and row widths are very large compared to canopy height, the situation will be virtually as presented by Eqs 3, 4 and 5.
The approach followed below is that in intermediate cases the relative difference between the irradiation at the soil surface below row and path will serve to characterize the degree of heterogeneity. This relative difference is given by the ratio of (SP_{ni} - SR_{ni})/(1 - I_{comp}/I_0). In homogeneous canopies SP_{ni} and SR_{ni} will be identical so that this relative difference is zero.

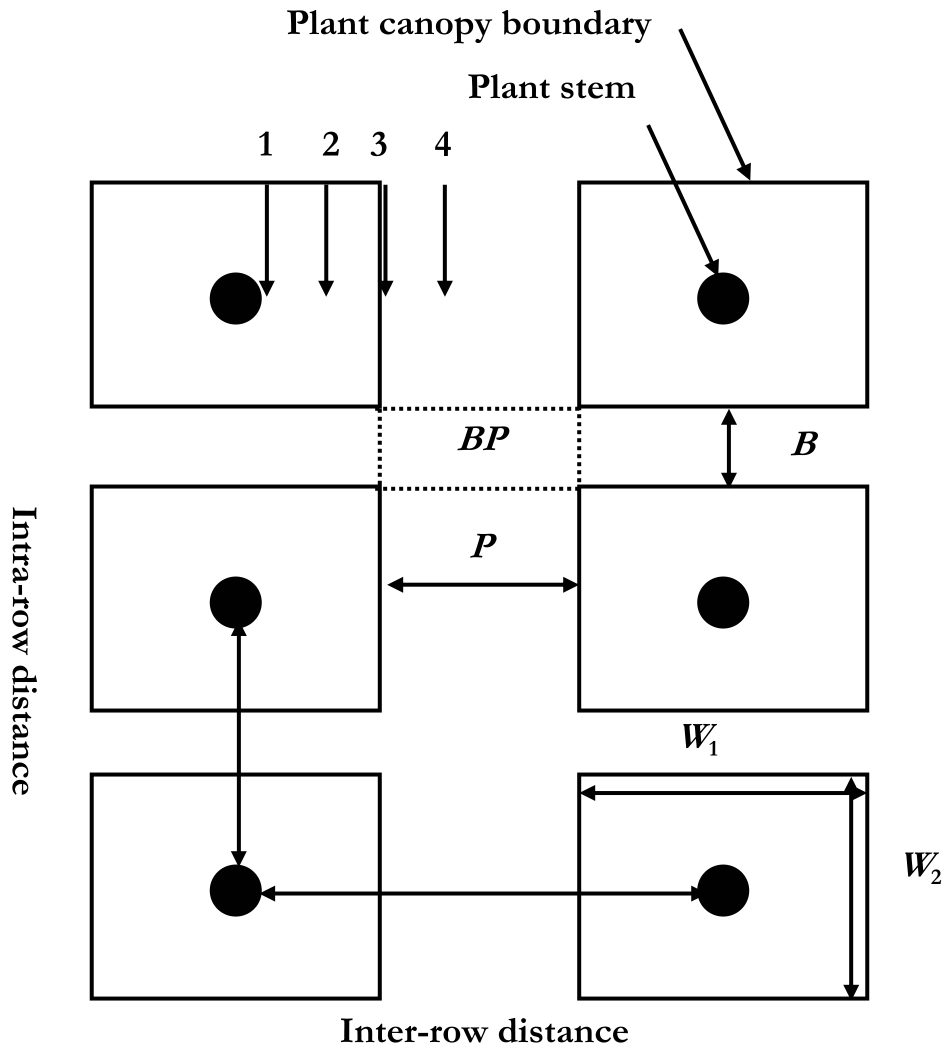


Figure 4. *Layout of the experiment for radiation interception measurements. P is the bare path width, B the intra-row bare area, BP the bare area between B and P, W_1 is the row width towards the path and W_2 towards the intra-row area. The numbers 1 to 4 indicate where the four below canopy measurements are taken.*

The approximating equation for the total fraction of radiation intercepted by the plant canopy will be:

$$F_{int,row\_crop} = F_{int} - \frac{(F_{int} - F_{int,comp}) * (SP_{ni} - SR_{ni})}{(1 - \frac{I_{comp}}{I_0})} \qquad (9)$$

Rows of cuboids

Although plants are planted in rows, rows most often are not continuous as assumed above, at least not during part of the growing period (Fig. 1). The above-presented procedure for estimating radiation interception by crops grown in rows could be followed for crops that can be represented by arrays of cuboids.

Table 1. Plant arrangements for small and large plants in two experimental groups.

	Small plants[1]		Large plants[1]	
	Row distance	Intra-row distance	Row distance	Intra-row distance
Plant arrangement	(m)	(m)	(m)	(m)
Group 1				
1	0.19	0.19	0.23	0.23
2	0.40	0.40	0.40	0.40
3	0.50	0.40	0.50	0.40
4	0.75	0.40	0.75	0.40
Group 2				
5	0.30	0.19	0.30	0.23
6	0.30	0.30	0.30	0.30
7	-[2]	-	0.40	0.40
8	-	-	0.50	0.23
9	-	-	0.50	0.30

[1] *see Table 2*

[2] *= not determined*

The compressed LAI for rows of cuboids, $LAI_{comp,cub}$, is not only related to P, but also to the bare soil between the plants within the row, B (Fig. 4).
Analogous to Eq. 5, the fraction radiation intercepted for the compressed leaf area index for rows of cuboids, $F_{int,comp,cub}$, is calculated. The *view factor* of the bare soil between plants in the row (for infinite LAI), IB_{black}, can be defined by replacing P in Eq. 6 by B and SB_{ni} can be calculated (Eq. 7). The bare area between P and B, BP is not yet included (Fig. 4). The *view factor* IBP_{black} for BP is relative to those for P and B according to the following equation:

$$IBP_{black} = \frac{\left(IP_{black} * P * W + IB_{black} * B * W + SB_{ni} * P * B\right)}{\left(W * P + W * B + P * B\right)} \tag{10}$$

Adding transmitted radiation reaching the soil surface in case of non-infinite leaf area index gives:

$$SBP_{ni} = IBP_{black} + \left(1 - IBP_{black}\right) * e^{-k*LAI} \tag{11}$$

Finally, the approximating equation for the total fraction of radiation intercepted by the plant canopy of rows of cuboids will be:

Table 2. Plant height (H), plant width across the row (W1), plant width in the row (W2), and leaf and stem area of the small and large plants in the two experimental groups. Average of 6 plants. Standard error of the mean in parentheses.

	Plant size	H (m)	W_1 (m)	W_2 (m)	Leaf area (cm^2 $plant^{-1}$)	Stem area (cm^2 $plant^{-1}$)
Group 1	Small	0.46 (0.3)	0.20 (1.2)	0.15 (1.0)	391 (14)	14 (0.6)
	Large	0.85 (1.4)	0.39 (1.2)	0.33 (1.1)	4478 (290)	n.d.[1]
Group 2	Small	0.45 (0.5)	0.19 (1.0)	0.13 (1.4)	490 (33)	17 (1.3)
	Large	0.92 (1.4)	0.33 (1.2)	0.27 (1.5)	5488 (416)	n.d.[1]

[1] *n.d. = not determined*

$$F_{int,cub} = F_{int} - \frac{\left(F_{int} - F_{int,comp,cub}\right) * \left(SBP_{ni} - SR_{ni}\right)}{(1 - \frac{I_{comp,cub}}{I_0})} \tag{12}$$

If B decreases to zero (a continuous row), the fraction radiation intercepted becomes identical to that given by Eq. 9.

Materials and methods

Mid March 2001, 100 small (height: 0.25 - 0.35 m) and 100 large (height: 0.6 - 0.8 m) plants of *Thuja occidentalis* 'Brabant' were transplanted to nursery containers and placed in an unheated greenhouse. The plants were used to form two experimental groups.

On an overcast day, 26 April 2001, 20 small and 20 large, uniform plants were selected and placed outdoors at the Applied Plant Research Nursery Stock unit in Boskoop in two plots consisting of 4 rows of 5 plants each (Group 1). Inter- and intra-row plant distances were varied to create different plant arrangements (Table 1). Light interception was measured the same day on 6 plants in the middle of each plot, using a Licor *LAI*-2000 Plant Canopy Analyzer (Lincoln, NB, USA). The recordings were carried out facing south with a 270° viewcap (Nackaerts *et al.*, 2000). A reference reading was taken above the plant canopy, followed by 4 readings at the soil level at equidistant intervals between the stem base and the middle of the path (Fig. 4). Light interception was calculated from these 5 readings according to the Licor *LAI*-2000 Plant Canopy Analyzer reference manual (Anonymous, 1992). The average amount of light intercepted per plant per plot was considered the light interception estimated of that particular plot. The light interception of that particular plot was measured twice (2 replicates) and three times (3 replicates) if $LAI < 0.2$, to account for a larger variability at lower LAI.

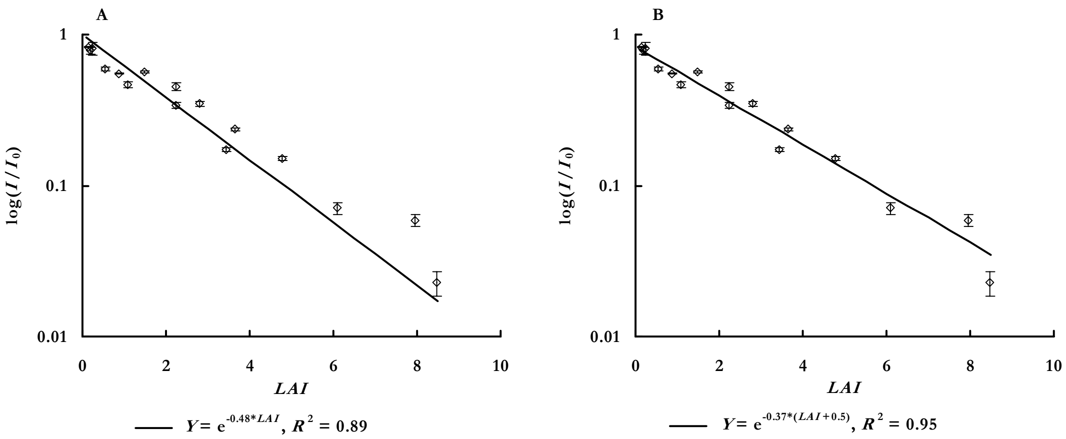


Figure 5. *Intercepted fraction of radiation (logarithmic scale) by small and large Thuja occidentalis 'Brabant' plants at different LAI at the start of the experiment. A: for measured LAI values; B: for measured LAI values + 0.5, to account for the large interception of radiation with grazing incidence from the sky zone just above the horizon. Error bars indicate standard error of means.*

The day after the interception was measured (27 April 2001), plant height (*H*) and plant width (across the row: W_1 and in the row: W_2) were recorded. The leaves (defined as the green parts of the plant) of the 6 small and 6 large plants were removed and the one-sided projected area of the leaves was measured with a LI-COR 3100 area meter (Lincoln, NB, USA). The radiation interception recordings were repeated for the defoliated plants in the two plots with the highest plant density (arrangement 1) and for the generally used plant density for field-grown *Thuja* (arrangement 3, Table 1).
The Licor *LAI*-2000 Plant Canopy Analyzer not being sensitive enough, the one-sided projected area of the stems of the small plants was measured with the LI-COR 3100 area meter.
On 1 May 2001, (an overcast day) 20 small and 20 large additional plants were selected and placed outdoors at the same location, and light interception was measured as described above on different plant arrangements (Table 1, Group 2). The next day, the 6 small and 6 large record plants were destructively harvested, following the same procedure as described for group 1.
LAI (m^2 [leaf] m^{-2} [soil]) was calculated from the destructively determined leaf area for each of the plant densities, assuming a homogeneous crop canopy. LAI_{comp} was calculated according to Eq. 3 and $LAI_{comp,cub}$ as proposed in the section '*Rows of cuboids*'.
The extinction coefficient *k* was calculated fitting Eq. 1 to the recorded data by using the statistical program GENSTAT 6, release 1 and the fraction radiation intercepted was calculated using Eq. 2, 9 and 12. Although *k* theoretically consists of many different values, depending on the orientation of the leaves and on the direction of the incoming radiation (Goudriaan & Van Laar, 1994), one value of *k* was fitted. The clustering factor was calculated as the ratio between the actual *k* and the theoretical value k_{bl} [0.72 = (0.8 * $\sqrt{(1-\sigma)}$); where σ = scattering coefficient (0.2)] (Goudriaan & Van Laar, 1994).

Table 3. Measured fraction of radiation intercepted by stems (F_{stem}), LAI (based on the entire area), LAI_{comp}, $LAI_{comp,cub}$, estimated k value, and relative difference (%) between F_{int} (Eq. 2) and $F_{int,row\text{-}crop}$ (Eq. 9) and $F_{int,cub}$ (Eq. 12) for different plant arrangements and two experimental groups. See text for the various symbols.

		F_{stem}	LAI	LAI_{comp}	$LAI_{comp,cub}$	k	Relative difference	
Plant arrangement	Plant size[1]						$F_{int,row\text{-}crop}$	$F_{int,cub}$
Group 1								
1	Small	n.d.[2]	1.08	1.08	1.40	0.71	0.0	0.3
2		n.d.	0.24	0.49	1.34	0.87	1.2	5.1
3		n.d.	0.20	0.49	1.34	1.26	1.7	5.4
4		n.d.	0.13	0.49	1.34	1.47	2.3	5.9
1	Large	0.13	8.46	8.46	8.46	0.45	0.0	0.0
2		n.d.	2.80	2.91	3.52	0.38	0.0	0.6
3		0.09	2.24	2.91	3.52	0.42	1.0	2.0
4		n.d.	1.49	2.91	3.52	0.38	5.1	6.5
Group 2								
5	Small	n.d.	0.86	1.37	2.08	0.69	1.5	3.6
6		n.d.	0.54	0.87	2.08	0.97	1.0	5.6
5	Large	n.d.	7.95	7.95	7.95	0.36	0.0	0.0
6		n.d.	6.10	6.10	6.80	0.43	0.0	0.0
7		n.d.	3.43	4.16	6.19	0.51	0.6	2.8
8		n.d.	4.77	7.24	7.24	0.40	2.8	2.8
9		n.d.	3.66	5.55	6.19	0.39	2.6	3.1

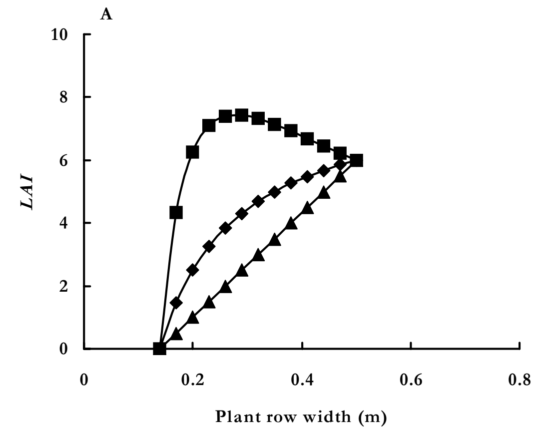
[1] *for specification see Table 2*
[2] *n.d. = not determined*

Results

Extinction coefficient

The one sided projected area of the stems of the small plants was 14 cm² on 26 April (Group 1) and 17 cm² on 1 May 2001 (Group 2), which was less than 4% of that of the leaves (Table 2). The contribution of this stem area to the leaf area index was low and within the standard error of the leaf area measurements.

The fraction radiation intercepted by the stem area, F_{stem}, of the larger plants was 0.13 for plant arrangement 1 and 0.09 for plant arrangement 3 (Table 3), whereas the fraction radiation intercepted at the same plant arrangements for stems plus leaves was 0.98 and 0.60 respectively (Fig. 9). F_{stem} was therefore 3.3 and 8.1% of the interception by the plant canopy $[(-\ln(1-F_{stem})/k)/(LAI + (-\ln(1-F_{stem})/k)]$.



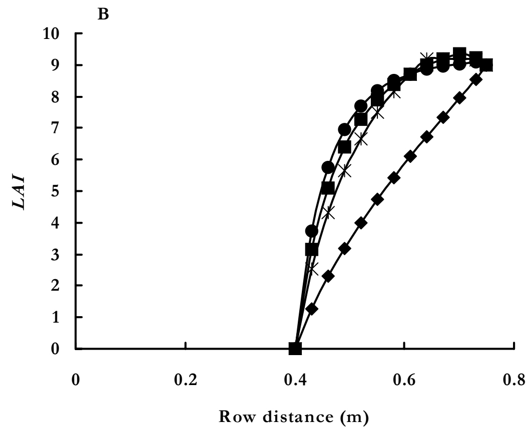


Figure 6. *(right, A). Effect of plant row width on LAI of a homogeneous canopy (▲), LAI_{comp} (♦) and $LAI_{comp,cub}$ (■) at an inter-row- and intra-row distance of 0.5 m. Plant row width varies simultaneously with LAI (based on the entire area) from 0.14 m for LAI = 0.0 to 0.5 m for LAI = 6.0.*

Figure 7. *(left, B). Effect of inter-row distance on LAI_{comp} (♦) and on $LAI_{comp,cub}$ at different intra-row distances of 0.3 m (■), 0.4 m (*) and 0.5 m (●), both at W_1 = W_2 = 0.25 m.*

The leaf area index of some plant arrangements was less than 0.5 (Table 3). The extinction coefficient *k* decreased with increasing *LAI* (Table 3) but was stable at *LAI* 1.5 and higher. The best fitting value of *k* for all interception measurements was 0.48 ± 0.03 (R^2 = 0.89, Fig. 5A).

Radiation interception predicted for different plant arrangements

The leaf area index calculated on the basis of the entire area (*LAI*) was lower than LAI_{comp}, which in turn was lower than $LAI_{comp,cub}$, depending on path width and intra-row gaps (Table 3). Plant width exceeded row distance for small plants at plant arrangement 1 and for large plants at arrangements 1, 5 and 6. Therefore *P* was zero, *LAI* was equal to LAI_{comp}, and $(W+P)/W$ was equal to 1 (Table 3). The same occurred along the rows for large plants at plant arrangements 1, 5 and 8: $LAI_{comp,cub}$ was equal to LAI_{comp} because W_2 exceeded the intra-row distance (Table 3). The differences between *LAI* and LAI_{comp}, and between *LAI* and $LAI_{comp,cub}$, were larger for narrower plants (large bare inter- and intra-row areas), and when leaf area increased (Fig. 6 and 7). So in comparison with $F_{int,row\text{-}crop}$ and $F_{int,cub}$, F_{int} was mostly overestimated at low plant densities with high *LAI* (Table 3).
The fraction radiation intercepted was also related to plant height. At the standard row distance of 0.5 m, an intra-row distance of 0.4 m and a leaf area index of 1, the fraction radiation intercepted was smaller the row-of-cuboids system than for the homogeneous canopy (Fig. 8A).
The fraction radiation intercepted that was calculated with the simple exponential formula for radiation extinction (Eq. 1) resulted in 0.38.

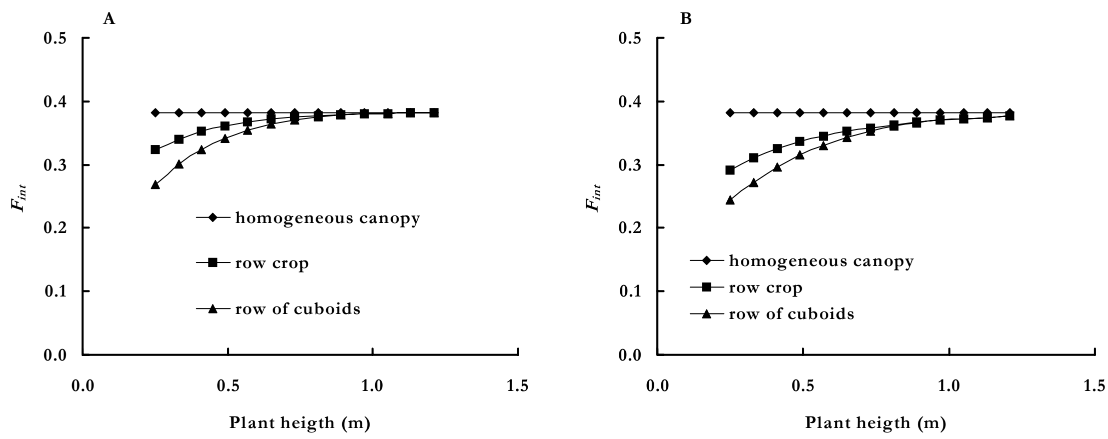
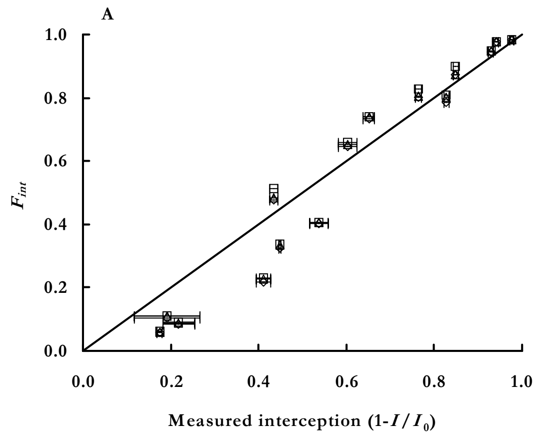


Figure 8. *Effect of plant height on the calculated fraction radiation intercepted (F_{int}) at LAI of 1 and row distances of 0.5 (A) and 0.75 m (B) for different plant arrangements.*

When $F_{int,row\text{-}crop}$ was used, the fraction radiation intercepted at low plant heights was much lower due to the row effect. It was even lower when $F_{int,cub}$ was used. The effect of plant height increased at larger distances between plant rows (cf. Fig. 8A and B).
However, in practice the differences between the measured interception and F_{int}, $F_{int,row\text{-}crop}$ or $F_{int,cub}$ were small (Fig. 9).
The differences between the measured and the calculated fraction of radiation intercepted at low *LAI* did not improve with either of the used methods (Fig. 9). F_{int} was already smaller than the measured fraction of radiation intercepted. $F_{int,row\text{-}crop}$ and $F_{int,cub}$ were even smaller and therefore the discrepancy between measured and calculated radiation intercepted was larger. The relative difference between F_{int} and $F_{int,row\text{-}crop}$ or $F_{int,cub}$ varied between 0 and 6.6%, depending on plant arrangement (Table 3).

Discussion

The very low *LAI* values at some plant arrangements are realistic for one-year old transplants in spring. Leaf area index increases throughout the first growing season and values close to 1 are reached by the end of the summer (De Beuze *et al.*, 2004). *LAI* values between 1 and 6 have been observed in the field in the second growing season and the plant arrangements investigated represent the range of leaf area indices generally found in cropping systems in practice.
Interception recordings for estimating *k* should be corrected for the interception by the stem because *k* is based on leaf area only. However, for the small plants in our investigation such a correction was not considered necessary because the average data on leaf-intercepted radiation varied by 12%, whereas the contribution of the stem area (4%) to the radiation-intercepting area at a *LAI* = 1 was smaller than this variation.



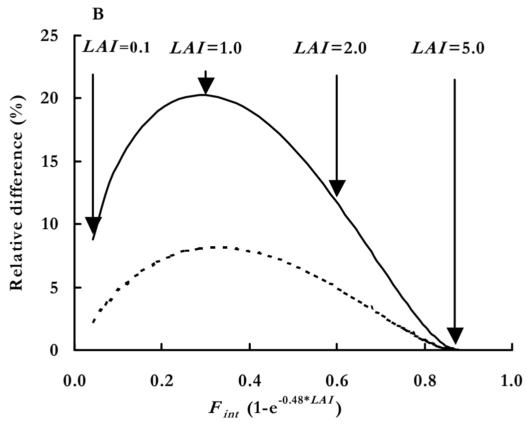


Figure 9 (right, A). Calculated (F_{int}) compared with measured fraction of intercepted radiation for different plant arrangements.

Figure 10 (left, B). Relative difference between F_{int} and $F_{int,row\text{-}crop}$ or $F_{int,cub}$ for plants of different size (LAI: 0.1 - 5, plant height: 0.25 - 1.10 m, W_1 and W_2: 0.13 - 0.5 m).

At plant arrangements 1 and 3 the fraction of radiation intercepted by bare stems of the large plants was 3.2 and 8.1%, respectively, of the intercepted radiation by the plant canopy. Also, these percentages were within the variations of the measurements and no correction was made either.

A k value of 0.48 for *Thuja occidentalis* 'Brabant' is considerably lower than the theoretical k_{bl} value of black leaves with a spherical leaf angle distribution (Goudriaan & Van Laar, 1994). The resulting clustering factor was 1.5, which is smaller than values found for other coniferous crops: 1.72 for Scots pine (Stenberg *et al.*, 1994) and 1.61 for Douglas fir (Smith *et al.*, 1993). However, the large k-values (>1) found at low LAI are an indication of a large interception with grazing incidence from the sky zone just above the horizon. If LAI increases, this fraction of radiation is already intercepted and so k becomes smaller with increasing LAI. To account for this effect in a practical way, the measured LAI was increased by a factor of 0.5 (SE = 0.09) for the whole range of interception assessments. The factor 0.5 was found by using the FITNONLINEAR procedure of the statistical program GENSTAT 6, release 1 by fitting $I/I_0 = e^{-k*(LAI + a)}$. Using this equation with $a = 0.5$, a better fit between k and interception measurements was found (R^2 = 0. 95 against R^2 = 0.89 earlier) whereas k was now smaller: 0.37 ± 0.02 (Fig. 5B).

Although the differences between $F_{int,row\text{-}crop}$ and $F_{int,cub}$ in relation to F_{int}, are small for the plant arrangements investigated (Table 3), calculations with increasing plant height (0.2-1.10 m), row width and intra-row width (0.1 - 0.5 m) and LAI (0 - 5) show that $F_{int,row\text{-}crop}$ and $F_{int,cub}$ are overestimated by 8 up to 20% respectively (Fig. 10).

The row crop approach has been investigated for other row cropping systems (Heuvelink, 1996; Palmer, 1989; Wagenmakers, 1995). In these studies additional adjustments for rows of cuboids did not seem necessary because intra-row planting distances were usually small (no bare intra-row area) and LAI increased rapidly.

For field-grown nursery stock, however, the bare area between plants is considerable (Petersen & Hill, 1985), indicating relatively large path widths and large bare intra-row areas. An overestimate of the fraction radiation intercepted of 20% on a daily basis leads to a substantial surplus of total intercepted radiation during the growing season and subsequently to an overestimate of dry matter production.
After one growing season the total amount of overestimated dry matter may almost double due to a positive feedback of increasing dry matter production on *LAI*. The fraction radiation intercepted by the canopy of field-grown conifers is therefore best estimated by the method which describes the canopy as rows of cuboids.

CHAPTER 3

Dry mass production and leaf area development of field-grown ornamental conifers: measurements and simulation

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Abstract

A dynamic simulation model of dry mass (*DM*) production and leaf area index (*LAI*) development in ornamental conifers, CONGRO, was developed. The concept of a constant radiation use efficiency (*RUE*) was combined with a model for radiation interception by row crops. A field trial was used to calibrate *RUE*, *DM* partitioning and the specific leaf area (*SLA*). *LAI* increase was simulated through leaf dry mass increase and *SLA*. Ten independent trials (1991-1999) were used for validation. Predicted aboveground *DM* agreed well with measured data (R^2 = 0.94) with a standard error of the regression of 149 g m^{-2}. Predicted *LAI* agreed less with experimental field data (R^2 = 0.90), standard error of the regression was 0.312 m^2 m^{-2}. Sensitivity analysis showed a large positive and sometimes more than proportional effect of *RUE*, *SLA* and partitioning into the leaf dry mass on simulated total *DM*, *LDM*, *LAI* and intercepted radiation.

Keywords: crop growth, eastern white cedar, radiation use efficiency, rows of cuboids, sensitivity analysis, simulation model, *Thuja*, validation.

† Deceased

Introduction

At present, the area of nursery stock production in the Netherlands exceeds 12000 ha. This horticultural sector has to comply with strict regulations with respect to water extraction and water use, application of manure and application of nitrogen fertilisers (Krekels & Smit, 1999). Governmental policy is focused on the reduction of water extraction because groundwater tables have already been lowered by agricultural activities during the last decades. In addition, attention is paid to decrease nutrient leaching to prevent groundwater and surface water pollution. Growers are therefore restricted in the use of production factors like water and fertilisers. Within these restrictions growers therefore need to optimise their limited resources for maximum production and minimum environmental impact. One way to support growers in the decisions on water use is the use of crop growth models combined with transpiration and soil water balance models (Itier, 1994; Leuning, 1995; Pronk & Challa, 2000). Dynamic crop growth models exist for many horticultural crops (see Marcelis *et al.*, 1998 for a recent review), but not for nursery stock. Although there are forest growth models (Bartelink, 1998a; Dewar, 1997; Landsberg & Waring, 1997; Mohren, 1987; Mohren *et al.*, 1993) these have various drawbacks for application on production nurseries: they require permanently closed canopies and/or much larger time scales. Furthermore, these models often use detailed and complicated approaches for radiation absorption (Bartelink, 1998b).

However, a relatively simple method for radiation interception by small conifers grown in rows as cuboids has been proposed by Pronk *et al.* (2003a). This method accounts for incomplete cover, leaf area clustering and the upright structure of the crop and is based on the radiation interception by row crops according to Goudriaan (1977).

The purpose of this study is to present and evaluate the first step in a decision support model to optimise water and nutrient use and to minimise environmental impact in nursery stock production. This involves the development of a simple crop growth model CONGRO (CONifer GROwth) for field-grown ornamental conifers under field conditions with ample supply of water and nutrients, and no pests, diseases and weeds (potential growing conditions, Fig. 1). CONGRO estimates dry mass (*DM*) production and *LAI* development during a two-year-growing period. The simple concept of Monteith (1977) of a constant radiation use efficiency (*RUE*) was used and calibrated with field data. Independent trials were used to validate the model. A sensitivity analysis was conducted to explore the effects of input parameters or factors on *DM* production, *LAI* development and radiation interception.

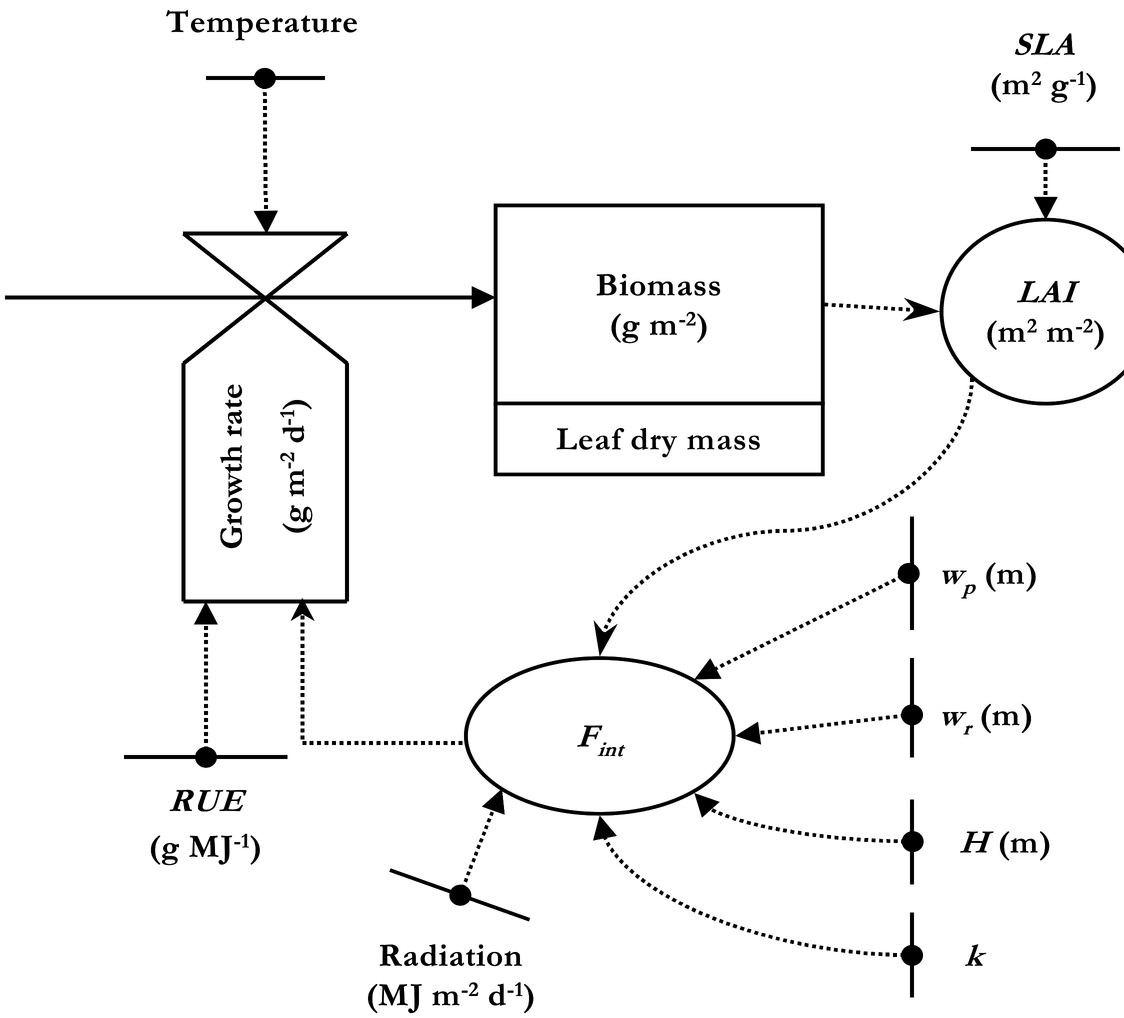

Figure 1. General structure of the model CONGRO. For abbreviations of the parameters see Table 1.

Model description

Dry mass production

Daily *DM* production is assumed to be proportional to daily intercepted photosynthetically active radiation:

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where d*DM*/dt is the crop growth rate (g [*DM*] m^{-2} d^{-1}), F_{int} is the fraction of photosynthetically active radiation (*PAR*) intercepted, *RUE* is the radiation use efficiency (g [*DM*] MJ^{-1} intercepted *PAR*), *DTR* is the daily global radiation (MJ m^{-2} d^{-1}) and F_{par} is the fraction of *PAR* in *DTR* (Table 1).

Table 1. List of abbreviations, input parameters and values used in the model CONGRO.

Abbr.	Explanation	Unit		
DM	dry mass	g [*DM*] m^{-2} [ground]		
LDM	dry mass of leaves	g [*DM*] m^{-2} [ground]		
SDM	dry mass of stems	g [*DM*] m^{-2} [ground]		
BDM	below ground dry mass	g [*DM*] m^{-2} [ground]		
DTR	daily solar radiation	MJ m^{-2} [ground] d^{-1}		
PAR	Photosynthetically active radiation	MJ m^{-2} [ground] d^{-1}		
LAI	leaf area index	m^2 [leaf] m^{-2} [ground]		
$F_{int,cub}$	fraction intercepted *PAR*	-		
TSUM	Temperature sum	°C d		
Param.	**Explanation**	**Unit**	**Value**	**Reference**
BUDB	Budburst in second growing season	°C d	220	Thomas & Moncrieff, 1982
F_{LDM}	Fraction daily *DM* to leaves	-	function of *TSUM*	trial 1
F_{SDM}	Fraction daily *DM* to stems	-	function of *TSUM*	trial 1
F_{par}	average fraction of PAR in *DTR*	-	0.47	Gijzen, 1992
H	plant Height	m	function of *TSUM*	trial 1
iBDM	initial Below ground Dry Mass	g m^{-2}	measured or 21	trial 2-11
iLDM	initial Dry Mass of the leaves	g m^{-2}	measured or 42	trial 2-11
iSDM	initial Dry Mass of the stems	g m^{-2}	measured or 9	trial 2-11
k	radiation extinction coefficient	m^2 [ground] m^{-2} [leaf]	0.42	Pronk *et al.*, 2003
RUE	Radiation Use Efficiency	g [*DM*] MJ^{-1} IPAR	3.31	trial 1
SLA	Specific Leaf Area	m^2 [leaf] g^{-1} [*LDM*]	function of time	trial 1
STGR	STart GRowth after transplanting	°C d	280	trial 1
TBASE	base temperature	°C	4.4	Thomas & Moncrieff, 1982
w_p	planting row distance	m	0.5	
w_r	width of a crop row	m	function of *TSUM*	trial 1

All radiation is considered to be diffuse for the calculations of F_{int} (Uniform OverCast sky Goudriaan, 1977). This simplifies calculations on incoming fluxes and allows for an average value for the radiation extinction coefficient (*k*; m^2 [ground] m^{-2} [leaf]) within the canopy (Goudriaan & Van Laar, 1994). After being sown or planted in rows, most agricultural field crops reach complete ground cover within a short period (Haverkort & Goudriaan, 1994). However, small conifers planted in rows may never reach a complete ground cover or even complete row cover (Petersen & Hill, 1985). In such cases the F_{int} is smaller than in homogeneous crops with the same *LAI*. For crops standing in rows of cuboids, $F_{int,cub}$ is described by Pronk *et al.* (2003a) as:

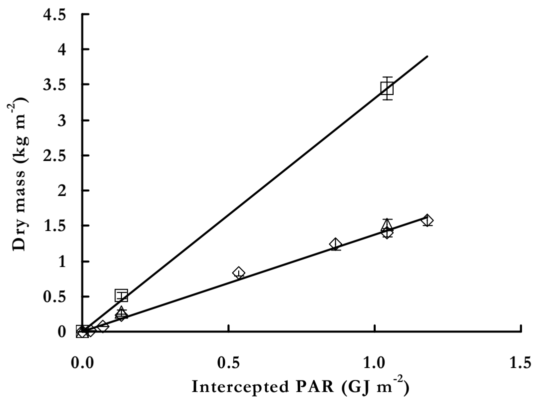

Figure 2. Relationships between crop dry mass production and accumulated intercepted photosynthetically active radiation of field-grown Thuja. Aboveground (◊); subterranean (Δ); total dry mass (□). The slopes of the fitted lines indicate radiation use efficiencies (g [DM] MJ^{-1} intercepted PAR) for aboveground (---; y = 1.38x, R^2 = 0.99) and total dry mass (—; y = 3.31x, R^2 = 0.99). Error bars indicate standard errors of means when larger than symbols (aboveground: n = 16, subterranean: n = 4; total: n = 4).

$$F_{int,cub} = F_{int} - \frac{\left(F_{int} - F_{int,comp,cub}\right) * (SBP_{ni} - SR_{ni})}{(1 - \frac{I_{comp,cub}}{I_0})} \qquad (2)$$

in which F_{int} is the fraction intercepted for a homogeneous canopy with the same *LAI* ($1\text{-}e^{(-k*LAI)}$), $F_{int,comp,cub}$ is the fraction radiation intercepted if all plants were homogeneously compressed into a ground area identical to the vertical projection of just the cuboids and $(SBP_{ni}\text{-}SR_{ni})/(1\text{-}I_{comp,cub}/I_0)$ is the relative difference in radiation intensity on the soil surface below the plant canopy and that of the path (see also Table 1). This difference serves as a measure for the degree of heterogeneity of the canopy. If the difference is zero, we will have a regular homogeneous canopy, for instance when the paths are very narrow in comparison to the crop height. If the relative difference is unity, we will have the other extreme of a path width being very much larger than crop height. The interpolation between these two extremes, as done in Eq. 2, replaces a complicated radiation interception model (Pronk *et al.*, 2003a).

The *RUE* was derived from total *DM* measurements over a two-year period and the calculated intercepted radiation according to Eq. 2 with measured *LAI* and plant height and width as forcing functions of time (Fig. 2). Only three destructive measurements were available to derive *RUE* for total *DM* production. Aboveground *DM* (leaves and stems) was measured more frequently and strongly linearly related to intercepted radiation (Fig. 2). Total *DM* is expected to be linearly related to the intercepted radiation as well (Cannell *et al.*, 1987) and therefore used to derive a value of a presumably constant *RUE* over the two-year growing period. *RUE* may be underestimated as no root turnover was taken into account (Fogel, 1983). Root

Table 2. *Average (n = 16) plant height (H; m) and crop row width (w_r ; m) of Thuja occidentalis 'Brabant' (trial 1).*

		Month								
Year		Jan.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Dec.
1998	H	-[1]	0.31	0.31	0.43	0.52	0.60	0.68	0.69	0.69
"	w_r	-[1]	0.17	0.17	0.22	0.27	0.31	0.33	0.33	0.33
1999	H	0.69	0.70	0.80	0.98	1.16	1.28	1.42	1.45	
"	w_r	0.32	0.32	0.36	0.40	0.46	0.50[2]	0.50	0.50	

[1] *Before planting*

[2] *Complete ground cover, crop row width is no longer relevant in calculations for intercepted radiation*

turnover is very difficult to measure and unlikely to be measured adequately from frequent sampling schemes, due to large variability of the results (Van Noordwijk, 1993). Nevertheless, pinboards as we used often yield the best quantitative information on root systems (Caldwell & Virginia, 1991).
In the model, crop growth did not start on the day of planting but was delayed to account for transplanting stress.
The length of the delay was calculated as the temperature sum between planting and the moment plants started to increase in height (trial 1). For the calculation of the temperature sum the threshold value, base temperature (*TBASE*), was used as proposed by Thomas & Moncrieff (1982) of 4.4 ºC (Table 2). In the second growing season bud burst and crop growth started at a temperature sum of 220 °C d since 1 January (Thomson & Moncrieff, 1982). Plant height increase of 1999 was used to evaluate bud burst (trial 1, Table 2). Crop growth and leaf area increase were terminated in the first year on 31 October and in the second year at the moment of root pruning as root pruning is known to stop the aboveground dry mass production (Wopereis, 1975).

Dry mass partitioning and leaf area increase

The dry mass produced is partitioned among leaves, stems and subterranean organs using partitioning coefficients which are related to thermal time with *TBASE* as mentioned above (trial 1, Fig. 3A, B and C). The calculation of thermal time started at the day of planting in the first year and was reset at 1 January of the second year. Partitioning of dry mass is commonly dependent on the development stage of the crop, which in turn depends on the temperature sum (Goudriaan & Van Laar, 1994).
Just one developmental stage was used in our approach, the vegetative stage. Partitioning was therefore related directly to thermal time. Subterranean dry mass was not determined at each sampling date. The fraction partitioned to the various sinks was calibrated as follows: a simulation run with forced *LAI* and *RUE* was used to calculate

total dry mass (*TDM*) produced between the various sampling dates. The dry mass was then partitioned between the various organs in such that aboveground biomass was exactly simulated.
Increase of *LAI* (m^2 [leaf] m^{-2} [ground] d^{-1}) was derived from the amount of dry mass allocated to the leaves (*LDM*; g m^{-2}) by:

$$\frac{\mathrm{d}LAI}{\mathrm{d}t} = \frac{\mathrm{d}LDM}{\mathrm{d}t} * SLA \qquad (3)$$

in which the *SLA* (m^2 kg^{-1}) is the *SLA* of the new leaves. According to our measurements *SLA* varied within one growing season with a peak value in August (Fig. 3D). The peak value in August of the second growing season was followed by a negative value of *SLA* because of a strong decline in *LAI*, but not in leaf dry mass (see also Fig. 4B and D). The period to calculate *SLA* of the new leaves was increased to obtain a positive *SLA* value and as a consequence the peak value of *SLA* in the second year was not shown. The *SLA* used in the model was calculated using the leaf area increase and dry mass produced of leaves between two harvesting dates.

Model input

Plant height (*H*; m) and width of the crop row (w_r; m) were used as forcing input functions of time (Table 2). Distance (w_p; m) between rows at planting of small conifers cropping systems was 0.5 m (Table 3). The model requires data on the initial *LDM* (*iLDM*), the initial stem dry mass (*iSDM*), the initial below ground dry mass (*iBDM*), the initial *LAI* (*iLAI* = *iLDM* * *SLA*), daily total radiation (*DTR*), planting date and daily minimum and maximum temperature.

Materials and methods

Field trial for model calibration

One-year-old container grown cuttings (called transplants further on) of *Thuja occidentalis* 'Brabant' were planted at the Horst experimental research location in the Netherlands on 24 April 1998 (trial 1, Table 3). The crop was grown on beds (width 1.75 m; distance between beds 0.25 m) with three rows per bed and a planting row distance (w_p) of 0.5 m. The trial was designed to investigate optimal irrigation strategies under potential growing conditions (treatments: no irrigation, 0.25 and 0.5 L per plant per day during the growing season and irrigation according to local practises, 4 replicates). Treatments with maximum *DM* production were selected for model calibration. Plants for *DM* and leaf area determination were selected at random from the middle row and dried at 70 °C for 48 h. No corrections were made to correct *DM* at 70 °C to values at 105 °C because less than 1% weight loss can be expected due to increased temperature (Steyn, 1959). No leaf pruning was done and root pruning was done on 25 October 1999. Total below ground dry mass (*BDM*) was determined by a pinboard analysis (see also Pronk *et al.*, 2002 for a detailed description; Schuurman & Goedewaagen, 1971), early November in the first year (1998) and mid September in the second year. Leaf area was determined using a LI-COR model 3100 Area Meter (Lincoln, NB, USA).

Trials for model validation

We used nine field trials (2 through 10, Table 3) from the same experimental location and one pot trial from the Boskoop experimental location (trial 11) to validate the model. The ten trials were designed originally to investigate optimal strategies for fertilisation and/or irrigation. In all field trials transplants of *Thuja* had been planted out in the field in April, except for trials 4 and 5, which were planted in March. All species and varieties used – *Thuja plicata* 'Excelsa', *Thuja plicata* 'Atrovirens' and *Thuja occidentalis* 'Brabant' – had similar growth characteristics. Crops were grown as described as above and again treatments with maximum *DM* production were selected and used for model validation. For trials 2 to 8 plants were dried at 105 °C for 48 h., for trials 9 and 10 plants were dried at 70 °C for 48 h. Total *BDM* was measured in the harvested root balls. Root balls were washed carefully to prevent loss of small roots and the entire root system was oven dried. Cultivation practices such as leaf and root pruning were carried out according to commercial practice (Table 3).

In 1999 transplants of *Thuja occidentalis* 'Brabant' were potted in 50 L containers, early March, filled with sand, fertilised and placed in a non-heated greenhouse (trial 11). The pots were placed on a container bed mid April at the Nursery Stock Research Unit of the Applied Plant Research at Boskoop and drip-irrigated daily. Water content in the substrate was measured every two weeks using a TDR-sensor to ensure field capacity. The water supply was adjusted if necessary (data not shown). *LDM* and *SDM*, dried at 70 °C for 48 h. and leaf area were determined eight times during the growing season. Again, treatments with maximum *DM* production were selected and used for model validation. Leaf area was determined using a LI-COR Model 3100 Area Meter (Lincoln, NB, USA).

Weather data were collected at both sites. Missing data at the Horst research location were substituted with data from the Sevenum meteorological station (10 km away) until 1994 and from Arcen meteorological station (11 km away) thereafter. The data set of the Boskoop research location was complete.

In some trials, leaf area was determined destructively using a LI-COR Model 3100 Area Meter. However, in other trials *LAI* was estimated non-destructively from light interception measurements at five zenith angles simultaneously, using the LI-COR Model 2000 Plant Canopy Analyzer (Lincoln, NB, USA). *LAI* was calculated from these readings according to Miller (1967). As this LI-COR Plant Canopy Analyzer underestimates *LAI* due to leaf clustering a correction factor was determined in a different trial (not published) (Gower & Norman, 1991; Smith *et al.*, 1993; Stenberg *et al.*, 1994). *LAI* was estimated with the LI-COR Plant Canopy Analyzer on 1-year and 2-year old container grown cuttings of *Thuja occidentalis* 'Brabant' in a plot of twenty plants, arranged at six different planting distances. Measurements were done twice on six plants in the center of the plot, using a 270° view restrictor on a day with a uniform overcast sky. One above canopy measurement was taken and four below canopy measurements, starting at the stem base of the tree and taking the next three measurements at equal distances to half the planting row distance. The six transplants and six larger plants were analyzed afterwards for leaf area with the LI-COR Model 3100 Area Meter. For both measurements, *LAI* was calculated as the average of six plants. A correction factor of 1.58 was found to correct the *LAI* estimated with the LI-COR Model 2000 Plant Canopy Analyzer.

Model validation and sensitivity analysis

Initial *LDM* and initial *SDM* were not measured for trial 2-10. However, initial *ADM* was available for most validation trials and was divided into *iLDM* and *iSDM* according to the average ratio found for trial 1 and 11 (*iLDM* = 0.84 * initial *ADM*). When the initial *ADM* was not available either, the average *iLDM* and *iSDM* of the validation trials was used as initial value (Table 3). On average *iLDM* was 45 g m^{-2} and *iSDM* 8.5 g m^{-2}. When *iBDM* was not known, the average value of 21 g m^{-2} was used.
The sensitivity of predicted total dry mass (calculated as the sum of *LDM*, *SDM* and *BDM*), *LDM*, *LAI* and F_{int} to changes in the model-input parameters was tested for the entire growing period. Mean values for temperature and radiation from the Horst research site from 1994 to 1998 were used in the sensitivity analysis.

A standard situation was defined in which *iLDM* was set at 42 g m^{-2}, *iSDM* at 8 g m^{-2}, *iBDM* at 21 g m^{-2} and *iLAI* at 0.18 m^2 m^{-2}. The assumed plant spacing was 0.5 by 0.4 m. No leaf or root pruning occurred.
The simulation ended on 31 October of the second growing year. The effects of a change in model input parameters were investigated by calculating the relative partial sensitivity of the model output as described by Heuvelink (1999):

$$\frac{\delta O / O}{\delta I / I} \qquad (4)$$

in which $\delta O/O$ is the relative change in model output, and $\delta I/I$ the relative change in the input value or input data.
Sensitivity was calculated as the mean sensitivity to four levels of change in the model input for *RUE*, *SLA*, F_{LDM}, *H*, w_r, *iLDM*, *iLAI* and *TBASE* for crop growth: -10%, -5%, 5% and 10%. For temperature, the sensitivity was calculated as the average sensitivity to changes of -2, -1, 1 and 2 °C.

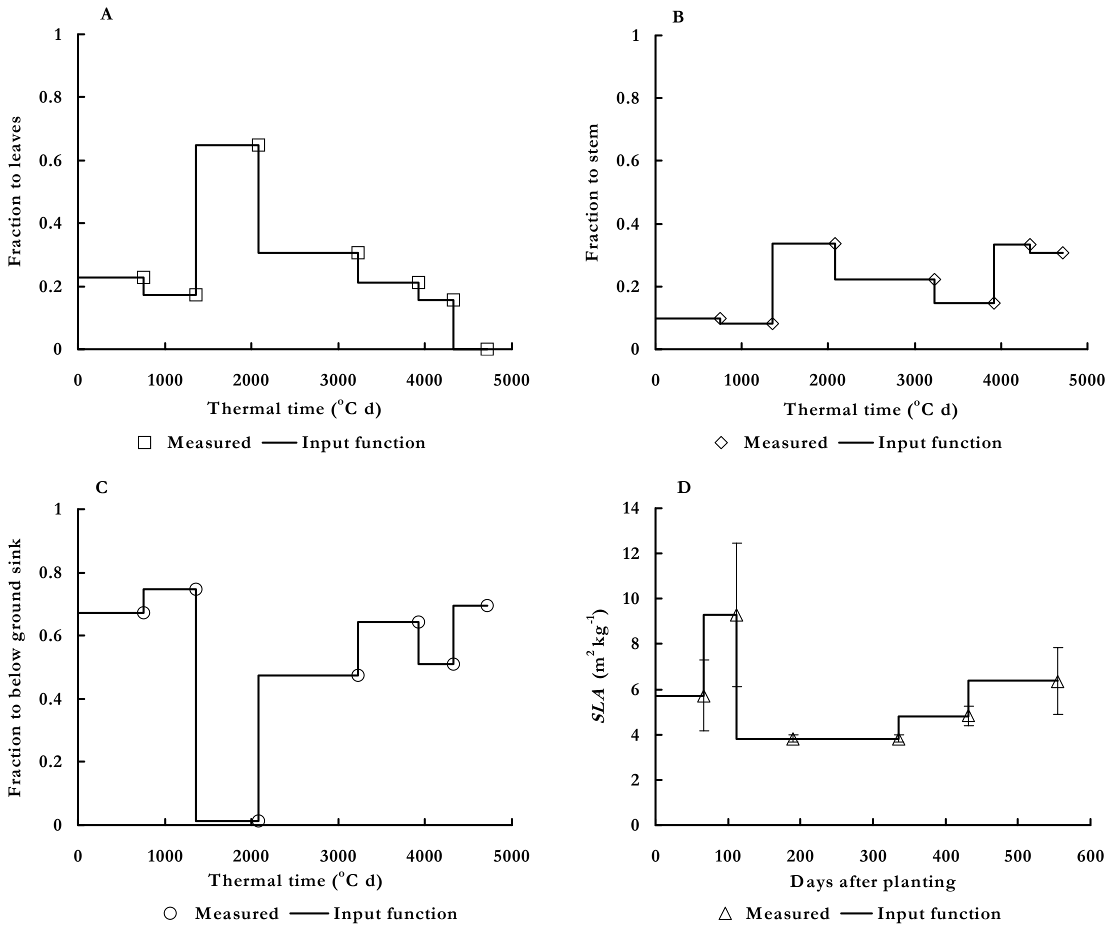

Figure 3. *The partitioning of dry mass produced among the various sinks (leaves (A), stems (B) and roots (C)) as a function of thermal time (ºC d.) after planting (24 April 1998) for Thuja during the two growing seasons and the specific leaf area (D), as a function of the number of days after planting. Increase of thermal time in the second growing season starts at 1 January and is based on the actual daily temperature. Solid lines indicate the relationship used in the model.*

Table 3. *Basic information on trials*[1]

Trial	Crop	Use[2]	Planting day	Distance (m)	Year of measurements	Leaf pruning[3]	Root pruning[3]	Initial *ADM* (g m^{-2})	Initial *BDM* (g m^{-2})	Measurements
1	*Thuja occidentalis* 'Brabant'	C	24 Apr. '98	0.4	1998 & 1999	-	30 Sept.	34	15	3 x *ADM*, 2 x *BDM*, 3 x LA 4 x *ADM*, 1 x *BDM*, 4 x LA
2	*Thuja occidentalis* 'Brabant'	V	15 Apr. '94	0.4	1994	-	-	34	15	final *ADM* + *BDM*, 2 x LI
3	*Thuja plicata* 'Excelsa'	V	11 May '94	0.4	1994	-	-	47	20	final *ADM* + *BDM*, 2 x LI
4	*Thuja occidentalis* 'Brabant'	V	18 Mar. '91	0.3	1991 & 1992	20 May	16 Sept.	38	32	3 x *ADM*, 3 x *BDM*, 1 x LI 2 x *ADM*, 4 x LI in 1992
5	*Thuja plicata* 'Excelsa'	V	25 Mar. '92	0.4	1992 & 1993	20 April	18 Aug.	65	-[4]	6 x *ADM*, 6 x LI in 1992 4 x *ADM*, final *BDM*, 10 x LI in 1993
6	*Thuja occidentalis* 'Brabant'	V	18 Mar. '92	0.45	1992 & 1993	26 May	17 Sept.	52	-	2 x *ADM*, 3 x LI in 1992 final *ADM* + *BDM*, 7 x LI in 1993
7	*Thuja plicata* 'Excelsa'	V	18 Mar. '92	0.4	1992 & 1993	26 May	17 Sept.	52		2 x *ADM*, 3 x LI in 1992 final *ADM* + *BDM*, 7 x LI in 1993
8	*Thuja occidentalis* 'Brabant'	V	1 Apr. '93	0.4	1993 & 1994	-	25 Sept.	-[4]		3 x LI in 1993 final *ADM*, 2 x LI in 1994
9	*Thuja occidentalis* 'Brabant'	V	4 Apr. '96	0.4	1997	-	26 Sept.	-	-	final *ADM* + *BDM*, 1 x LI in 1997
10	*Thuja plicata* 'Atrovirens'	V	23 Apr. '97	0.4	1998	16 June	25 Sept.	-	-	final *LDM* + *SDM* + *BDM*, LA in 1998
11[5]	*Thuja occidentalis* 'Brabant'	V	24 Apr. '99	0.4	1999	-	-	70		5 x *LDM*, 5 x *SDM*, 5 x LA

[1] *Distance = within row planting distance; ADM = Aboveground Dry Mass; LA = Leaf Area, determined with a LI-COR Model 3100 Area Meter (Lincoln, NB, USA), LI = light interception, determined with a LI-COR Model 2000 Plant Canopy Analyzer*

[2] *C = calibration; V = validation*

[3] *Pruning only in second growing year; '-' means no pruning; root pruning 0.2 m below soil surface*

[4] *Not determined. The value of 51 g m^{-2} was used as initial ADM*

[5] *Thuja occidentalis 'Brabant' was grown in 50 L pots in a sandy substrate*

Results

Model calibration

The measured *LDM* and *SDM* in the calibration experiment (trial 1), showed acceptable values for the coefficients of variation (cv): less than 10% (Fig. 4). The measured *iLAI* was 0.12 in trial 1 (Fig. 4D) and increased to a *LAI* of 0.96 at the end of the first growing season. Complete ground cover was obtained only in the course of the second growing season (see w_r, Table 2). The cv of the *LAI* varied between 6% and 10% in 1998 and 5% and 11% in 1999. *SLA* of the new leaves varied between 3.8 and 9.3 m^2 kg^{-1} (Fig. 3D).

The temperature sum to initiate crop growth after planting was 280 ºC d. The discrepancy between the date of the measured plant height increase and the calculated bud burst was less than two weeks.

The measured *TDM* produced at the end of the first growing season was underestimated by the simulated *TDM* generated with *LAI* as an input function by 21.6% (Fig. 4A). Because of the priority to meet aboveground dry mass demand, *LDM* and *SDM* were underestimated by only 3 and 0.2%, respectively, and the subterranean dry mass was underestimated by 46% (Fig. 4C). In September of the second growing season the measured *TDM* was well simulated and less than 3% discrepancies were found for each sink. Simulated *LDM* and *SDM* followed the measured *LDM* and *SDM*, which indicates that the partitioning parameters were calibrated satisfactorily (Fig. 4B).

In the run with simulated *LAI*, through *SLA*, differences between measured and simulated *LDM*, *SDM* and *LAI* at the end of the first growing season were all very small (< 6%, Fig. 4B and D) and increased slightly in the second growing season (8%). The discrepancy between the measured and simulated *TDM* produced at the end of the first year was increased to 24% and to 9.8% at the end of the second year (Fig. 4A).

Model validation

The *ADM* and *LAI* of the validation experiments, trials 2-11 were in the same range as in the calibration experiment, although incidentally the cv for *ADM* measurements was larger (Fig. 5).

The slope of the linear regression relating simulated to measured *ADM* was 1.06 (R^2 = 0.94) and was significant larger than 1 (p<0.001). The standard error of the regression was 149 g m^{-2}. However, the maximum overestimation of the measured *ADM* was 80% (Fig. 5A, trial 3, *ADM* in October, second year) and the maximum underestimation was 47% (trial 4, *ADM* in August, first year).

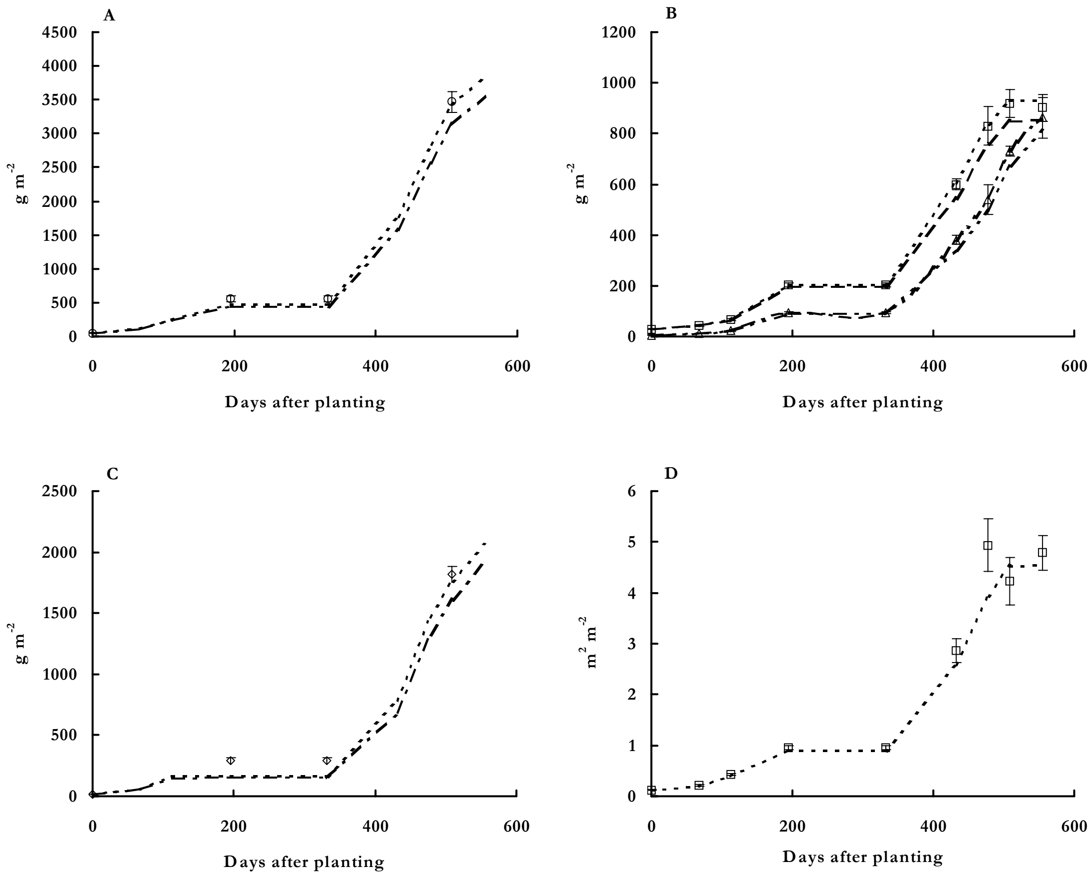

Figure 4. *Measured, simulated with LAI as input function (---), and simulated with simulated LAI (— - —), total dry mass (A, TDM (○)), leaf and stem dry mass (B, LDM (□) and SDM (Δ)), below ground dry mass (C, BDM (◊)) and leaf area index (D, LAI (□) for the calibration trial (1998-1999). Error bars indicate standard error of the means when larger than symbols. If no bars are show, standard error of the means is either smaller than the symbol or single estimates or measurements are presented.*

Measured *BDM* was considerably less than the simulated value in all trials (data not shown). This is not surprising because only the *DM* in the root balls was measured in the validation trials. By root pruning, either in August to induce compact rooting, or a few weeks before harvesting to facilitate hand harvesting, large amounts of *BDM* are lost (Watson & Himelick, 1982).

The slope of the linear regression relating simulated *LAI* to measured or estimated *LAI* was 1.11 (R^2 = 0.90, Fig. 5B), which was significantly larger than 1 (p<0.001). The standard error of the regression was 0.312 m^2 m^{-2}. Maximum overestimation was 84% (trial 7, *LAI* in September, second year) and maximum underestimation was 50% (trial 8, *LAI* in July, first year).

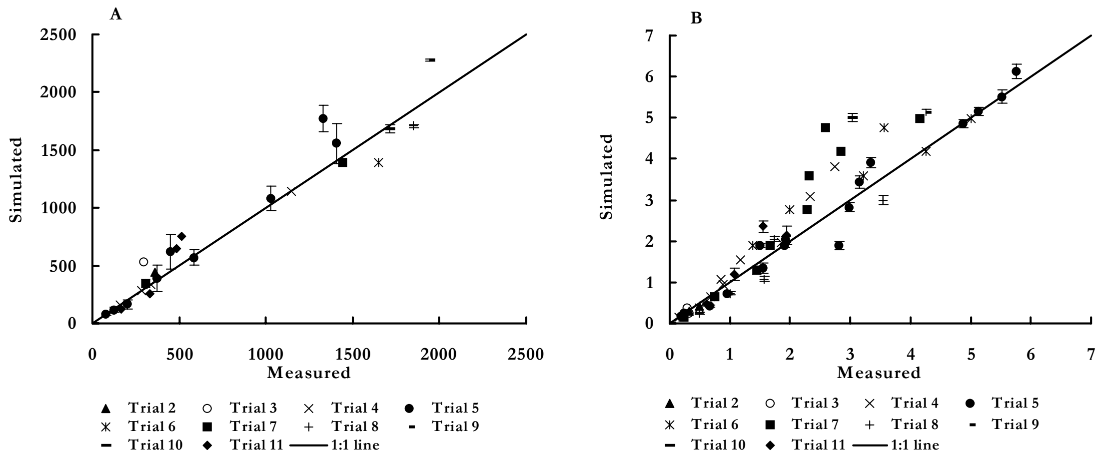

Figure 5. *Measured versus simulated aboveground dry mass (ADM, g m^{-2}) (A, trials 2-11; $y = 1.06x$; $R^2 = 0.94$) and leaf area index (LAI, m^2 m^{-2}) (B, trials 2-11; $y = 1.11x$; $R^2 = 0.90$). Error bars indicate standard error of the means when larger than symbols. If no bars are show, standard error of the means is either smaller than the symbol or single estimates or measurements are presented.*

Sensitivity analysis

The sensitivity analysis showed that *RUE*, *SLA*, F_{LDM} and temperature had a large influence on total dry mass, *LDM* and *LAI*, whereas *iLDM*, *iLAI*, *H*, w_r and *TBASE* were less important (Table 4). In addition, *RUE*, *SLA* and F_{LDM} influenced F_{int} although to less extent.

A higher *iLDM* resulted in a relatively small increase of *TDM* and *LDM* because the absolute amount of the increase was small compared to *TDM* and *LDM* at the end of the simulation period. No effect was found on *LAI* or F_{int}.

A higher *iLAI* resulted in an increased *TDM*, *LDM*, *LAI* and F_{int} to a smaller extent. This positive relationship is explained by the increased interception of radiation, resulting in a higher dry mass production.

A higher *RUE* resulted in a more than proportional increase of *TDM* and *LDM*. In the model, dry mass production is strongly related to *RUE* and a 1% increase of *RUE* resulted in 1.85 and 1.84% increase of *TDM* and *LDM*, respectively. Also, *LAI* increased with 1.85% because in the model *LAI* is directly related to dry mass production. Less but still a considerable effect was found on $F_{int,cub}$, caused by increased *LAI*.

A more than proportional increase of *LAI* was found at higher *SLA*, explained by the direct relationship between *SLA* and *LAI*, and amplified by the positive feedback of a higher *LAI* on a higher $F_{int,cub}$, resulting in a higher dry mass production. The influence of *SLA* on $F_{int,cub}$, *TDM* and *LDM* was smaller (Table 4).

F_{LDM} influenced *TDM*, *LDM* and *LAI* strongly because dry mass partitioned to the leaves increased *LAI* and subsequently $F_{int,cub}$. Subsequently, an increase of $F_{int,cub}$ resulted in more dry mass production.

Table 4. *Simulated Total Dry Mass (TDM, g m^{-2}), Leaf Dry Mass (LDM, g m^{-2}), Leaf Area Index (LAI, m^2 leaf m^{-2} ground) and fraction intercepted photosynthetically active radiation ($F_{int,cub}$) at reference conditions at the end of a simulation over two seasons and the partial sensitivity (%/% or %/°C) of the model output to changes in initial Leaf Dry Mass (iLDM, gm^{-2}) and initial Leaf Area Index (iLAI, m^2 m^{-2}), Radiation Use Efficiency (RUE, g [DM] MJ^{-1} [intercepted PAR]), Specific Leaf Area (SLA, m^2 [leaf] kg^{-1} [LDM]), Fraction of total daily Dry Mass to the Leaves (F_{LDM}), height (H, m), crop width (w_r, m), threshold temperature (TBASE) and temperature (°C).*

	TDM (g m^{-2})	*LDM* (g m^{-2})	*LAI* (m^2 m^{-2})	$F_{int,cub}$ (-)
Reference output	3785	979	4.8	0.87
Partial sensitivities:				
iLDM	0.01	0.04	0.00	0.00
i*LAI*	0.32	0.37	0.40	0.12
RUE	1.85	1.84	1.85	0.57
SLA	0.82	0.83	1.76	0.56
F_{LDM}	0.86	1.82	1.83	0.58
H	0.04	0.05	0.05	0.02
w_r	0.17	0.19	0.19	0.06
TBASE[1]	-0.12	0.25	0.22	0.07
Temperature[1]	0.67	-1.01	-0.85	-0.26

[1] *partial sensitivity to temperature was expressed per 1 °C change instead of per relative change*

A higher and wider plant resulted in slightly higher *TDM*, *LDM* and *LAI* due to an increasing $F_{int,cub}$. The model was not so sensitive to changes in these plant characteristics although crop width had a larger influence than plant height.

TDM decreased at a higher *TBASE* because the growing period was shortened. First, the period to reach the temperature sum for transplanting stress was extended and second, the period to reach bud burst was extended as well. *LDM* increased at a higher *TBASE* because F_{LDM} depends on thermal time (including *TBASE*) and the period with a higher F_{LDM} was lengthened at an increased *TBASE*. Increased *LDM* resulted in increased *LAI*.

The influence of temperature on *TDM*, *LDM*, *LAI* and F_{int} was opposite to that of *TBASE*. Although the effect of temperature was opposite to that of *TBASE*, the relationships of model outputs and temperature are equal to those of model outputs and *TBASE*.

Discussion and conclusions

Despite its simplicity, the model we developed was able to predict dry mass production and *ADM* for field-grown transplants of *Thuja* satisfactorily, by combining the concept of *RUE* with a radiation intercepting function for non-continuous row crops and *SLA*. However, comparable cropping systems were used for model development and validation. Although this may constrain general use of the model, the cropping system used to calibrate and validate the model is widely practised throughout the Netherlands.

LAI was overestimated by 11% by the model (Fig. 5B) although the standard error of the regression was only 0.312 m^2 m^{-2}. However, incidentally discrepancies of 80% were found. A discrepancy in predicted *LAI* is mostly found between a *LAI* of 2 and 4. First, leaf pruning is not included and may cause discrepancies during May and June of the second year. Second, leaf material turns into stem mass and that process is not explicitly included in the model. Changes in *LAI* are induced only by *SLA* and dry mass partitioned to the leaves and not by complicated physiological processes of lignification of leaf material.

The shortage of *TDM* produced at the end of the first growing season may be due to an underestimation of *RUE* in the first year. Measured *LDM* and *SDM* increase in the first year show an exponential increase during the first 150 days after planting followed by a linear increase (Fig. 4B). However, one single value of *RUE* was used in view of the high correlation between intercepted radiation and *ADM* (Fig. 2). Partitioning of *DM* the below ground parts varied between 24 to 68% (Ågren *et al.*, 1980; Pregitzer *et al.*, 1990). Especially the subterranean sink is difficult to determine for field-grown crops (Fogel, 1983). Our partitioning parameter complies with the values of Ågren *et al.* (1980) and Pregitzet *et al.* (1990).

The model output is strongly influenced by *RUE* (Table 4). Many different units are used for *RUE* (intercepted versus absorbed, solar versus *PAR*, growing season versus entire year) and *RUE* is calibrated for various organs, shoots, total biomass or grain yield for example. In our model, *RUE* is used during the growing season only. These values are in agreement with values found for coniferous forests when values are adjusted to comparable units (growing period, plant parts) (Bartelink, 1998b; Landsberg *et al.*, 1997). *RUE* of agricultural crops varies between 1.09 and 4.41 g MJ^{-1} intercepted *PAR* for shoots (Sinclair & Muchow, 1999). Our *RUE* for shoots was in line with these findings. The increase of *RUE* to include below ground parts in our trial is larger than the increase found for agricultural crops, suggesting that *Thuja* partitioned more dry mass to the below ground sink than arable crops do. *RUE* is known to depend on seasonal variations (Sinclair & Muchow, 1999). It may differ considerably during establishment of the crop and during seed growth. However, *RUE* is relatively constant during the vegetative stage that we investigated. In addition, *RUE* of herbaceous tree species was found relatively constant during the growing season (Baldocchi *et al.*, 1987; Cannell *et al.*, 1987).

The model was most sensitive to changes in partitioning coefficients and *SLA*. This demonstrates the importance of accurate prediction of these parameters. Indeed, many crop growth models are sensitive to *SLA* (e.g. Heuvelink, 1999). *SLA* depends on many factors, e.g. light intensity, temperature and nutrient status of the crop, but no such validated relationships are available for *Thuja* and therefore the present simple approach was used.

An adequate estimate of *LAI* is most important for crop water use and light interception. This simple crop growth model CONGRO for field-grown ornamental conifers under potential growing conditions provides a good estimate on *LAI*, light interception and dry mass production. This model is the first successful step in the development of a decision support model for growers to optimize water and nutrient use and to minimize environmental impact in nursery stock production.

CHAPTER 4

Development of fine and coarse roots of *Thuja occidentalis* 'Brabant' in non-irrigated and drip-irrigated field plots

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Abstract

Aboveground dry mass, total root dry mass and root length density of the fine roots of *Thuja occidentalis* 'Brabant' were determined under non and drip-irrigated field conditions. Two-dimensional diffusion parameters for dynamic root growth were estimated based on dry mass production of the fine roots and the concept of the convective-diffusion model of cylindrical root growth and proliferation. Drip irrigation increased aboveground dry mass and the shoot:root ratio compared with no irrigation. Dry mass of the coarse roots increased as well due to drip irrigation. No effect on total or fine root dry mass was found. Drip irrigation increased root length densities in the top 0.1 m but not significantly. However, drip irrigation decreased root proliferation in depth by 27%, whereas proliferation in the horizontal direction was not altered. Measured root length densities were overestimated by 6 to 21% by the model ($0.68 < R^2 < 0.92$).

Keywords: diffusion parameters, eastern white cedar, root length density, root growth and proliferation, shoot:root ratio

† Deceased

Introduction

Drip irrigation is used on sandy soils to overcome water shortage in field-grown nursery stock and increases growth of short turn nursery stock (Pronk & Ravesloot, 1998). The amount of water that needs to be applied by drip irrigation depends on factors including weather conditions, soil type and on the cropping system. Excessive irrigation may lead to leaching of nitrogen and subsequent pollution of groundwater (Pionke *et al.*, 1990), whereas too little irrigation or no irrigation could reduce crop growth. The pressure on growers of field-grown nursery stock to develop advanced irrigation strategies to minimize leaching on sandy soils has increased recently by local authorities. Many different techniques for irrigation and water saving strategies are being developed for horticultural field crops to avoid excessive or sub-optimal irrigation (Petersen & Hill, 1985; Ponder *et al.*, 1984; Schuch & Burger, 1997). One of the approaches is the development of decision support models to improve water use efficiency (Heerman *et al.*, 1990). Besides information on crop growth, leaf area increase, transpiration rates, evaporation rates, weather conditions and soil type, uptake of water and nutrients by a growing root system is an important component of such decision support models. Root water uptake and drip irrigation applications induce water gradients within the soil profile with soil moisture tension as result. Changing root systems during the growing season complicate the estimate on soil moisture tension in the rooted area. Soil moisture tension plays a key role in the moment of irrigation (Parchomchuk *et al.*, 1997) whereas actual rooting depth provides information on the actual amount of application to prevent leaching. Modeling of growth and activities of root systems however, is complicated and therefore often simplified to one-dimensional representations of the root system (Jones *et al.*, 1991; Van Noordwijk *et al.*, 1985). One-dimensional continuum root growth models are however, less suitable when looking at drip-irrigated systems because the observed strong horizontal water flow patterns near the emitter on sandy substrates (Heinen, 1997) are almost imperative to include in the models. In addition, one-dimensional continuum root growth models are less suitable when looking at crops grown in rows (Klepper & Rickman, 1990; Timlin *et al.*, 1992). Trees are widely spaced in rows in field-grown nursery stock and one emitter is positioned near the stem. This system may even need a cylindrical approach as irrigation is applied at one point only and water distribution occurs in three dimensions.

A relatively simple two-dimensional convective-diffusion model of root growth and proliferation was recently proposed by Acock and Pachepsky (Acock & Pachepsky, 1996). Their study indicated that the complex approach, in which root proliferation was viewed as a result of a diffusion-like gradient-driven propagation in all directions and convective-like propagation downwards due to geotropism, could be simplified as no geotropic trend in root development had to be considered. Little information is available on both root growth and root distribution of short-term field-grown coniferous nursery stock. Some data are available on fine root distribution of coniferous forests (Bowen, 1984; Olsthoorn, 1991; Olsthoorn & Tiktak, 1991), indicating that root length densities of the fine roots are lower than commonly found with agricultural crops (De Willigen & Van Noordwijk, 1987). Total root growth of *Gardenia jasminoides* 'Ellis' and the fine root concentration in the 0-20 cm layer was

increased by trickle irrigation (Ponder *et al.*, 1984). Torreano & Morris (1998) found that under dry conditions, less fine roots of half sibs of *Pinus taeda* L. are localized in the dry areas (the top layer) and increased fine root concentrations were found deeper in the soil profile. For well-established fruit trees, irrigation leads to increased root growth (Atkinson *et al.*, 1980) and terminated irrigation reduces fine root concentrations in the top soil (Espeleta & Eissenstat, 1998).
However, these data are generally insufficient to predict root growth and root distribution under different irrigation strategies in short term field-grown conifers. The purpose of this study was therefore to quantify root growth patterns as related to irrigation strategies. Therefore, we designed a field trial including two irrigation strategies (no irrigation and drip irrigation, respectively) and determined root dry mass (total below ground biomass) and fine root distribution of field grown *Thuja occidentalis* 'Brabant' (eastern white cedar) at different moments in a two-year growing cycle. The data of this trial were then used to obtain root diffusion parameters for a model based on the concept of the convective-diffusion model of two-dimensional root growth and proliferation (Acock & Pachepsky, 1996). These parameters were then used to explore effects of drip irrigation on root distributions.

Theory on two-dimensional root growth

Acock and Pachevsky (Acock & Pachepsky, 1996) described root growth as a convective–diffusive process in which the flux of root mass density $\bar{q}$ (kg m^{-2} day^{-1}) is given as:

$$\bar{q} = -D\nabla Y + \bar{g}Y \tag{1}$$

where Y (kg [dry mass] m^{-3} [soil]) is the root mass density of the fine roots (diameter < 0.2 cm) and D the root diffusion coefficient with components in the x, y and z directions (m^2 day^{-1}). The convective term ($\bar{g}\,Y$; m day^{-1}) acts in the vertical direction only and accounts for possible geotropic effects. Using data from Chen & Lieth (1993) on root development of potted chrysanthemum plants, Acock and Pachepsky (Acock & Pachepsky, 1996) concluded that there is no geotropic trend in root development. Furthermore, they concluded that the diffusion coefficients did not depend on root density. Here we will consider root proliferation as a diffusion process without geotropy and with a first-order decay rate. The soil surface area is therefore divided into circles with one circle per tree. The diameter of the circle was half the planting row distance (0.25 m). The rooting area is confined to the cylindrical volume below the circle with a know depth (0.35 m). It is therefore that the diffusion equation is formulated in cylindrical coordinates in two dimensions:

$$\frac{\partial L_{rv}}{\partial t} = \frac{1}{R} * \frac{\partial}{\partial R}\left(R * D_r \frac{\partial L_{rv}}{\partial R}\right) + \frac{\partial}{\partial Z}\left(D_z * \frac{\partial L_{rv}}{\partial Z}\right) - \Lambda L_{rv} + Q_L f(r,z) \tag{2}$$

where L_{rv} is the root length density of the fine roots (cm cm^{-3}), R the cylindrical coordinate (cm), D_r the diffusion coefficient in the R direction (cm^2 day^{-1}), Z the coordinate related to depth (cm), D_z the diffusion coefficient in the Z direction (cm^2 day^{-1}), Λ (day^{-1}) the decay rate of fine roots and Q_L the growth rate of fine roots at a given location in the root system (cm cm^{-3} day^{-1}). The function $f(r,z)$ describes the spatial distribution of incoming root dry mass. It is 1 at those points where there is input of root dry mass and the value zero elsewhere. There is no flux of roots over the radial or vertical boundaries.

Materials and Methods

Field experiment

A field trial was carried out on a sandy siliceous mesic udic Plaggept (Soil Conservation Service, 1975) at the experimental location within the Dutch cropping area of ornamental conifers at Horst (lat. 51°25'N, long. 06°05'E), the Netherlands. Uniform container-grown one-year-old rooted cuttings of *Thuja occidentalis* 'Brabant' (called transplants further on) were planted on beds in April 1998 (three rows per bed; row distance: 0.5 m; inter row distance: 0.4 m and width of the beds: 1.7 m) for a two-year growing period. Treatments included no irrigation and drip irrigation at a rate of 0.5 L of water per plant per day starting mid May for 90 days in 1998 and 1999. The treatments were randomized in a complete block design (4 blocks). On-site weather data were collected throughout the experiment. Aboveground and root dry mass, root length density and root diameter were measured just before planting on 6 randomly selected transplants by cutting the transplants at the soil surface. The entire root system per transplant (container volume: 810 ml) was cleaned carefully with tap water. The cleaned roots were then divided in fine (diameter <0.2 cm) and coarse (diameter >0.2 cm) root fractions by visual assessment and stored at -18 ºC for further analysis. The total root length of the fine roots of the entire root system of the 6 transplants was estimated using the modified Newman line intersect method (Oliveira M. do Rosario *et al.*, 2000; Tennant, 1975). The roots were then evenly distributed on a glass plate and placed under binoculars with a calibrated mm ocular. Root diameter of 50 randomly selected roots of each plant was measured and averaged.

The same numerical method for the total dry mass of the coarse roots per plant was used. Dry mass of the aboveground parts was determined after drying at 70 ºC for 48 hours; dry mass of the fine and coarse roots was determined after drying at 105 ºC for 48 hours. Dry mass of shoots was determined at 70 ºC to enable nutrient analysis afterwards. The root length density (L_{rv}) of these 6 transplants was calculated as the total length per plant divided by the soil volume of the container and used as the initial condition in the calculations.

At the end of the first growing season (early November 1998), aboveground dry mass and L_{rv} of the fine roots were determined of 4 plants in the non-irrigated and 4 plants

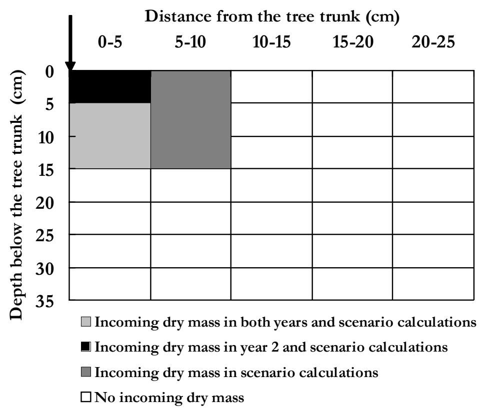

Figure 1. The position of the incoming daily dry mass as used in the fitting program. The shaded areas indicate incoming daily dry mass in the first or second growing season.

in the drip-irrigated treatment. The pinboard technique was used to sample the roots (Boehm, 1979; Oliveira M. do Rosario *et al.*, 2000; Schuurman & Goedewaagen, 1971). A soil pit of approximately 1.0 to 0.7 to 0.7 m^3 was dug just outside the sampling location in the treatment perpendicular to the rows. The profile wall was smoothened at the stem base of two trees. The pinboard (0.50 to 0.40 m with pins in a 0.05 m grid and 0.10 m in length) was placed vertically with the pins against the profile face and forced into the soil.

The top row of pins was placed at ground level and included the stem of both trees at either outer corner of the board. The pinboard was cut loose containing some extra cm -soil around all edges of the board. In the laboratory the extra soil and roots were removed and the remaining soil was carefully washed away. At all times surface running by roots was prevented. After washing away the soil, the root system was cut according to the 0.05 to 0.05 m grid and divided in fine and coarse root fractions. The dry mass of the fractions and L_{rv} of the fine roots were determined for every sampled volume as described above. Root diameter was determined on 10 randomly selected roots of 3 sampled volumes per plant and averaged per plant. From the grid samples the total dry mass of the fine roots per plant was calculated. The coefficient of variation was calculated per layer in depth and per layer in the horizontal direction.

Mid September 1999, the aboveground dry mass was determined and a pinboard analysis was taken again of 4 plants per treatment. This time the WinRHIZO system (Release 3.1, Regent Instruments Inc., Quebec, Canada) for image analysis was used to determine total root length and average root diameter of each sampled volume. Dry mass of the aboveground parts and of fine and coarse roots were determined after drying at 70 °C for 48 hours. Total dry mass of the fine and coarse roots was calculated as in 1998.

Table 1. *Precipitation and radiation at the research location during the growing seasons of the experiment and the five-year average.*

	Precipitation (mm month^{-1})			Radiation (MJ month^{-1})		
Month	1998	1999	1993-1997	1998	1999	1993-1997
May	27	68	67	534	554	507
June	112	58	51	477	571	556
July	64	71	52	447	651	546
August	67	95	67	477	451	482
Total	270	292	236	1930	2227	2095

During the growing period, soil moisture tension was measured regularly with four tensiometers in both treatments. All tensiometers were placed at 0.15 m depth. Two tensiometers per treatment were placed directly below and two 0.25 m beside (half the planting row distance) the tree to follow the soil moisture conditions within the rooting area. Plant available water was 20% calculated from the drying (15.8 (12%) - 10 (32%) kPa) and 10% calculated from the wetting (15.8 (6%) - 10 (16%) kPa) water retention curve.

Fitting root growth parameters

A parameter fit program was developed to fit some or all of the parameters D_r, D_z, Λ and Q_L of Eq. 2 (De Willigen *et al.*, 2002). Q_L was calculated from the measured dry mass increase of the fine roots M_r (g cm^{-3} day^{-1}) by:

$$Q_L = \frac{M_r}{\left(\pi * R_0^{\ 2} * \rho_r * d_r\right)} \tag{3}$$

where R_0 is the measured root radius (Table 2), ρ_r the assumed root mass bulk density of 1 g cm^{-3} and d_r is the percentage dry mass of roots (11%; (Barrs, 1968)). For each year and treatment Q_L was calculated. The fitting period in 1998 was 150 days. Bud burst initiated crop growth in the second growing season at a temperature sum of 220 °C d starting on 1 January with a threshold value of 4.4 °C (Thomson & Moncrieff, 1982), resulting in a fitting period of 172 days in 1999. Q_L was forced as a constant input parameter in the fit program during the fitting period.
Input of root dry mass occurred only at the main stem at 5-10 and 10-15 cm depth in 1998 and 0-5, 5-10 and 10-15 cm depth in 1999 (Fig. 1).
As mentioned earlier, extension of the root system is described as a diffusion process. Growth of roots with a diameter larger then 0.2 cm was not considered in this approach as we were interested in water and nutrient uptake and less in root architecture.

Table 2. Results of the statistical analysis at a 5% LSD level of total root dry mass (below), dry mass of fine (fine) and coarse (coarse) roots, total aboveground dry mass (above) and the root diameter (RD).

Year	Treatment	Root properties below (g plant^{-1})	 fine (g plant^{-1})	 coarse (g plant^{-1})	 above (g plant^{-1})	 *RD* (cm)
1998	Starting material[1]	3.0	2.0	1.0	6.7	0.055
"	No irrigation[2]	34.7 a	15.6 a	19.0 a	40.9 a	0.061 a
"	Drip irrigation	34.6 a	14.8 a	20.0 a	34.0 a	0.063 a
1999	No irrigation	346.6 b	309.7 b	36.9 b	246.4 b	0.079 b
"	Drip irrigation	363.2 b	292.7 b	70.5 c	330.2 c	0.074 b
LSD		30.2	20.0	22.8	60.1	-[3]

[1] *Starting material (n = 6) was not included in the statistical analysis*
[2] *Analysis are done on 4 plants per treatment in 1998 and 1999*
[3] *No LSD is given because the analysis is done on transformed data to ensure a normal distribution of the residuals*

Statistical analysis

Total root dry mass was calculated by adding the dry mass of the fine and the coarse roots. Total aboveground dry mass, root dry mass, dry mass of the fine and coarse roots and root diameter were analysed with an analysis of variance with the statistical program GENSTAT 5, release 4.1. The fitted diffusion parameters and the calculated root growth rates of the fine roots (Q_L) were also analysed with an analysis of variance. A data transformation was used (1/(parameter+1)) if necessary to ensure a normal distribution of the residuals.

Results

Field experiment

Precipitation in 1998 was low in May and high in June (Table 1). Global radiation was 15% lower during the wet period in June than the five-year average. In July and August weather conditions were close to the five-year average. No differences between treatments were found in soil moisture tension for most of the growing season due to the low water demand of the transplanted crop (small plants, low leaf area index) and the wet cloudy weather in June (Fig. 2A). Only during a sunny and relatively dry period that lasted from August 5 to August 20, differences in soil moisture tension were found (Fig. 2A). There were no differences in total root dry mass and fine or coarse root dry mass between the non-irrigated and drip-irrigated treatments that year (Table 2).

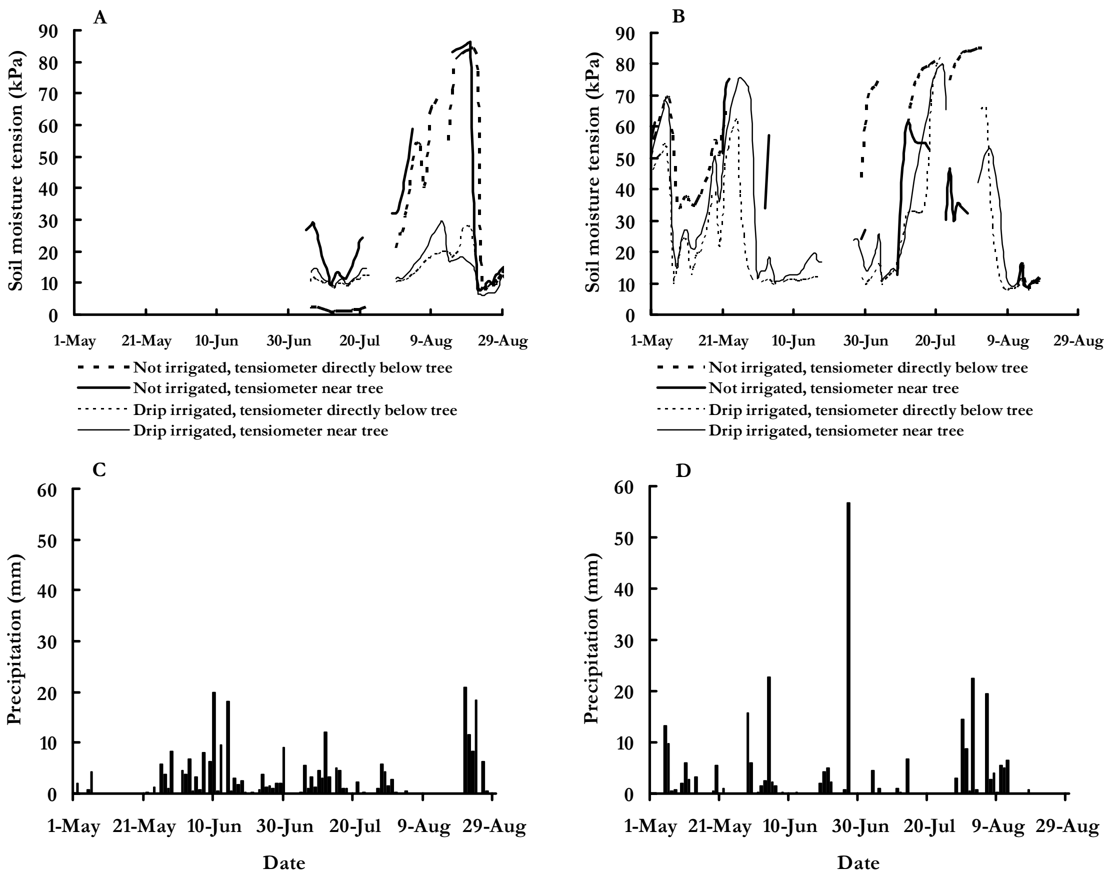

Figure 2. Soil moisture tension at 0.15 m depth directly below and beside the tree trunk in 1998 (A) and 1999 (B) and daily precipitation of 1998 (C) and 1999 (D). Missing data indicate high suctions as tensiometers have difficulties to sustain pressure heads in the tubes at suctions of 75 kPa and higher.

The weather conditions in 1999 were in line with the five-year average (Table 1). The larger plants in the second growing season had a higher demand for water. This resulted in differences in soil moisture tensions (wet and dry conditions) throughout the growing season although the drip-irrigated treatment had high soil moisture tensions at times as well (Fig. 2B).

The L_{rv} of the treatments in 1998 showed similar growth patterns (Fig. 3A and B). L_{rv} increased slightly with depth over the first 15 cm and decreased soon after. No roots were found deeper than 25 cm after the first year. In that year, hardly any roots were found at 5-10 cm from the tree trunk. The L_{rv} in 1999 was larger compared with 1998, especially in the top 15 cm (Fig. 3A and C). The highest root concentration was found in the top 5 cm of the irrigated treatment. Except from the top 5 cm, the same growth patterns for the non and drip-irrigated treatments were found: L_{rv} in the top layer was high and is sharply decreased towards 20 cm depth. There were hardly any roots present below 30 cm.

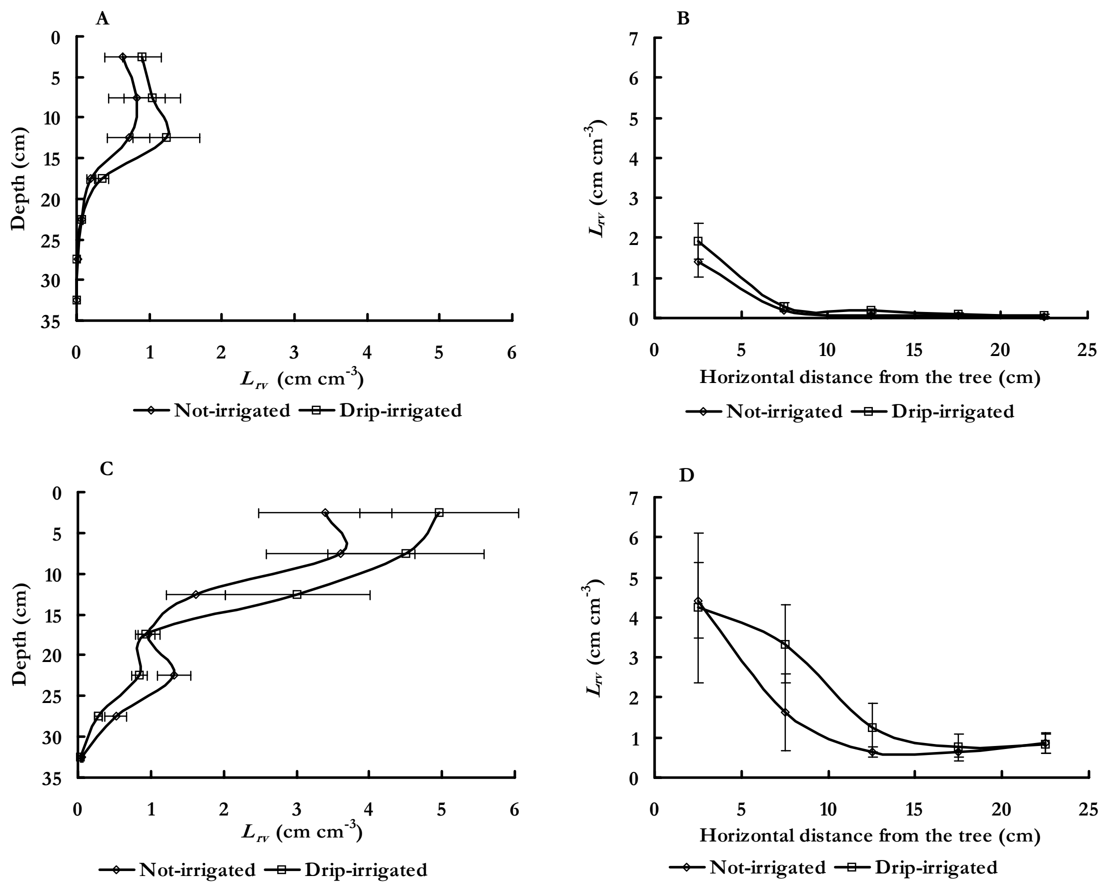

Figure 3. *Root length density (L_{rv}) distribution at different depths in 1998 (A); L_{rv} distribution at horizontal distance from the tree trunk in 1998 (B); L_{rv} distribution at different depths in 1999 (C); and L_{rv} distribution at horizontal distance from the tree trunk in 1999 (D). Error bars indicate standard error of means.*

A higher concentration of roots (not significant) was found at 5-10 cm distance from the trunk in the drip-irrigated treatment in 1999 compared with the non-irrigated treatment. The coefficients of variation of the L_{rv} ranged from 11 to 47%.

Dry mass production, root diameter and statistical analysis

Total root dry mass and fine root dry mass were not affected by drip irrigation in 1998 and 1999 (Table 2). However, a significant increase in total root dry mass and fine root dry mass over the years was found. In 1999, coarse root dry mass was larger in the drip-irrigated treatment. The total aboveground dry mass was largest for the non-irrigated treatment in 1998 (Table 2) but not significantly different from the drip-irrigated treatment in that year. However, the shoot:total root dry mass ratio in 1998 of the non-irrigated treatment was significant larger than the drip-irrigated treatment in that year (Table 3). This ratio decreased significantly in 1999 under dry conditions whereas it did not change in the drip-irrigated treatment over the two years.

Table 3. *Results of statistical analysis of the ratios between aboveground dry mass (above) and total root dry mass (below), fine (fine) and coarse root dry mass (coarse).*

		Ratio's		
Year	Treatment	above:below (g g^{-1})	above:fine (g g^{-1})	above:coarse (g g^{-1})
1998	Starting material[1]	2.25	3.32	6.98
"	No irrigation[2]	1.18 c	2.60 c	2.22 a
"	Drip irrigation	0.98 b	2.40 c	1.71 a
1999	No irrigation	0.70 a	0.79 a	6.94 b
"	Drip irrigation	0.92 b	1.13 b	5.16 b
LSD		0.1803	-[3]	1.703

[1] *Starting material (n = 6) was not included in the statistical analysis*
[2] *Analysis are done on 4 plants per treatment in 1998 and 1999*
[3] *No LSD is given because the analysis is done on transformed data to ensure a normal distribution of the residuals*

This decrease was due to a decreased ratio of the shoot:fine root dry mass, caused by a significantly reduced aboveground dry mass production in the non-irrigated treatment in 1999 (Table 2). The shoot:coarse root dry mass ratio did not change between treatments. The root diameter decreased over time, but did not differ between treatments (Table 2).

Root growth parameters and statistical analysis

There was no effect of drip irrigation on Q_L in both years (Table 4). However, Q_L was larger in the second growing year compared with the first year. The same results were found for D_r: no effect of drip irrigation but an increase in the second growing year. Drip irrigation however, did affect D_z in the second growing year. The estimated diffusion parameter in the vertical direction was 3.6 times larger in the non-irrigated treatment (Table 4). In addition, less fine roots were found in the top 10 cm with the non-irrigated treatment (Fig. 3C). The decay rates were low (Table 4), which is consistent with our assumption. The measured L_{rv} was underestimated by 6 to 21% by the model with the fitted diffusion parameters (Fig. 4).

Table 4. The mean root growth rate of the fine roots (Q_L) and the estimated convective diffusion parameters for two-dimensional root growth of fine roots: diffusion coefficient in the horizontal direction (D_r), in the vertical direction (D_z) and a constant decay rate (Λ).

Year	Treatment	Q_L (g cm^{-3} day^{-1})	D_r (cm^2 day^{-1})	D_z (cm^2 day^{-1})	Λ (day^{-1})
1998	No irrigation	0.0290 a	0.4139 a	0.7796 a	0.0405 a
"	Drip irrigation	0.0209 a	0.2540 a	0.5490 a	0.0213 b
1999	No irrigation	0.3230 b	3.6721 b	4.3294 b	0.0727 a
"	Drip irrigation	0.3507 b	5.0700 b	1.1640 a	0.0335 b
LSD		-[1]	2.105	-[1]	-[1]

[1] *No LSD is given because the analysis is done on transformed data to ensure a normal distribution of the residuals*

Discussion

The weather is an important factor when irrigation is investigated in field-grown crops in the moderate climatic zone. Because the transpiration need of small plants is low and precipitation was evenly distributed in 1998 (Fig. 2A and C), hardly any differences in soil moisture tension have been realised and as a result no differences in aboveground dry mass, root dry mass or L_{rv} related to the treatments were found. This confirms that irrigation, depending on crop stage and the weather conditions, is not always an important factor for optimal crop production. When irrigation is applied regardless of the weather conditions nutrient losses to the environment may become a problem.

We found differences in soil moisture tension in 1999 (Fig. 2B); hence the application rate of 0.5 L per plant per day was not enough to ensure field capacity during the growing season and may have limited potential crop growth.

In 1998 there were no differences in total aboveground or total root dry mass. However, total aboveground dry mass was reduced significantly in the non-irrigated treatment in 1999, whereas total root dry mass was not (Table 2).

This resulted in a decreased shoot:total root dry mass and that is commonly found for water stressed crops (Klepper, 1990). Less root dry mass was also found in the coarse roots in the non-irrigated treatment and more (albeit not significant) dry mass in the fine roots, suggesting an increased water uptake capacity. To evaluate effects of drought stress it may be of more interest to investigate the shoot:fine root dry mass ratio as suggested by Cannell (1985), because water stress is more likely to have a major effect on fine root longevity, productivity and distribution (Ponder *et al.*, 1984; Reynolds, 1974; Torreano & Morris, 1998). In addition, fine roots occupy a key position in water uptake due to their large contribution to total root length (Bowen, 1985).

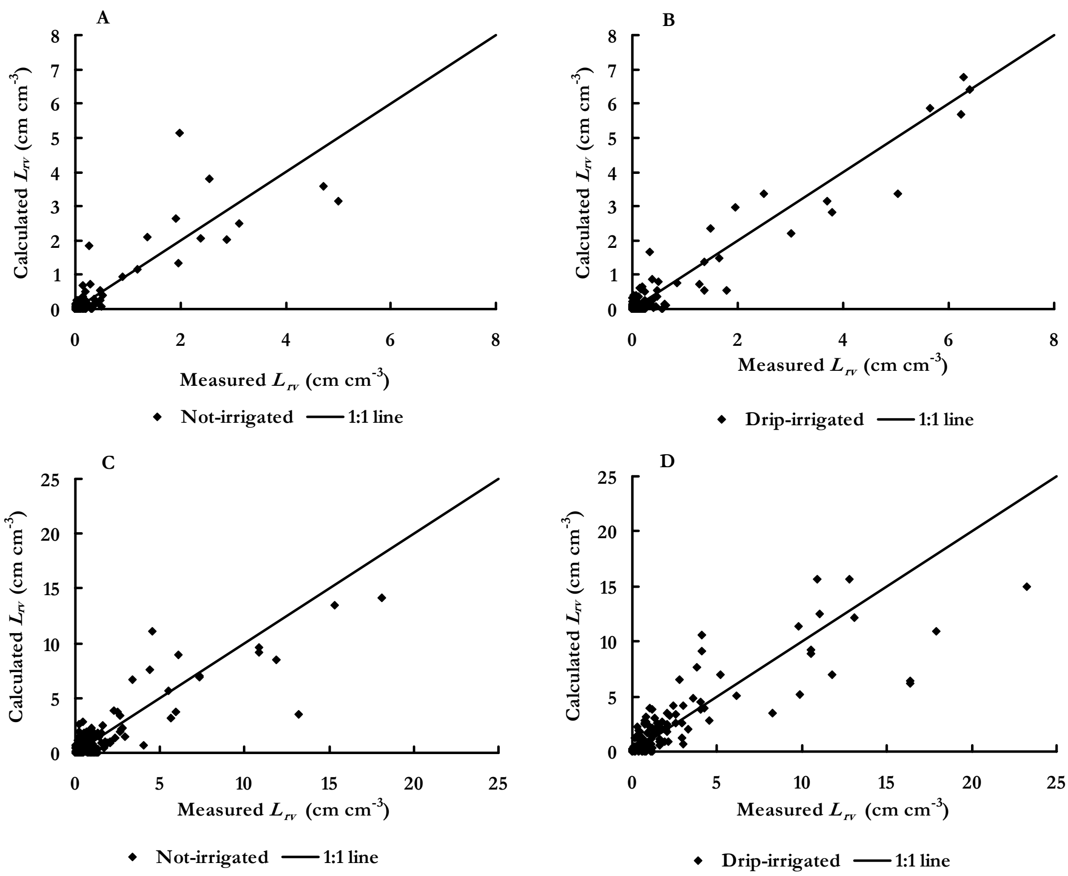

Figure 4. Measured versus calculated root length density (L_{rv}) for A: 1998 ($R^2 = 0.79$, $y = 0.81x$); B: 1998 ($R^2 = 0.93$, $y = 0.94x$); C: 1999 ($R^2 = 0.75$, $y = 0.81x$); D: 1999 ($R^2 = 0.68$, $y = 0.79x$).

Besides a slight increase in fine root dry mass in the non-irrigated treatment in 1999, we found a lower L_{rv} in the top 10 cm of the profile of that treatment (Fig. 3). This result is in agreement with findings of Torreano & Morris (1998) for transplanted half sibs of *Pinus taeda* L. and that of Ponder *et al.* (1984) for transplanted one-year-old rooted cuttings of *Gardenia jasminoides* 'Ellis'. Similar results have been reported for agricultural crops (Blum & Arkin, 1984; Klepper *et al.*, 1973). Less roots in the dry top layer is likely to be a result of an increased decay in that layer (Espeleta and Eissenstat, 1998; Klepper, 1990).
The coefficient of variation (cv) of L_{rv} is relatively low compared with cv's of L_{rv} found by Olsthoorn for Douglas-fir on sandy soils (1991) which varied between 48 and 304% and Van Noordwijk *et al*, (1985) for established grassland (31-56%) and oats (27- 63%). Using the fitted diffusion parameters, the model underestimated measured L_{rv} by 6% for the drip-irrigated treatment in 1998 and by 21% for the same treatment in 1999 (Fig. 4). The model predicts a continuous, approximately exponential decrease with distance from the location where the input of roots takes place (where $f(r,z) = 1$), in our case just below the tree trunk (Fig. 1). We found, however, that L_{rv} at 0-5 and 5-10 cm beside the tree trunk in the drip-irrigated treatment were comparable in 1999 (Fig. 3D).

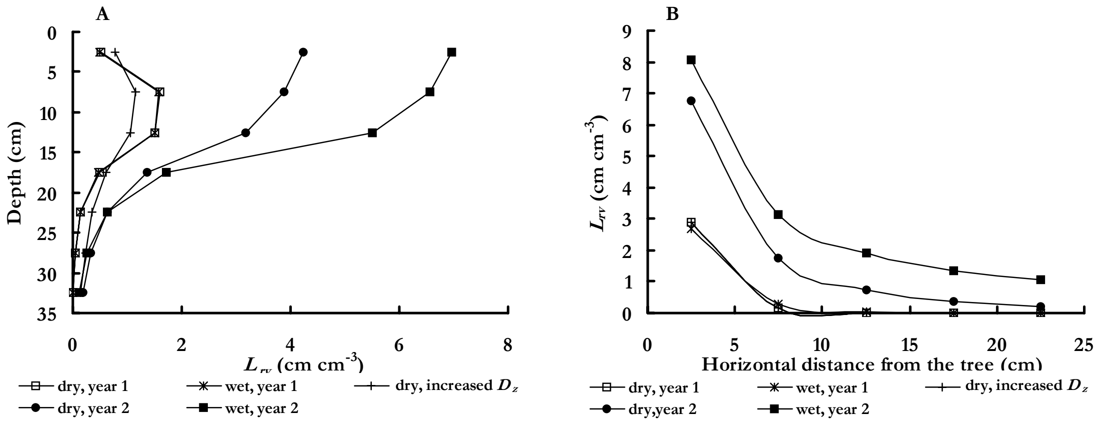

Figure 5. Calculated effects of dry or wet conditions on root length density distribution and different values of the function f(r,z) for incoming dry mass. A: Root length density distribution in depth; B: Root length density distribution at different horizontal distances of the tree.

The increase of the coarse root system in 1999 compared with 1998 (drip-irrigated treatment), suggested that dry mass did not enter the root system at the initial location only, as assumed in the model, but also through the coarse root system at 5-10 cm distance from the initial location. Acock and Pachepsky (Acock & Pachepsky, 1996) included two classes of roots in their theoretical approach: young and mature roots. In the model validation they used one class of roots: young roots. Although no explicit definition was given on 'young' and 'mature', for woody plants it is commonly interpreted as young roots having a root diameter < 0.2 cm and mature roots a diameter > 0.2 cm. Mature roots (>0.2 cm in diameter) were not included in our approach. We are only interested in the water and nutrient uptake of the root system and we did not measure root length density of the mature roots as they contribute little to total root length.

We used the model to explore effects of dry conditions on root growth by transplants. To do so, we increased D_z in the first year by 3.6 times. A small effect was found on L_{rv} in relation to depth: at dry conditions there were less roots at 5-10 and 10-15 cm and L_{rv} increased at the deeper layers compared to the drip-irrigated treatment (Fig. 5A). The increased D_z did not affect the distribution in the horizontal distance from the tree (Fig. 5B) nor the total L_{rv}. The initial L_{rv} distribution has no effect on the L_{rv} distribution at the end of the growing period (see Eq. 2).

A dry season followed by a wet season has the same L_{rv} distribution at the end of the second year as a wet season followed by a wet one. L_{rv} is only affected by the growth rate of the fine roots, the diffusion parameters and the function $f(r,z)$.

The effect of $f(r,z)$ on the L_{rv} was explored by increasing the number of locations of incoming dry mass in the second year, r = 1 and 2 and z = 1, 2 and 3 (Fig. 1). L_{rv} calculated in this way decreased similar with increasing distance from the tree trunk as was measured for the drip-irrigated treatment (compare Fig. 3D and Fig. 5B). A better agreement was found between calculated and measured L_{rv} for the drip-irrigated treatment (R^2 = 0.81; y = 0.85x) and less agreement was found for the non-irrigated treatment (R^2 = 0.74; y = 0.77x). Drip irrigation stimulates coarse root development, most likely also at a larger distance from the tree trunk. That may explain the better fit between calculated and measured L_{rv} for the drip-irrigated treatment.

Drip irrigation had an effect on root growth and proliferation of short-term field-grown *Thuja*. The convective-diffusion model described this effect satisfactorily during a two-year growing period. Implementing these root diffusion parameters in decision support models will help to improve the effectiveness of irrigation and minimize leaching in short term field-grown conifers.

Acknowledgement

We would like to thank Gerard Brouwer from Plant Research International for his help with root sampling and his support with data analysis and Marius Heinen from Alterra Green World Research for his critical remarks on the model application.

CHAPTER 5

Dry mass production and water use of non and drip-irrigated *Thuja occidentalis* 'Brabant': field experiments and modeling

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Plant and Soil (in press)

Abstract

Generally, irrigation increases dry mass production (*DM*) on sandy soils of horticultural crops and at the same time increases the risk of percolation losses of water and chemicals to below the root zone. However, the effects of irrigation are highly site-specific and not easily determined, which hampers the development of proper management tools and guidelines. A two-dimensional soil-water balance model combined with a crop growth model was parameterized and validated, and used to investigate *DM* and water use of *Thuja occidentalis* 'Brabant' in a field trial under non- and drip-irrigated conditions. Measured leaf *DM* and leaf area index (*LAI*) were not affected by irrigation but irrigation increased stem *DM* and the specific leaf area. Simulated *DM* and *LAI* were in good agreement with the measurements. Simulated pressure head followed the measured pressure head, although model's performance was better under dry than under wet conditions. Simulation experiments indicated that increasing irrigation threshold levels increased *DM* production and leaching relatively to no irrigation, when the irrigation threshold level was measured at 0.25 m depth.

Keywords: conifer growth model, decision support tool, eastern white cedar, sandy soil, two-dimensional soil water model

† Deceased

Introduction

On sandy soils, dry mass production of many agricultural crops is often reduced by the limited amount of water in the root environment. In general, irrigation increases dry mass production. Field-grown nursery stock production can also benefit from irrigation as shown by Ponder *et al.* (1984), Hornig *et al.* (1997) and Pronk & Ravesloot (1998). Especially drip irrigation was found to improve dry mass production of several field-grown nursery stock crops (Pronk & Ravesloot, 1998).

However, irrigation may increase leaching of nitrogen (*N*) on sandy soils (e.g. Pang *et al.*, 1997; Pionke *et al.*, 1990; Sanchez *et al.*, 1994; Smika & Watts, 1978). It is likely that this occurs in field-grown nursery stock as well as when irrigation rates and/or methods are poorly matched to soil conditions and plant requirement. So far, most studies on irrigation strategies of field-grown nursery stock crops focus on dry mass production and on root growth and establishment after transplanting (Gilman *et al.*, 1996; Ponder *et al.*, 1984; Pronk & Ravesloot, 1998). Some studies suggest that leaching is not increased by irrigation, as tensiometer readings did not indicate downward water movement (Averdieck & Bohne, 1994; Hornig *et al.*, 1997). However, in these studies pressure head was measured once a week only, while high-pressure head levels could occur within a week when high precipitation or irrigation rates are intermittently high. Leaching may have occurred within that week. If irrigation strategies are to be evaluated on both increasing dry mass production and leaching, lysimeters may be a better way to evaluate leaching. Alternatively, the pressure head should be calculated in between measurements to estimate leaching, using soil-water balance models. When irrigation strategies have to protect the environment by minimizing the percolation losses of water and chemicals to below the root zone, the combination of crop growth models and soil-water balance models can be a useful tool to evaluate the environmental performance of the various irrigation strategies.

Drip irrigation is common in field-grown nursery stock crops, with one emitter positioned at the stem base of the tree. This application method increases the hydraulic gradient in the soil from the emitter point to the area where no water is applied (Coelho & Or, 1996). To simulate the water dynamics in such drip-irrigated system, two-dimensional or three-dimensional soil-water models are necessary to include the horizontal transport of water (Ahuja & Nielsen, 1949). Combining a two dimensional soil-water balance model with crop growth models enables us to investigate the effect of drip irrigation on dry mass production and water use of the crop, and to develop irrigation strategies, which are efficient and environmentally sustainable.

To investigate dry mass production and water use of the crop under non and drip-irrigated conditions we undertook a field trial and compared dry mass production under dry (no irrigation) and wet (drip irrigation) conditions on a sandy soil with transplants of the ornamental conifer *Thuja occidentalis* 'Brabant'. We monitored pressure head at three depths continuously and used the results to validate the combined model for dry mass production for *Thuja* (CONifer GROwth, Pronk *et al.*, 2003b) with the two-dimensional soil water balance model FUSSIM2 (Heinen, 2001; Heinen & De Willigen, 1998; 2001).

Materials and methods

Model structure

Two models, one to simulate dry mass production of ornamental conifers (CONifer GROwth, Pronk *et al.*, 2003b) and one to simulate the soil water balance (FUSSIM2, Heinen, 2001; Heinen & De Willigen, 1998; 2001), were coupled through a synchronization shell (FSE4, Rappoldt & Van Kraalingen, 2001). This shell allows the models to work independently while synchronizing data exchange. The driving variables (weather data) are known at a daily basis and therefore, communication between the two models occurs once a day. The crop growth model CONGRO simulates daily dry mass production, partitioning of dry mass to the various organs. For the purpose of this study, daily water demand (T_p and E_p, Table 1) was implemented using independent trials and the concept of the water use efficiency (*WUE*). Daily water demand is imposed on the soil water balance model FUSSIM2. For the current water status in the soil, FUSSIM2 estimates the actual water uptake by the plant (T_a) and the actual water loss by evaporation (E_a). After this exchange of model information, the two models compute independently the changes during the day involved. When T_a is less than T_p, the CONGRO model reduces dry mass production by a factor equal to actual water removal divided by demanded water need (T_a/T_p, Van Keulen, 1986). The following subsections briefly summarize the essential characteristics of the two models. A list of abbreviations is included in Table 1.

Dry mass production and leaf area increase

CONGRO simulates potential dry mass of *Thuja occidentalis* 'Brabant' using the concept of a radiation use efficiency and actual weather data (Pronk *et al.*, 2003b; Van Ittersum *et al.*, 2003):

$$\frac{\mathrm{d}DM}{\mathrm{d}t} = F_{int} * RUE * DRT * F_{par} \tag{1}$$

where $\mathrm{d}DM/\mathrm{dt}$ is the crop growth rate (g [DM] m^{-2} d^{-1}), F_{int} is the fraction of photosynthetically active radiation (*PAR*) intercepted by small conifers grown in rows (Pronk *et al.*, 2003a), *RUE* is the radiation use efficiency (g [DM] MJ^{-1} [intercepted PAR]), *DTR* is the daily global radiation (MJ m^{-2} d^{-1}) and F_{par} is the fraction of *PAR* in *DTR* (Table 1).

Dry mass is distributed to leaves, stems, fine (diameter < 0.2 cm) and coarse roots (diameter > 0.2 cm), with partitioning functions depending on thermal time during the growing period.

Table 1a. List of abbreviations used in the models.

Abbreviation	Explanation	Unit
DTR	daily solar radiation	MJ m^{-2} [ground] d^{-1}
PAR	photosynthetically active radiation	MJ m^{-2} [ground] d^{-1}
F_{int}	fraction intercepted photosynthetically active radiation	-
LAI	leaf area index	m^2 [leaf] m^{-2} ([round]
DM	dry mass	g [dry mass] m^{-2} [ground]
LDM	dry mass of the leaves	g [dry mass] m^{-2} [ground]
SDM	dry mass of the stems	g [dry mass] m^{-2} [ground]
FRDM	dry mass of the fine roots	g [dry mass] m^{-2} [ground]
CRDM	dry mass of the coarse roots	g [dry mass] m^{-2} [ground]
L_{rv}	fine root length density	m m^{-3}
T_p	potential transpiration	m d^{-1}
T_a	actual transpiration	m d^{-1}
E_p	potential evaporation	m d^{-1}
E_a	actual evaporation	m d^{-1}
Q_L	growth rate of the length of the fine roots	m m^{-3} d^{-1}
S	effective degree of saturation	-
Sw	sink strength for water or root water uptake	m^3 m^{-3} d^{-1}
q	volumetric water content	m^3 m^{-3}
qr	residual volumetric water content	m^3 m^{-3}
qs	saturated volumetric water content	m^3 m^{-3}
h	pressure head	m
a	curve-shape parameter	m^{-1}
n	curve-shape parameter	-
m	curve-shape parameter	-
l	curve-shape parameter	-
K	hydraulic conductivity	m d^{-1}
K_s	hydraulic conductivity at saturation	m d^{-1}

A basal temperature of 4.4 °C is used to calculate the thermal time (Thomson & Moncrieff, 1982).
Leaf area increase is calculated through the specific leaf area (*SLA*, m^2 g^{-1}). Daily dry mass increase is partitioned to the leaves (F_{lv}) by:

$$\frac{\mathrm{d}LAI}{\mathrm{d}t} = F_{lv} * SLA * \frac{\mathrm{d}DM}{\mathrm{d}t} \quad (2)$$

Table 1B. *List of input parameters and values.*

Parameters	Explanation	Unit	Value	Reference
RUE	Radiation Use Efficiency	g [DM] MJ^{-1} [intercepted PAR]	3.3	(Pronk *et al.*, 2003a)
F_{lv}	Fraction of daily DM partitioned to the leaves	-	function of thermal time	(Pronk *et al.*, 2003a)
H	plant Height	m	function of time	(Pronk *et al.*, 2003a)
$w_{r,2}$	width of a crop row	m	function of time	(Pronk *et al.*, 2003a)
SLA	Specific Leaf Area	m^2 [leaf] g^{-1} [LDM]	function of time	(Pronk *et al.*, 2003a)
F_{par}	average fraction of PAR in DTR	-	0.47	(Gijzen & Goudriaan, 1989)
k	radiation extinction coefficient	m [ground] m [leaf]	0.48	(Pronk *et al.*, 2003a)
w_p	planting row distance	m	0.5	
D_r	diffusion parameter in the horizontal direction	m d^{-1}	year 1: 0.33; year 2: 2.18	(Pronk *et al.*, 2002)
D_z	diffusion parameter in the vertical direction	m d^{-1}	year 1: 0.66; year 2: 1.38	(Pronk *et al.*, 2002)
Λ	decay rate of the fine roots	d^{-1}	year 1: 0.031; year 2: 0.088	(Pronk *et al.*, 2002)
K_1	root hydraulic conductance	m d^{-1}	$11.5*10^{-6}$	(Rudinger *et al.*, 1994)
WUE	water use efficiency	kg [DM] kg^{-1} [H_2O]	$7.6*10^{-3}$	this study, Fig. 3
a	constant in transpiration reduction function	-	2.8	(based on data from Edwards, 1993), Fig. 2
$h_{r,1/2}$	root water pressure head where $T_a = 0.5\ T_p$	m	- 87	(based on data from Edwards, 1993), Fig. 2

Conifer stands at production nurseries grow for several years. However, *DM* increases only between budburst and dormancy (the end of October). Budburst after planting in the spring is induced at a temperature sum of 280-degree day, using the basal temperature mentioned above. The concept of Thomson & Moncrieff (1982) to initiate budburst following dormancy (at a temperature sum of 220-degree days after 1 January) is used. This concept was proven to work well for conifers under Dutch climatic conditions by Mohren (1987). Our simulations (and experimental data collection) start at planting and end at the end of October in the second year. No changes in model parameters were made when the tree growth model was linked to the soil water balance model.

Water movement in porous media

The two-dimensional simulation model FUSSIM2 (Heinen, 2001; Heinen & De Willigen, 1998; 2001) for water flow, solute transport, and uptake of water and nutrients by roots in variably saturated porous media, solves the Richards equation:

$$\frac{\partial \theta(h)}{\partial t} = \nabla \bullet [K(\theta)\nabla h(\theta)] - \frac{\partial K(\theta)}{\partial z} - S_w \tag{3}$$

Eq. 3 holds for variably saturated, heterogeneous, isotropic, rigid, isothermal porous media and incompressible water. In Eq. 3 t is the time (d), z the vertical co-ordinate oriented positively downwards (m), θ the volumetric water content (m^3 m^{-3}), h the pressure head (m), K the hydraulic conductivity (m d^{-1}) and S_w the sink strength for water (m^3 m^{-3} d^{-1}).
FUSSIM2 simulates soil water dynamics for a single, representative conifer. Root growth is considered to occur in a cylinder. For the purpose of this study, the FUSSIM2 model was modified to cylindrical co-ordinates in which the (x, z) co-ordinates were replaced by (r, z) co-ordinates and r represents the radius of the system (De Willigen & Heinen, 2001). Subsequently, water transport is simulated over the radius as well as over the vertical co-ordinates.
Water movement is determined by the interrelationships between h, θ and K. FUSSIM2 uses the $\theta(h)$ relationship given by Van Genuchten (1980):

$$S(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^n\right)^m} \tag{4}$$

where S is the effective degree of saturation (dimensionless), θ_r is a residual θ (m^3 m^{-3}), θ_s is θ at saturation (m^3 m^{-3}), and α (m^{-1}), n and m (both dimensionless) are curve shape parameters. FUSSIM2 uses Eq. 4 for both the main drying curve as for the main wetting curve with only the α-parameter differing between the two curves: α_d and α_w, respectively, with $\alpha_d > \alpha_w$. The model of Mualem (1984) describes intermediate pathways in the hysteretic $\theta(h)$ relationship. For m = 1-1/n, the Mualem (Mualem, 1976) $K(\theta)$ relationship is given by:

$$K(\theta) = K_s S^{\lambda} \left[1 - \left(1 - S^{1/m}\right)^m\right]^2 \tag{5}$$

where K is the hydraulic conductivity (m d^{-1}), K_s is K at saturation (m d^{-1}) and λ is a dimensionless curve shape parameter.

Water uptake by roots under potential and limited conditions

In Eq. 3 the sink strength S_w represents uptake of water by the roots. De Willigen & Van Noordwijk (1987) obtained an approximate analytical expression for root water uptake, based on an analysis of water movement towards a single root. Their main focus was on the capabilities of the soil to transport water towards the root surface. The transport of water towards the root surface should be large enough to fulfill the demand of water. This approach can be up-scaled towards a whole root system (e.g. Heinen, 1997; Heinen & De Willigen, 1998). The main parameters and variables in this model are the root length density (L_{rv}) distribution (m m^{-3}; see next section), the hydraulic conductance of the root K_1 (m d^{-1}), the potential transpiration rate T_p (m d^{-1}) and the soil hydraulic properties (see above). The model yields an estimate of the root water potential, h_r (m), which is assumed to be uniform over the whole root system. When h_r decreases, reduction in water uptake will most likely occur. Therefore, the actual transpiration rate T_a can be assumed to be a function of the potential transpiration rate T_p and h_r according to:

$$T_a = f_r(h_r)T_p \tag{6}$$

Campbell (1985; 1991) introduced the following reduction function:

$$f_r(h_r) = \left[1 + \left(\frac{h_r}{h_{r,1/2}}\right)^a\right]^{-1} \tag{7}$$

where $h_{r,1/2}$ is a species-dependent root water pressure head at which $T_a = T_p/2$ and a is a species-dependent dimensionless parameter. This relationship was parameterized using data from Edwards (1993): $h_{r,1/2}$ = -87 m and a = 2.8 (Fig. 1).

Two-dimensional root growth

The root water uptake routine in FUSSIM2 needs the root length density distribution L_{rv} as a function of time. Based on known root dry matter production (e.g. from the CONGRO model) dry matter is transformed into total root length production by assuming a constant root radius, root dry matter content and root fresh bulk density. De Willigen *et al.* (2002) described a model that distributes roots in two dimensions according to a diffusion-type process. Heinen *et al.* (2003) showed that such a model works well for a variety of observed rooting patterns. This model has shown to be suitable to describe rooting patterns for *Thuja occidentalis* 'Brabant' (Pronk *et al.*, 2002). In cylindrical co-ordinates, the L_{rv} distribution is given by:

$$\frac{\partial L_{rv}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_r\frac{\partial L_{rv}}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial L_{rv}}{\partial z}\right) - \Lambda L_{rv} + Q_L f(r,z) \qquad (8)$$

In Eq. 8 L_{rv} is the root length density of the fine roots (m m^{-3}), r the radial co-ordinate (m), D_r the diffusion coefficient in the r direction (m^2 d^{-1}). D_z is the diffusion coefficient in the z direction (m^2 d^{-1}), Λ the decay rate of fine young roots (d^{-1}) and Q_L the growth rate of fine roots at a given location in the root system (m m^{-3} d^{-1}). The function f(r, z) becomes 1 at the position where roots enter the soil, otherwise $f(r, z)$ is zero.

Experimental site description

A field trial was conducted in 1998 and 1999 on the sandy siliceous mesic udic Plaggept (Soil Conservation Service, 1975) at the experimental location within the cropping area of ornamental conifers at Horst in the Netherlands (51°25'N, 06°05'E). A field description was made for the soil profile and a particle size distribution was established for three layers. The computer program 'Staringreeks' (Wösten *et al.*, 2001), was used to estimate the Van Genuchten-Mualem parameters of Eq. 4 and 5 (Table 2).

Field trial for model parameterization

Four treatments were included in the field trial (randomized block design, four blocks) with transplanted *Thuja occidentalis* 'Brabant': no irrigation (treatment A), drip irrigation according to local practices (treatment B), drip irrigation with 0.25 L per plant per day (treatment C) and drip irrigation with 0.5 L per plant per day (treatment D).

Drip irrigation was applied at the stem base by placing one pressure compensated emitter (flow rate 2.4 L h^{-1}) per tree and not postponed at periods with high rainfall. Trees were planted on 24th of April 1998 at a row distance of 0.5 m and 0.4 m distance in the row, 81 trees per plot.

Drip irrigation in treatments C and D was applied only in the period from mid May till mid August, 227 mm and 445 mm in 1998 respectively and 227 mm and 445 mm in 1999. In treatment B drip irrigation of 15 mm was applied on 25 May 1998 and on 20 and 29 July 1999.

Dry mass of leaves and stems (oven dried at 70 °C for 48 h., 1 plant per plot per harvest time) and *LAI*, using a LI-COR model 3100 Area Meter (Lincoln, NB, USA), were determined periodically in all treatments. Trees were cut at the soil surface. The final harvest was in November 1999. The specific leaf area (*SLA*) was calculated as the *LAI* divided by leaf dry mass (*LDM*) at each destructive harvest time.

Soil pressure head (h) was measured in treatments A and D at three depths in replicate (0.15, 0.35 and 0.55 m) and at two distances from the tree: directly below and 0.25 m (half the planting row distance) from the tree. One reading per sensor per minute was taken and the averaged value over a period of 2 hours (during the growing season) and4 hours (between growing periods) was stored in a data logger. Data collecting was carried out every two weeks during the growing period and monthly in the winter period. For the purpose of this study data were averaged to daily values. At 0.15 m

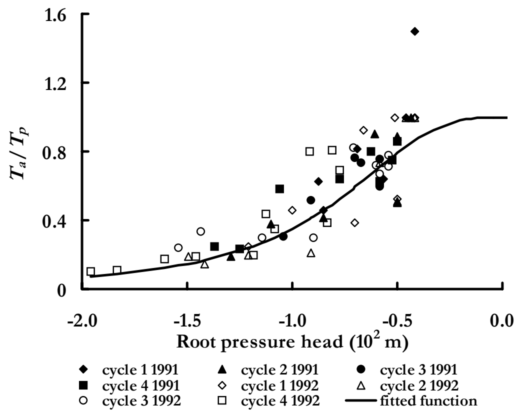

Figure 1. The transpiration reduction function f_r (h_r), as a function of the root pressure head of 8 sets of measured drying cycles of Thuja occidentalis (data from Edwards, 1993). Solid symbols represent drying cycles in 1991, open symbols in 1992. $R^2 = 0.85$, $a = 2.8 \pm 0.3$, $h_{r,1/2} = -87 \pm 4.0$ m).

depth, *h* was measured with tensiometers whereas Watermark model 200 Granular Matrix Sensors were used at 0.35 and 0.55 m depths. Two additional Watermark sensors were placed in treatment D at a depth of 0.85 m, one at either distance.
The Watermark sensor readings were corrected for temperature at corresponding depths according to Spaans & Baker (1992). The pressure head was calculated from the normalized block resistance using the calibration curve based on data of Spaans & Baker (1992). Missing data in the figures in the results section are either due to very dry conditions (<-75 kPa) when tensiometers were not working properly (as indicated in the product specifications), or to malfunctioning of the data logger.

Water use efficiency

A separate trial was carried out to determine the water use efficiency of *Thuja*. Therefore, daily water loss was measured on 12 and 29 July (10 plants) and 3 August (5 plants) in 1999 and on 13 June and 2 August (5 plants) and 5 September in 2000 (2 plants) of plants in containers. In all cases *Thuja occidentalis* 'Brabant was used and only on 12 and 19 July 1999 5 plants of *Thuja occidentalis* 'Frieslandia' were included. The container was placed in a plastic bag and sealed around the stem to prevent water losses other than from the leaves. Plants were weighed at 8 am and after 24 hours. Leaf area of each plant was determined afterwards using a LI-COR model 3100 Area Meter. Total water loss per plant per day was calculated and net dry mass production per plant per day was calculated according to Eq. 1. In this case, F_{int} was calculated for individual plants using the plant's geometry (height and width, Pronk *et al.*, 2003a). *WUE* was found as the slope of the assumed linear relationship between the calculated dry mass production (*DM*) per plant per day and the measured transpiration (T_a) per plant per day:

$$WUE = \frac{\mathrm{d}DM / \mathrm{d}t}{T_a * 1000} \tag{9}$$

Table 2. The Van Genuchten parameters describing the hydraulic characteristics of the sandy siliceous mesic udic Plaggept soil for each soil layer, calculated with the program 'Staringreeks' (Wösten et al., 2001).

	Van Genuchten parameters						
Depth (m)	θ_s ($m^3\ m^{-3}$)	θ_r ($m^3\ m^{-3}$)	α_d ($10^{-2}\ m^{-1}$)	α_w ($10^{-2}\ m^{-1}$)	n (-)	λ (-)	K_s ($m\ d^{-1}$)
0-0.35	0.476	0.01	0.0225	0.1250	1.400	0.09	0.18
0.35-0.65	0.472	0.01	0.0202	0.0880	1.481	0.02	0.29
0.65-1.00	0.491	0.01	0.0161	0.0886	1.550	-0.042	0.21

Boundary conditions for the simulation model FUSSIM2

The simulations were carried out for one tree. The system under consideration had a surface area of 0.196 m^2 and a depth of 1 m. The water flux over the top of the soil was equal to the difference between input (precipitation and irrigation) and output (evaporation). In the model the irrigation was applied on 0.045 m^2 around the tree. Since the water table was at a rather constant level of 3.2 m below the soil surface, a free drainage bottom boundary condition was used. This simple condition does not need any input information. Its validity follows from the comparison between simulated and measured pressure heads. As an alternative validation for this condition a second simulation run was carried out in which the measured pressure head at 0.85 m below soil surface was used as bottom boundary condition (drip-irrigated treatment only). The disadvantage of such type boundary condition is that it needs site specific input (*i.e.* time course of pressure head). No lateral transport was allowed across the cylindrical side of the system, which seems to be justified as all trees were equal in size and the site had no slope.

Statistical procedures

Analysis of variance was performed on *LDM*, *SDM*, *LAI*, *SLA* and *h* with the statistical program GENSTAT 6 to determine effects of treatments. Time was included in the analysis as a factor. A logarithmic transformation on *h* was used to obtain a normal distribution of the residuals. Loss of measured data due to low values of *h* (<-75 kPa) increased the average pressure head, especially in treatment A and less often in treatment D.

The mean differences (M), the relative error (E), the correlation coefficient (r) and the number of simulations within 2.5 and 5 kPa of the observations (Addiscott & Whitmore, 1987) were used to evaluate the goodness of fit between measured and simulated *h*. For the goodness of fit we excluded all measured and accompanying simulated *h* values at conditions drier than –75 kPa, because the observed discrepancies between measured and simulated *h* values are artificially increased at lower *h* values due to physical limits of equipment with which *h* was measured.

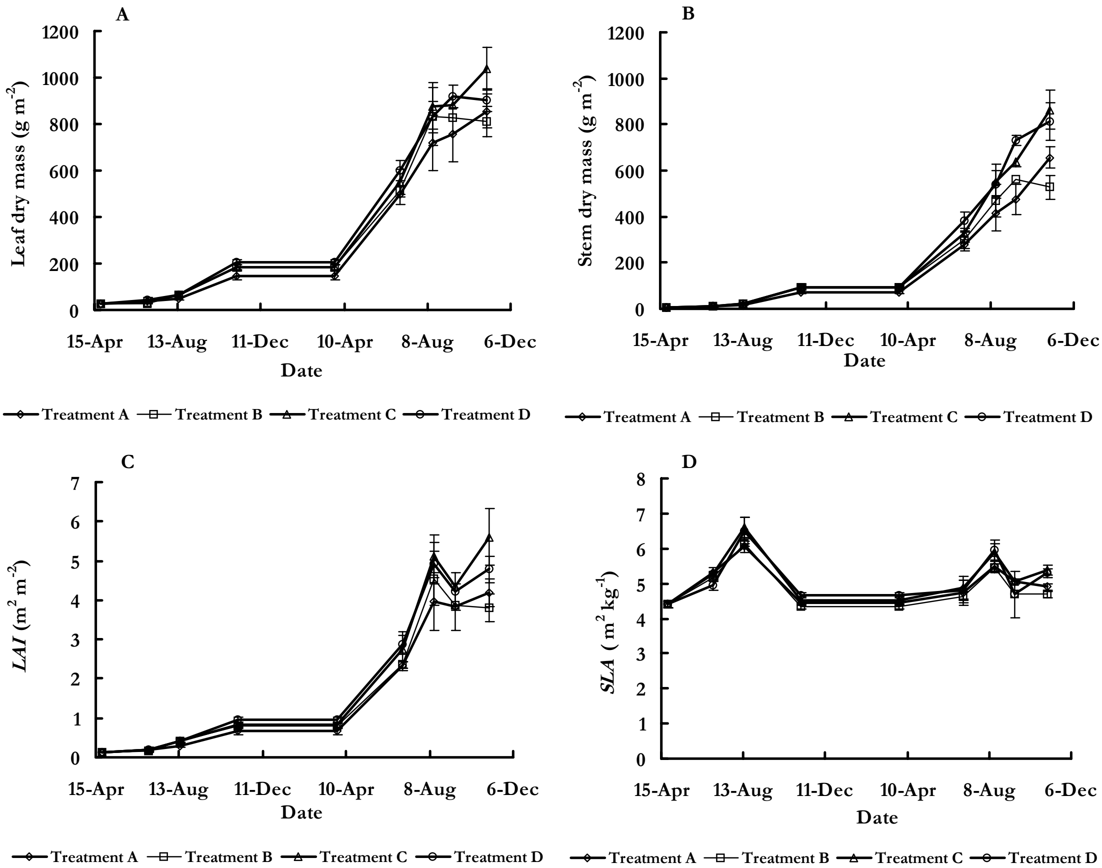

Figure 2. *Measured leaf dry mass (A), stem dry mass (B), leaf area index (C) and specific leaf area (D) of the non- and drip-irrigated trees (treatment A and D respectively). Error bars indicate standard error of the means and are not shown when smaller than the height of symbol.*

Sensitivity analysis

After the coupling of a conifer growth model with a soil water balance model, the model's sensitivity for *WUE*, transpiration reduction function parameters and the site-specific characterization of the soil was tested.

The sensitivity of predicted cumulative potential and actual transpiration (T_p and T_a, respectively), *LAI*, leaf-, stem-, fine- and coarse root dry mass (*LDM*, *SDM*, *FRDM* and *CRDM*) to changes in different model-input parameters was tested for the entire growing period. Mean values for temperature and radiation from the Horst research site from 1993 to 2002 were used in the sensitivity analysis. The initial *LAI*, *LDM*, *SDM, FRDM* and *CRDM* were set at 0.18 m^2 m^{-2} and 42, 8, 11.2 and 9.8 g m^{-2} respectively. The initial pressure head was set at field capacity (h = -10 kPa) and drip irrigation was applied of 0.5 L per plant per day between mid May and half August. The simulation started at the day of planting and ended one and a half-year later. The effects of a change in model input parameters under well-watered conditions were investigated by calculating the relative partial sensitivity of the model output, the elasticity (*EL*) as:

$$EL = \frac{I}{O}\frac{\mathrm{d}O}{\mathrm{d}I} \qquad (10)$$

Table 3. Probability of F-test for the effect of treatment and time on measured leaf dry mass (LDM), stem dry mass (SDM), leaf area index (LAI) and the specific leaf area (SLA)

Source of variation	*LDM*	*SDM*	*LAI*	*SLA*
Treatment	0.339	0.044	0.183	0.019
Time	<0.001	<0.001	<0.001	<0.001
Linear	<0.001	<0.001	<0.001	<0.001
Quadratic	<0.001	<0.001	0.005	<0.001
Treatment x Time	0.815	<0.001	0.567	0.847

in which dO/O is the relative change in model output, and dI/I the relative change in the input value or input data. Sensitivity was calculated as the mean *EL* of four levels of change in the model input for *WUE*, *a*, K_1 and $h_{r,1/2}$ of -10%, -5%, 5% and 10%. For K_s and the ratio between α_w and α_d (by changing α_d) the range was increased to 10 levels of change, -75%, -50%, -25%, -10%, -5%, 5%, 10%, 25%, 50% and 75%, because of the larger variability of these soil parameters.

Model irrigation scheduling

Simulations were carried out in which irrigation was initiated by simulated *h* at 0.15 and 0.25 m depth below the tree with an application rate per irrigation event of 0.5 L per plant. Threshold values ranged from –15 to –100 kPa with 5 kPa intervals between the scenarios. No irrigation was applied when precipitation on that day exceeded 20 mm. Multiple applications were applied on the same day when simulated *h* was not yet in agreement with the threshold level. Although total water loss was not validated as such, absolute values on water loss were not considered but we compared total water loss at 1 m depth and dry mass production with the simulation results of the non-irrigated treatment (c.f. treatment A).

Results

Measured dry mass production and leaf area

LDM and *LAI* increased in time (Fig. 2A, C) but no differences related treatment or interaction between time and treatment were found (Table 3). *SDM* increased in time as well (Fig. 2B) and an interaction between time and treatment was found (Table 3): *SDM* of treatment B ceased to increase by mid August of the second growing season and was lower than the *SDM* of treatments A, C and D at the final harvest.

SDM of treatments A, C and D continued to increase although the increase of treatment A was smaller in the second growing season compared to the increase of treatments C and D. *SLA* varied in time (Fig. 2D), and treatment had an effect on *SLA* (Table 3). The *SLA* of treatment B was lower than the *SLA* of treatments C and D. However, the *SLA* of treatment A was not different from the *SLA* of treatment B or D. No interaction between time and treatment was found.

Simulated dry mass production and leaf area

In general, the correspondence between simulated and measured *LAI*, *LDM* and *SDM* was good (Fig. 3).

The largest discrepancy between simulated and measured *LAI* was found mid August (second growing season), when simulated *LAI* underestimated measured *LAI* with 11.5% in treatment D (Fig. 3A). However, no discrepancy was found at the final harvest. The largest discrepancy in treatment A was found in June (second growing season), when simulated *LAI* overestimated measured *LAI* by 19%. The slope of the linear regression (forced through the origin) relating simulated to measured *LAI* was 1.00 ± 0.022 (R^2 = 0.98).

The discrepancy between simulated and measured *LDM* of treatment D was small (<5%). In treatment A, *LDM* was overestimated with 16.8% in June of the first growing season. However, at the end of the second growing season L*DM* was underestimated with 9.5%. The slope of the linear regression relating simulated to measured *LDM* was 0.96 ± 0.013 (R^2 = 0.99), indicating a systematic underestimation of 4%.

The discrepancy between simulated and measured *SDM* of treatment A increased during the second growing season and an overestimation of 10.7% at the final harvest was found (Fig. 3C). The slope of the linear regression relating simulated to measured S*DM* was 1.03 ± 0.03 (R^2 = 0.97), indicating a systematic overestimation of 3%.

Water use efficiency

Water loss varied between 0.33 and 1.85 kg m^{-2} per day depending on the actual weather conditions. *WUE* was 7.6 10^{-3} kg dry mass kg^{-1} H_2O (R^2 = 0.92, Fig. 4).

Measured pressure head

For 1998, differences in *h* between treatments were only found during a sunny and relatively dry period that lasted from 5 August to 20 August (data not shown). Larger differences in *h* between treatments were found in 1999 (Figs 5 and 6). The *h* at 0.15 m depth became very low early May in treatments A and D (Figs 5A and 6A).

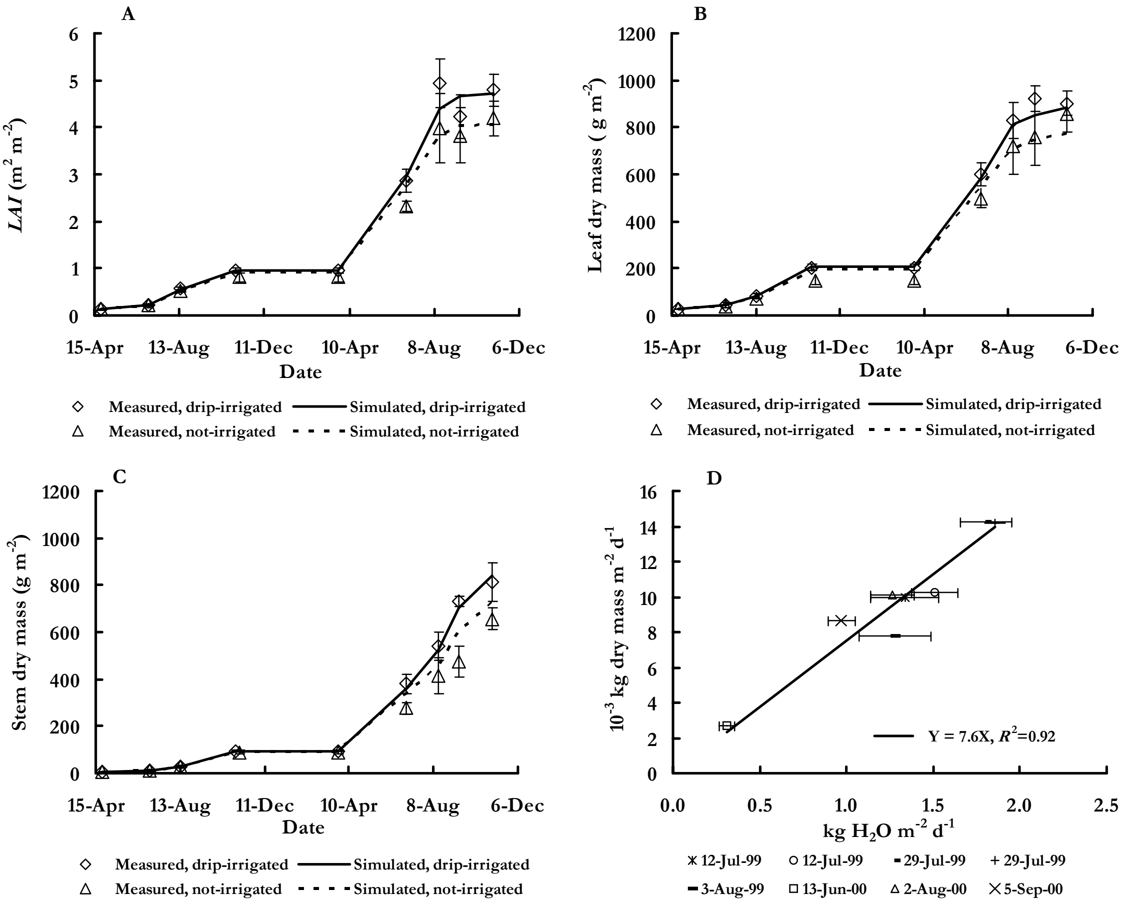

Figure 3. *Measured and simulated leaf area index (A), leaf dry mass (B) and stem dry mass (C) under non-irrigated and drip-irrigated trees. Error bars indicate standard error of the means and are not shown when smaller than the height of symbol.*

Figure 4. *The water use efficiency (D) as the slope of the linear regression between measured transpiration and calculated dry mass of Thuja occidentalis 'Brabant' and 'Frieslandia'. Error bars indicate standard error of means and are not shown when smaller than the height of symbol.*

This happened before drip irrigation started. After drip irrigation started, *h* measurements in treatment D were close to field capacity but occasionally decreased to very low values during hot and dry periods. In these periods, the fixed application rate of treatment D was insufficient to maintain field capacity and *h* values below -75 kPa were found on 26 May, 16-22 July and 3 August 1999 (Fig. 6A).
Although 1998 was wet and cloudy compared to the 10-year average (Table 4), the pressure heads of treatment A were lower than in treatment D at 0.15 m depth (Table 5). No differences were found at 0.55 m depth and position had no effect on h. In 1999, *h* measurements below the tree in treatment A were lower than in treatment D (Table 5). Furthermore, *h* between the tree was higher (wetter conditions) than below the tree in treatment A. The opposite was found in treatment D.

Table 4. *Precipitation and radiation per month and for the four month together at the research location during the growing seasons 1998 and 1999 of the experiment and the ten-year average for the period 1993-2002.*

	Precipitation (mm)			Radiation (MJ m^{-2})		
Month	1998	1999	1993-2002	1998	1999	1993-2002
May	27	68	61	534	554	512
June	112	58	62	477	571	556
July	64	71	61	447	651	534
August	67	95	71	477	451	477
Total	270	292	255	1930	2227	2079

The driest conditions were found in treatment A at 0.35 m depth. No differences within treatments were found below or between the trees at 0.35 m depth and no differences between treatments or position were found at 0.55 m depth. Because of that, *h* data below and between the trees were averaged per treatment at 0.35 and 0.55 m depths (Figs 5 and 6). The measurements at 0.85 m depth were close to the measurements at 0.55 m depth (data not shown).

Simulated pressure head

The simulated *h* followed similar wetting and drying patterns as the measured *h* (Figs 5 and 6). At the beginning of May in the second growing season, the simulated *h* between the trees at 0.15 m depth indicated wetter conditions than the measured *h* (Figs 5B and 6B, both treatments), whereas the simulated *h* below the tree at the same depth, was in agreement with the measurements (Figs 5A and 6A).

The model predicted wetter conditions than were measured in both treatments at depths of 0.35 and 0.55 m the winter period (Figs 5C, D and 6C, D). Half way through the second growing season, however, the simulated *h* indicated drier conditions in treatment A at 0.35 and 0.55 m depth. Differences between measured and simulated *h* were found at large precipitation intensity (Fig. 7A).

The simulated *h* showed a slow recovery to field capacity. Simulated *h* was in better agreement with the measurements when smaller amounts of precipitation rates occurred repeatedly (Fig. 7B).

The correlation coefficients (r) between measured and simulated *h* of treatment A, treatment D or both treatments together, were positive (Table 6). The mean difference (M) for treatment A was not different from zero, indicating that there were no systematic differences between measured and simulated *h*. M was significantly less than zero for treatment D and all data together and indicated systematic deviations. However, the simulations were within about 18% of the measurements (E) and most were within 5 kPa of the measured values (Table 6).

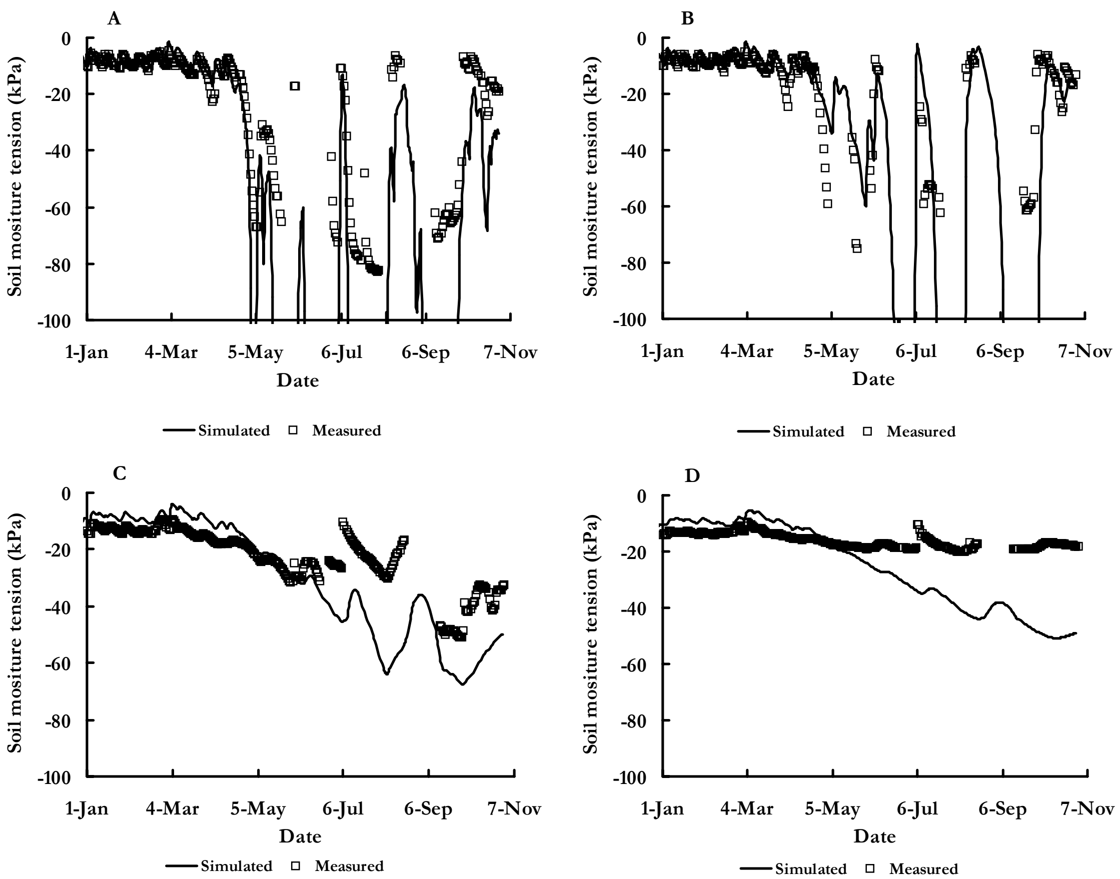

Figure 5. Measured and simulated pressure head in the non-irrigated plots (treatment A) at 0.15 m depth below (A) and near (B) the tree, 0.35 m depth (C) and 0.55 m depth (D) in 1999.

The simulated patterns of the pressure head with the alternative bottom boundary condition using measured pressure heads at 0.85 m below soil surface were similar to the ones presented above. Also, the leaching predicted by both types of bottom boundary condition were comparable (data not shown). Therefore, all other result in this manuscript refer to simulations with the free drainage bottom boundary condition.

Sensitivity analysis

Sensitivity analysis showed that *WUE* had a large influence on cumulative T_p and T_a whereas a, $h_{r,1/2}$, K_1, K_s and $\alpha_w : \alpha_d$ were less important (Table 7).

The sensitivity of all investigated input parameters showed a linear response in the tested range except for K_s and $\alpha_w : \alpha_d$.

A decrease of *WUE* of 10% increases the cumulative T_p with 9.8%. Although an *EL* of 1 is expected under well-watered conditions, it is less than 1. There are two possible reasons for this effect. First, the root system may be unable to fulfill the demand for water because there are not enough roots.

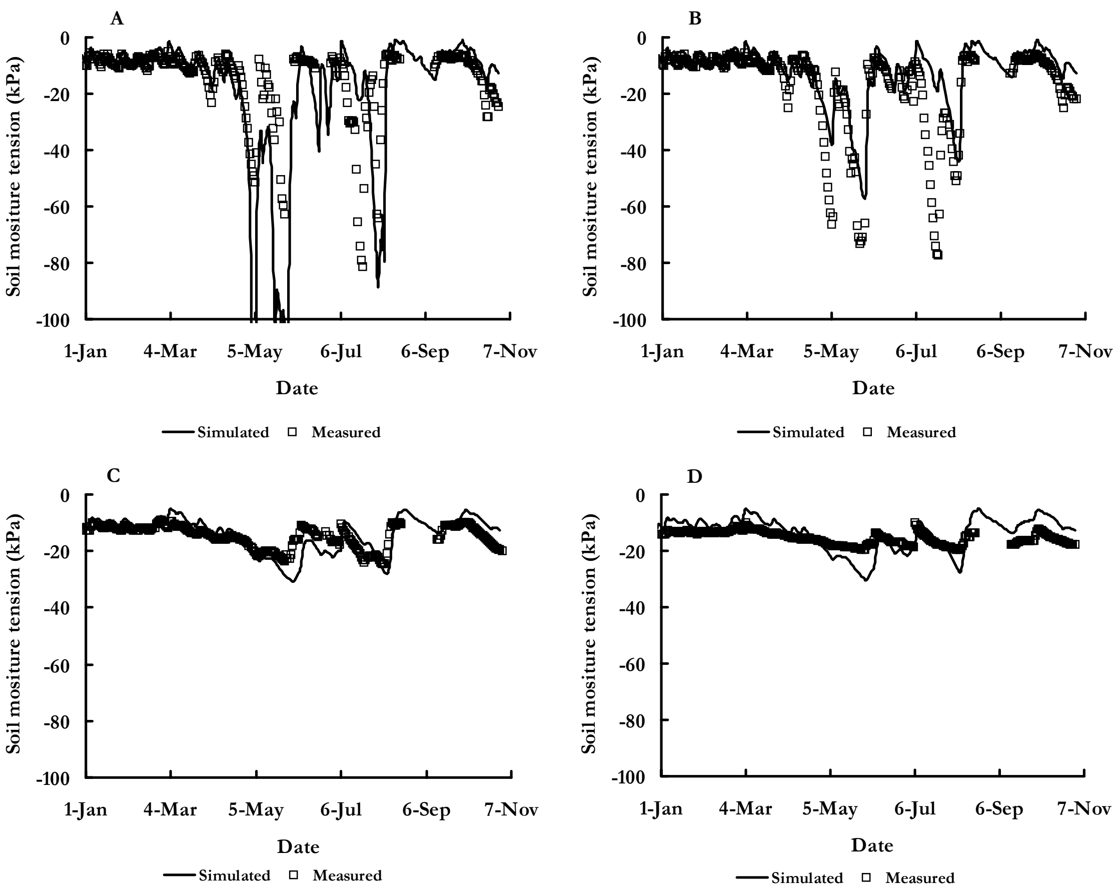

Figure 6. Measured and simulated pressure head in the drip-irrigated plots (treatment D) at 0.15 m depth below (A) and near (B) the tree, 0.35 m depth (C) and 0.55 m depth (D) in 1999.

In that case, $T_a < T_p$, less dry mass is produced, followed by less *LAI* and thus T_p is reduced. Second, h decreases and the root system can not fulfill the water demand. Again, T_a is less than T_p and thus T_p is reduced through a reduced *LAI*.

A similar effect was found for the cumulative T_a for the same reasons only slightly stronger (Table 7). There was a negative effect of the change in the input parameters a and K_1 on model output parameters whereas a positive effect was found for $h_{1/2}$. However, the sensitivity of the model output to these input parameters was within about 0.03. The effect of change in the site-specific characterization of the soil was small, but increased when input parameters were changed from -50% to -75% due to a non linear response of the model output (Table 7).

Results on model irrigation scheduling

Irrigation was applied only a few times in the first growing season (1998) and increased dry mass production by 5% at the most (Fig. 8A, C). Leaching in the first growing season increased up to 13% at an irrigation threshold level of -15 kPa (Fig. 8B, D). At the end of the second growing season, however, leaching was increased by 25% whereas dry mass increased by 15%.

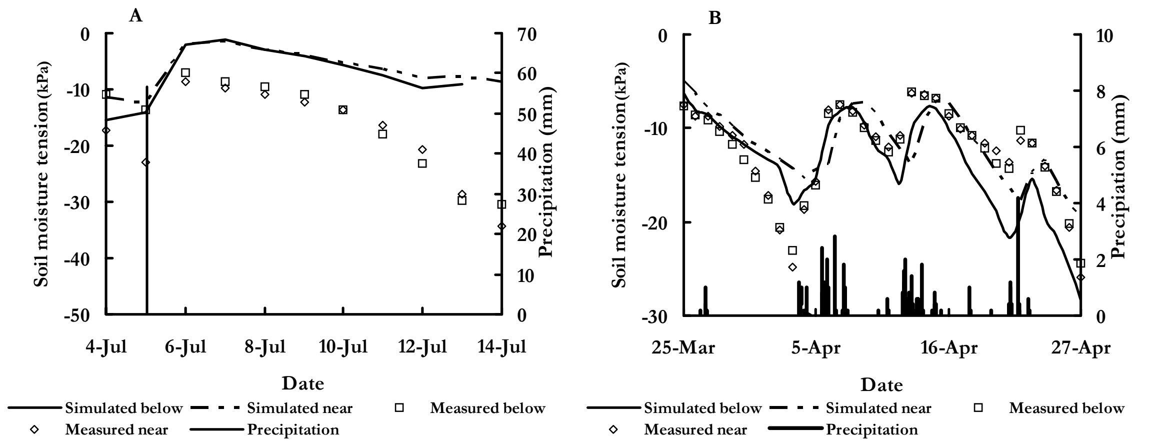

Figure 7. *Pressure head measured below and near the tree, and simulated below and near the tree in the non-irrigated at 0.15 m depth when 57 mm of precipitation occurred (A) and when small (<10 mm) amounts of precipitation occurred (B).*

When the irrigation threshold level was decreased to -100 kPa still an increased dry mass production was found of 15%, compared to no irrigation, when the irrigation threshold level was measured 0.15 m below the tree (Fig. 8A). A response was found when the irrigation threshold was measured at 0.25 m depth (Fig. 8C).

However, 7% increase in dry mass production was found with an irrigation threshold of -100 kPa in the second growing season. Leaching decreased faster with decreasing threshold levels when measured at 0.25 m compared to 0.15 m depth (Fig. 8B and C).

The decrease in leaching with decreasing threshold values was not monotonic. For example, in the first growing season the leaching at a threshold of -24 kPa was larger than at -20 kPa (Fig. 8B). This occurred when an irrigation event was postponed due to a lower threshold value, finely applied but then shortly followed by an extended period of wet conditions, for instance the winter period.

When the irrigation event took place earlier (higher threshold value), the soil profile was drier when the extended period of wet conditions arrived and consequently less leaching was simulated. Due to this delayed irrigation, the increased leaching was in some scenarios even larger than the amount of applied irrigation.

Discussion

Short periods of water stress in young coniferous trees do not lead to permanent losses of leaf elongation rates and subsequently to production losses (Miller, 1965). This suggests that *h* in the rooting environment in 1998 was not a production-limiting factor.

Longer periods of water stress, however, as observed in the second growing season, reduced *SDM* (treatments A and B) although *LAI* and *LDM* were not reduced.

Table 5. The geometric mean (antilogarithm of the mean of the logarithmic transformed data) of pressure head (kPa) measured at different depths in treatment A (no irrigation) and treatment D (drip irrigation 0.5 L per plant per day) below and between the trees in 1998 and 1999. Different letters denote significant difference (5%) of the means within a year. No LSD is given because analysis was done on logarithmic transformed data to obtain a normal distribution of the residuals

			Pressure head at different depths (m):					
Years	Treatments	Position	0.15		0.35		0.55	
1998	A: no irrigation	Below	-13.5		-15.0		-12.9	
“	A: no irrigation	Near	-12.2		-13.2		-13.4	
		Mean	-12.9	b c	-14.1	c	-13.2	b c
“	D: drip irrigation	Below	-9.8		-12.2		-13.2	
“	D: drip irrigation	Near	-10.6		-12.8		-12.5	
		Mean	-10.2	a	-12.6	b	-12.9	b c
1999	A: no irrigation	Below	-15.6	c d	-20.8	e	-15.3	c
“	A: no irrigation	Near	-11.7	a b	-19.8	d e	-16.3	c d
“	D: drip irrigation	Below	-10.8	a	-14.1	b c	-15.3	c
“	D: drip irrigation	Near	-13.7	b c	-14.9	c	-16.4	c d

Reduced leaf area in response to drought stress, is a common reaction of plants to reduce water loss by transpiration (El Sharkawy & Cock, 1987). The leaf area can be reduced through reduced expansion growth but also by shedding of older leaves. However, shedding of older leaves by increased lignification of leaf material was not observed in our trial.

The *h* in treatment A was lower below the tree than between the trees, indicating a horizontal gradient of the pressure head and thus a water flow towards the tree. In treatment D, wetter conditions were found below the tree than in between the trees, also indicating a horizontal gradient of the pressure head and thus water flow away from the area where daily irrigation was provided.

To simulate these measured horizontal gradients, it was necessary to use a soil moisture balance model that simulated both vertical and horizontal water transport.

This phenomenon of horizontal gradients in the soil profile is well known in drip-irrigated systems (Brandt *et al.*, 1971; Coelho & Or, 1996).

The combined plant-soil model was able to simulate dry mass production in treatment D successfully (Fig. 3).

The model slightly underestimated *LAI* and *LDM* in treatment A, whereas *SDM* was slightly overestimated. A lower *LAI* results in a reduced dry mass production and subsequently in a reduced *LAI*. This effect is amplified by the negative feedback of a lower *LAI* on F_{int}, resulting in a lower dry mass production. The model partitioned dry

Table 6. Statistical indices for the goodness of the fit between the observed and simulated pressure head (kPa) of treatment A (no irrigation), treatment D (drip irrigation 0.5 L per plant per day) and of all data. M is the mean difference between simulated and observed (kPa, standard error between brackets), E is the relative error (%), r the correlation coefficient and ±2.5 or ±5 are the number of simulations within 2.5 and 5 kPa of observations respectively.

	Statistical indices					
Treatment	M (kPa)	E (%)	r	+2.5 (%)	+5.0 (%)	Number of observations
A: no irrigation	-0.03 (0.23)	6	0.69	19	49	2394
D: drip irrigation	-2.5 (0.10)	18	0.67	34	67	3574
All data	-1.5 (0.11)	13	0.68	28	58	5968

mass to the various sinks independent of pressure heads. Irrigation is known to change dry mass partitioning between the various organs (Jones, 1992). Further adjustments in dry mass partitioning depending on *h* need to be made.

The systematic deviations between simulated and measured *h* indicate that the model predicts higher *h* values during wet conditions than were observed. Preferential flow in water repellent soils contributes to an increased transport of water into the deeper subsoil (Ritsema & Dekker, 2000). Our *h* measurements suggest that precipitation amounts, which are larger than those to obtain field capacity are transported to the deeper subsoil more rapidly than is simulated (Figs 5D and 7A). This effect (preferential flow) is currently not implemented in the model and may contribute to the systematic deviation between simulated and measured *h*. Another source of error may be the assumed bottom boundary condition of free drainage (unit gradient). Free drainage is only valid if the gradient in total soil water potential equals one.

This may not be the case during sharply fluctuating conditions near the soil surface, like large amounts of precipitation or irrigation, or high losses of water due to uptake or evaporation. In addition, errors in the soil physical characterization due to the fitting procedure may have contributed to the systematic deviations.

From the limited sensitivity analysis it appeared that the model was most sensitive to *WUE* (Table 7). *Thuja* produced 7.6 10^{-3} kg dry mass per kg water transpired which is high compared to the *WUE* of agricultural crops (1.1 10^{-3} to 2.7 10^{-3} kg *DM* kg^{-1} H_2O Jones, 1992; Van Keulen & Van Laar, 1986).

Stilma (2001) found values for *WUE* of *Thuja occidentalis* 'Brabant' of 8.26 10^{-3} to 9.09 10^{-3} kg dry mass per kg water transpired. In that study, *WUE* was measured on potted plants as dry mass increase and total water transpired over a period of 6 weeks. The values thus obtained are slightly higher than our values for *WUE*.

The instantaneous *WUE* (net photosynthesis measured as CO_2 uptake/transpiration measured as water loss) of deciduous forests are generally in the order of 6-12 mg CO_2 g^{-1} H_2O (Baldocchi *et al.*, 1987).

Table 7. *Output of the model at reference conditions and the mean elasticity (Eq. 9) of model output to a change (-10%, -5%, 5%, 10%) in Water Use Efficiency (WUE, kg kg^{-1}), a (-), the root water pressured head at which $T_a = 0.5T_p$ ($h_{r,1/2}$), the root hydraulic conductivity (K_1, cm d^{-1}), the saturated conductivity of the top soil (K_s, m d^{-1}) and the ratio between alpha wet (α_w, m^{-1}) and alpha dry (α_d, m^{-1}).*

	LAI (m^2 m^{-2})	*LDM* (g m^{-2})	*SDM* (g m^{-2})	*FRDM* (g m^{-2})	*CRDM* (g m^{-2})	ΣT_p (m)	ΣT_a (m)
Reference output	4.9	911	854	1540	343	0.476	0.475
Partial sensitivities:							
WUE	-0.02	-0.02	-0.02	-0.02	-0.02	0.98	0.97
a	-0.03	-0.03	-0.03	-0.03	-0.03	-0.02	-0.03
$h_{r,1/2}$	0.02	0.02	0.02	0.01	0.01	0.01	0.02
K_1	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01
K_s	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\alpha_w : \alpha_d$	0.00	0.00	0.00	0.00	0.00	0.00	0.00

This is equivalent to 2.7 10^{-3} to 5.5 10^{-3} kg dry mass per kg water, assuming an assimilation requirement for overall dry mass of 1.5 kg carbohydrates per kg dry mass (Penning de Vries *et al.*, 1983). These values are lower than our values but evergreen species tend to have higher instantaneous *WUE* than deciduous species (DeLucia *et al.*, 1988; Gower & Richards, 1990). Another estimate for *WUE* is the carbon isotope composition ($^{13}C/^{12}C$).

Marshall & Zhang (1994) showed that *Thuja* had the lowest carbon isotope discrimination and presumably the highest *WUE* of all investigated evergreen species. These results support our findings that *Thuja* uses water very efficiently to produce dry mass.

Decreasing irrigation threshold levels did not automatically decrease leaching (Fig. 8B, D) although that may be expected. Irrigation followed by prolonged wet periods increased leaching to larger amounts than were irrigated.

This effect was found more often and more pronounced when the irrigation threshold was situated at 0.15 m depth rather than at 0.25 m depth. The depth at which the irrigation threshold was situated had a large effect on dry mass production and leaching at decreasing threshold levels as well. These two aspects indicate that irrigation scheduling is more complicated than just using the best irrigation threshold level. The depth at which the irrigation threshold is measured and the actual and future weather data are very important and need to be taken into account as well as to develop irrigation guidelines with minimal environmental impact.

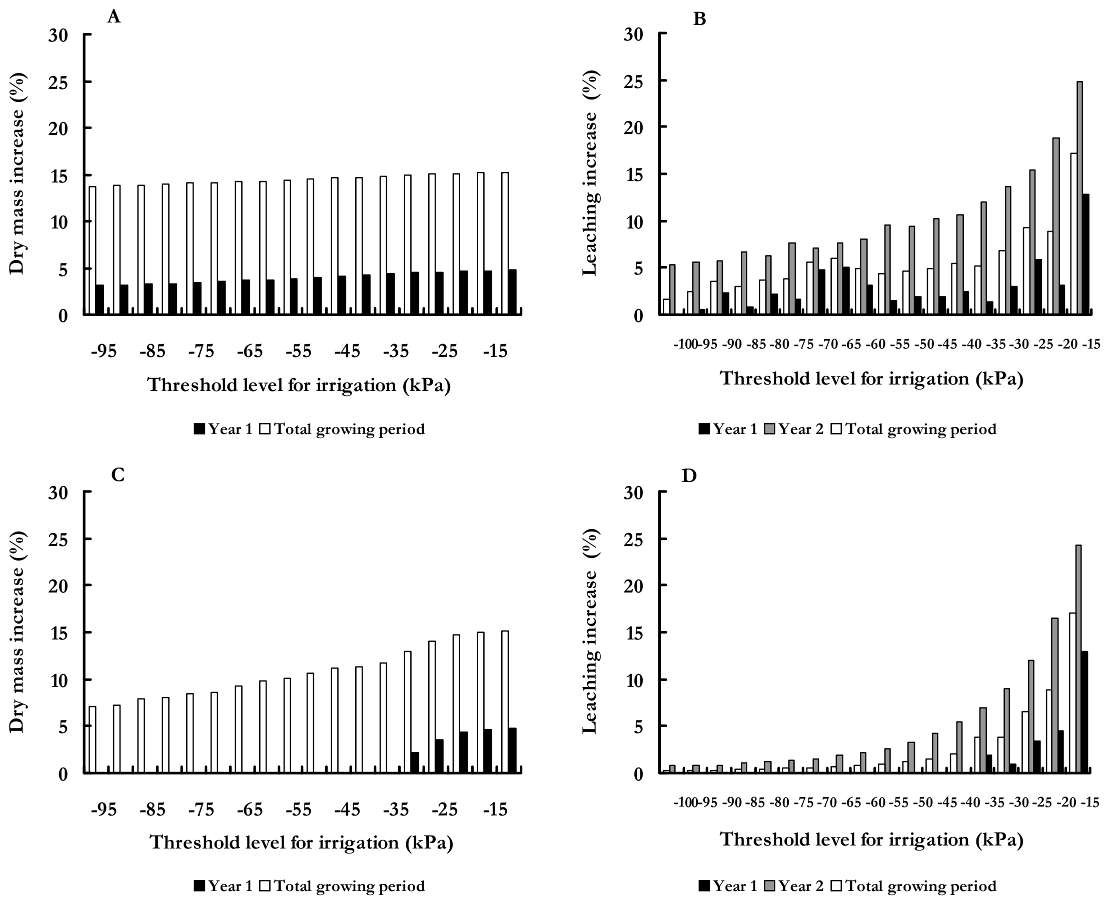

Figure 8. *Dry mass increase (%) in the first growing season and the total growing period and increase in leaching (%) in the first and second growing season, and the total growing period, compared to the non-irrigated treatment with threshold levels measured 0.15 m (A and B) and 0.25 m (C and D) below the tree. Irrigation threshold levels ranged from -15 to –100 kPa with 5 kPa intervals.*

Conclusions

Irrigation was not always necessary to increase dry mass production of *Thuja occidentalis* 'Brabant' under Dutch climatic conditions, as our results of 1998 showed.

Pressure head measurements and model calculations revealed that the need for irrigation may occur sooner than half May in the second growing season in warm and dry spring conditions. Calculations with the combined model could support growers in their decisions to irrigate during the growing season to increase dry mass production.

However, several modifications need to be made to the model: dry mass partitioning between leaf and stem dry mass and preferential flow are the two major aspects that need further development.

The combined model was able to predict effects of irrigation on dry mass production. With this tool we quantified the benefits of irrigation on dry mass production but also on leaching.

Results on leaching however were only considered relatively to the non-irrigated simulation, which limits statements on environmental benefits by optimal irrigation strategies. However, irrigation increased leaching and therefore the risk of nitrogen losses, as was found by many other researchers (Pang *et al.*, 1997; Sanchez *et al.*, 1994; Smika & Watts, 1978). This combined model, however, indicated that developing optimal irrigation strategies is more complicated when leaching is considered, because leaching can increase at lower irrigation threshold levels. The results on model irrigation scheduling do not allow the conclusion that there is one unique combination of irrigation threshold value and depth at which the value is to be monitored in order to obtain optimal production at minimal leaching. The user has to make his or her own trade-off decision what strategy to apply.

Acknowledgement

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CHAPTER 6

Model calculations of available nitrogen use efficiency by white cedar under different irrigation and fertilization strategies on a sandy soil

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(submitted)

Abstract

A combined conifer growth - soil water and nitrogen (N) balance model was calibrated to simulate N dynamics for *Thuja occidentalis* grown for two years on a sandy soil. The model was used to explore effects of three irrigation strategies combined with two fertilizer application methods and two application levels on the available N use efficiency (N_{aue}), N application rate (N_{appl}) and N loss (N_{loss}). Irrigation strategies were no irrigation, daily drip irrigation, and drip irrigation triggered by a pressure head threshold value. Fertilizer application methods were all at once or split-applications and application levels were either a recommended rate or a recommended rate corrected for the mineral N content in the topsoil ($N_{min,ts}$). Calibration was successful although discrepancies were found between simulated and measured $N_{min,ts}$. Average simulated N_{aue} was 31% in the first and 69% second growing season, respectively. Correcting for $N_{min,ts}$ reduced N_{appl} especially for the non irrigated and threshold-irrigated strategies. Simulated N_{loss} ranged from 118 kg N ha^{-1} when not irrigated with split-applications and correcting for $N_{min,ts}$, to 218 kg N ha^{-1} when daily irrigated with split-applications during the two-year growing period. Simulated N concentrations in the percolating soil solution at 1 m depth exceeded the limit of 11.3 mg NO_3-N L^{-1} in almost all cases. In conclusion, additional measures are necessary to improve N_{aue} especially in the year of planting to reduce N_{loss} and to develop conifer cropping systems on sandy soils within the framework of the EU nitrate-N limit.

Keywords: conifer growth model, environment, nitrogen loss, soil water and nitrogen balance model, *Thuja occidentalis*

Introduction

Irrigation usually increases dry mass (*DM*) production of ornamentals (Curtius & Bohne, 1996; Eakes *et al.*, 1990; Pronk *et al.*, 2004; Pronk & Ravesloot, 1998). However, irrigation may also increase the risks of nitrogen (N) losses to the environment due to increased denitrification and due to nitrate leaching to ground- and surface water (Pionke *et al.*, 1990). Currently, an increasing number of extraction points of the Dutch national groundwater monitoring program, exceeds the limit of 11.3 mg NO_3-N L^{-1} (Fraters *et al.*, 2004). In response, the Dutch Government increasingly regulates N-inputs in agriculture and horticulture (Ondersteijn *et al.*, 2002; RIVM, 2002). As N-inputs are constrained and will be further constrained in the near future, growers need to optimize the management of available N-sources. An important indicator for N management is the available N uptake efficiency (N_{aue}) defined as the N-uptake by the crop divided by the total N-supply, *i.e.*, by fertilizer applications and N mineralized during the cropping period (after Huggins & Pan, 2003). Possible management strategies to increase N_{aue} are split N-applications (Pronk & Challa, 2000) and adjusting N-applications for mineral N in the topsoil ($N_{min,ts}$) (Wehrmann *et al.*, 1988). These strategies may increase N_{aue} and decrease nitrate leaching but their effects depend on the applied irrigation strategy. But, will these optimized strategies produce sustainable, optimal yields and reduce the groundwater N concentration to below the limit of 50 mg nitrate-N L^{-1}?

To answer these questions for field-grown conifers, we modified and calibrated a combined model consisting of a tree growth model CONGRO (Pronk *et al.*, 2003b) and a water and N balance model FUSSIM2 (Heinen, 2001; Heinen & De Willigen, 1998; 2001). We simulated N uptake by *Thuja occidentalis* 'Brabant' during a two-year growing period and explored the effects of three irrigation strategies combined with two fertilization strategies and two application levels on N utilization and N leaching for 30 cultures.

Materials and Methods

Model structure

Two models were coupled through a synchronization shell (FSE, Rappoldt & Van Kraalingen, 2001). The model CONGRO (CONifer GROwth, Pronk *et al.*, 2002; Pronk *et al.*, 2003a) simulates *DM* production of ornamental conifers including root growth and proliferation. The other model, FUSSIM2, (Heinen, 2001) simulates the soil water and N balance. The synchronization shell allows the models to work independently while synchronizing data exchange. The driving variables are known at a daily basis and therefore, communication between the two models occurs once a day. CONGRO simulates daily *DM* production, partitioning of *DM* to the various organs, daily water demand (T_p) and daily N demand (N_p). T_p and N_p are imposed on FUSSIM2. For the current water and N status of the soil, FUSSIM2 estimates the actual water (T_a) and N uptake (N_a) by the plant, not taking into account changes that might occur during the forthcoming day. After this exchange of model information, the two models independently compute the changes during the day involved. When T_a or N_a is less than the demand, CONGRO uses the actual uptake rates. Reduction in water uptake causes reduction in *DM* production by a factor T_a/T_p (Pronk *et al.*, 2004). A critical N concentration of the top *DM* (N_{CTOP}, g N g DM^{-1}) is used to define a N growth reduction factor $N_{red} = 1 - (N_{CTOP} - N_{ATOP}) / (N_{CTOP} - N_{MTOP})$ where N_{ATOP} is the actual N concentration of the top *DM* (g N g DM^{-1}) and N_{MTOP} is the minimum N concentration of the top *DM* (g N g DM^{-1}) (Godwin and Jones, 1991). A N_{CTOP} of 0.0052 g g^{-1} in the first and 0.0042 g g^{-1} in the second year was used (Young and Chase, 1965). Dry mass production is reduced when N_{ATOP} becomes lower than N_{CTOP}, by dividing *DM* increase with N_{red}. The most limiting of either soil water or N stress is selected to modify *DM* production.

Mineral nitrogen transport

Although mineral nitrogen can be present in soils as NO_3-N and NH_4-N, our measurements indicated that N was dominantly present as NO_3-N, and, therefore, we do not consider NH_4-N. In FUSSIM2 nitrate transport is described by the classical convection-dispersion equation (CDE) in two dimensions (Heinen & De Willigen, 1998) with source and sink terms for mineralization, root uptake and denitrification. Atmospheric deposition of N is not considered. The dispersion-diffusion tensor needed in the CDE is taken from Bear and Verruijt (1987). In the latter expression the following information is needed: water flux density and volumetric water content which both come from the water balance part of FUSSIM2 and four parameters, *i.e.* the longitudinal and transversal dispersivities, a_T and a_L, respectively, the diffusion coefficient in free water D_0, and the tortuosity parameter τ. We obtained an average value for a_L of 0.10 m from Beven *et al.* (1993). According to Bear and Verruijt (1987) the ratio a_L/a_T is 10 to 20 and we used a_T = 0.01 m. For an ideal solution D_0 can be computed based on thermodynamics (e.g. Atkins, 1978) from the ionic mobility of an ion. For NO_3-N this results in D_0 = 1.64 cm^2 d^{-1}. The tortuosity τ is a function of volumetric water content and this relationship in FUSSIM2 is represented by a broken-line function based on data of Barraclough and Tinker (1981).

Root nitrogen uptake

Root N uptake (as NO_3-N) is assumed to be primarily dictated by the requirement of the plant, denoted as S_{sr} (mg N cm^{-3} d^{-1}). Required uptake can only be realized when the diffusion and mass flow processes in the substrate supply enough N to the root. When this demand is not met, it is assumed that the uptake rate equals the maximum possible rate of transport to the root (De Willigen & Van Noordwijk, 1994a; b). For zero-sink conditions, the maximum possible N uptake rate per unit of root surface area S_{sm} (mg cm^{-3} d^{-1}) is proportional to the bulk N concentration c according to $S_{sm} = \pi \Delta z L_{rv} D_0 G c$ where Δz (cm) is the thickness of the soil layer considered, L_{rv} is the root length density (cm cm^{-3}) in the layer and G is a dimensionless geometry function being a function of L_{rv}, root radius, and root water uptake (De Willigen & Van

Noordwijk, 1994a; b). The actual uptake rate used as the sink strength S_s is equal to the minimum of the required uptake rate and the maximum uptake rate according to $S_s = \min[S_{sr}, S_{sm}/\Delta z]$.

Nitrogen mineralization

Organic matter mineralization was assumed to follow a first order exponential decay (Hénin & Depuis, 1945) $dY/dt = -kY$ where t is the time (year), Y (mg C cm^{-3}) is the quantity of organic C at time t and k is the decay coefficient (≥ 0; year^{-1}). According to Janssen (1984; 1996) k varies with time according to $k = 2.82(a + ft)^{-1.6}$ where a is the so called apparent initial age (year), an index for the resistance of the organic matter and f is a temperature correction factor (Jenkinson & Ayanaba, 1977). The initial age was determined from potential mineralization measurements as described in a forthcoming subsection. The corresponding N mineralization rate S_m (mg N cm^{-3} d^{-1}) follows from $S_m = [(\lambda+1)/\beta(t)-\lambda/\alpha]dY/dt$ where λ is the constant ratio between assimilation and dissimilation, α is the constant C:N ratio of the microbial biomass and β is the time-dependent C:N ratio of the organic pool consisting of organic matter plus microbial biomass. For practical reasons, mineralization was not computed dynamically but it was computed beforehand and daily values for S_m were used. Here we used λ = 0.5 and α = 8 (Janssen, 1996). The NH_4-N formed during mineralization is directly nitrified to NO_3-N so that we consider N mineralized as NO_3-N formation.

Denitrification

Actual denitrification S_d was assumed to be related to potential denitrification corrected for soil conditions, *i.e.*, NO_3-N content, water-filled pore space and soil temperature (Heinen, 2003). The soil conditions are available from FUSSIM2. Potential denitrification as a function of soil depth, was taken from Zwart *et al.* (2002). Average values were used for the parameters in the reduction functions for soil conditions as given by Heinen (2003) for a sandy soil.

Nitrogen demand by the crop

The tree growth model CONGRO (CONifer GROwth) simulates *DM* increase and daily water demand of field-grown conifers (Pronk *et al.*, 2003a). It was modified to simulate the demand for N (N_p). Nitrogen demand was based on daily N increase calculated through the daily *DM* increase with measured N mass fractions of leaf and stem tissue (Fig. 1).

Standard values for the N mass fractions of the roots of 0.00165 g g^{-1} (first growing season) and 0.00170 g g^{-1} (second growing season) were used (Dyer, 1967; Young & Chase, 1965). The N supply by the soil, S_s, was calculated separately. Actual N uptake (N_a) was the minimum of N_p and S_s. Three possible situations concerning N_a can occur (Godwin & Jones, 1991). First, $N_a = N_p$ and no additional actions are needed. Second, $N_a < N_p$, which results in a deficiency demand. This deficiency demand is added to

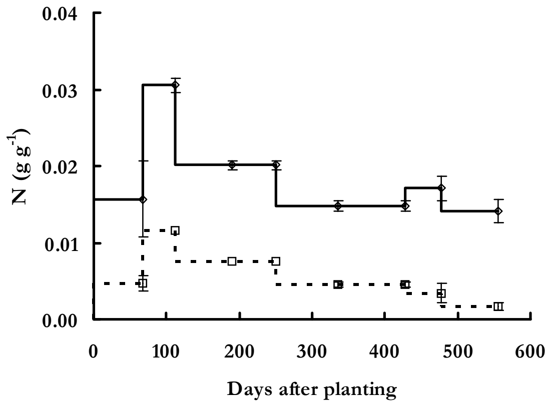

Figure 1. Measured nitrogen mass fraction (g g^{-1}) of leaves (◊) and stems (□) as a function of number of days after planting of Thuja occidentalis during a two-year growing period. Data are pooled for all treatments when not significant different. Error bars indicate standard error of means when larger than the symbol. Error bars are not shown when smaller than the height of symbol.

the demand of the next day. Excessive deficiency can result in reduced crop growth as described above. Third, $N_a > N_p$ which indicates luxury consumption. As by definition the root uptake model never results in $N_a > N_p$, this situation can only occur when at the same time *DM* increase is reduced due to limited water uptake and which results in less growth. Any surplus is subtracted from the demand of the next day. Na is prioritized among the various sinks in such a way that the leaves are always provided with N if uptake occurs.

Laboratory experiment for potential mineralization rates

The soil profile was characterized by Pronk *et al.* (2004) in April 1998 as a sandy siliceous mesic udic Plaggept (Soil Conservation Service, 1975). Samples were collected from three soil layers, 0-0.4, 0.4-0.6 and 0.6-0.9 m and incubated for analyzing C-release under laboratory conditions. Incubations continued for 12 weeks at 20 °C and 15% moisture content, the latter corresponding to field capacity (Hassink, 1994). Organic C was defined as dichromate-oxidizable C, according to Kurmies (Mebius, 1960) and total soil N was determined according to Deys (1961). The decay coefficient *k* was calculated and used to fit the apparent initial age a for each soil layer (Janssen, 1984).

Field trial for model calibration

The field trial comprised a systems comparison with four treatments differing in irrigation and fertilization. The four treatments (randomized block design, four blocks) with transplanted *Thuja occidentalis* 'Brabant' were: no irrigation (treatment A), drip irrigation according to local practices (treatment B), drip irrigation with 0.25 L and 0.5 L per plant per day (treatment C and D, respectively). Drip irrigation was applied at the stem base by placing one pressure compensated emitter per tree. Drip irrigation in treatment B was applied once in 1998 (15 mm on 25 May) and twice in 1999 (15 mm on 20 and 29 July). Drip irrigation in treatments C and D was applied only in the period from mid May till mid August of each growing season. Trees were planted on 24 April 1998 at a row distance of 0.5 m and 0.4 m distance in the row (five plants m^{-2}) and final harvest took place on 30 October 1999. For a detailed description of the trial layout, see Pronk *et al.* (2004).

Fertilizer N applications were derived from Dutch fertilization guidelines for field-grown conifers, *i.e.*, recommended optimum N application rates were derived from target levels of mineral N in the topsoil (0-0.3 m, $N_{min,ts}$) (Aendekerk & Geers, 1996). Measured $N_{min,ts}$ at the end of June 1998, mid of May 1999 and at the end of June 1999 was subtracted from the target value for N_{min}. The final application rates were 41, 41, 50 and 50 kg N ha^{-1} in 1998, and 46, 45, 90 and 82 kg N ha^{-1} in 1999 for treatments A, B, C and D, respectively. The N was applied as a row application in treatments A and B, and through N dissolved in the drip irrigation system in 30 days in treatments C and D. $N_{min,ts}$ was measured in a 1:2 soil:water (v:v) extract with 0.01 M $CaCl_2$ (Houba *et al.*, 2000).

Nitrogen mass fraction of leaves (N_{MFL}, g g^{-1}) and stems (N_{MFS}, g g^{-1}) was determined periodically in each treatment by destructive harvest (nine times in the two-year growing period). In 1998, *DM* of leaves and stems were bulked per treatment before analyzing. In 1999, leaf and stem tissues were analyzed per replicate per treatment. The results were analyzed with the statistical package GENSTAT release 7.1 (GenStat, 2003) using an unbalanced design for the analysis of variance in which time was included as a factor. The unbalanced design was necessary because no replicates of the N analysis of the plant tissues were available in 1998. In the crop growth model N_p was calculated with the measured N_{MFL} and N_{MFS}.

Negative temperature coefficient thermistors were used to measure soil temperature at three depths in duplicate and used to calculate field N mineralization rates (as described above).

To evaluate model calculations, additional soil mineral N measurements were done at three soil depths (0-0.3, 0.3-0.6 and 0.6-0.9 m) on 19 May, 25 August, 1 October 1998, and on 11 May and 30 September 1999.

Per replicate and for each treatment, 10 probes were collected. The replicates were bulked to one soil sample per treatment per soil depth. In May 1998, soil samples per treatments were bulked because at that moment (four weeks after planting and before irrigation started), no differences in N_{min} between treatments were expected.

Scenario calculations

Scenario calculations were done to evaluate effects of irrigation, split-fertilizer applications and application levels on N application rates (N_{appl}, kg N ha^{-1}), N shortage (N_{shor}, kg N ha^{-1}), the available N use efficiency (N_{aue}, %), the total amount of N lost from the system (N_{loss}, kg N ha^{-1}) and the N concentration in the percolating soil solution below 1 m depth (N_{conc}, mg N L^{-1}). N_{shor} was calculated as the integrated

Table 1. Strategies included in the scenario calculations consist of three irrigation strategies (IR1, IR2, IR3) combined with two fertilizer application strategies (F1, F2) and two application levels (AL1, AL2, kg ha⁻¹).

		Irrigation strategies and fertilizer application levels					
		No irrigation (IR1)		Daily drip irrigation (IR2)		Threshold irrigation (IR3)	
Fertilizer application	Year	Level 1 (AL1)	Level 2 (AL2)	Level 1 (AL1)	Level 2 (AL2)	Level 1 (AL1)	Level 2 (AL2)
One application (F1)	First	70	70 – $N_{min,ts}$[1]	70	70–$N_{min,ts}$	70	70 – $N_{min,ts}$
	Second	90	90 – $N_{min,ts}$	90	90–$N_{min,ts}$	90	90 – $N_{min,ts}$
Two applications (F2)	First	2*50	2*50 – $N_{min,ts}$	2*50	2*50 – $N_{min,ts}$	2 * 50	2*50 – $N_{min,ts}$
	Second	2*60	2*60 – $N_{min,ts}$	2*60	2*60 – $N_{min,ts}$	2 * 60	2*60 – $N_{min,ts}$

[1] *$N_{min,ts}$ is the mineral nitrogen content measured in the topsoil (0-0.3 m)*

difference between N_p and N_a, N_{aue} as total actual N uptake divided by N_{appl} plus the N mineralized in the corresponding growing period, and N_{conc} as N_{loss} divided by the total water losses over the bottom boundary of the system for that period. Twelve management strategies were considered in the scenario calculations: three irrigation strategies (IR1, IR2 and IR3) combined with two fertilization methods (F1 and F2) and two application levels (A1 and AL2) (Table 1). The three irrigation strategies were no irrigation (IR1), daily drip irrigation of 0.5 L per plant starting mid May for 90 days in each growing season (IR2) and an application of 0.5 L per plant (drip irrigation also) when a soil pressure head threshold level of –25 kPa was reached in the root environment at 0.25 m depth straight below the stem at any time of the cultivation period (IR3). The fertilizer application methods were one application each growing season (F1) or two applications each growing season (F2) (after Aendekerk *et al.*, 2000). The application levels for F1 were 70 kg N ha^{-1} in the year of planting and 90 kg N ha^{-1} mid May of the second growing season, not corrected (AL1) or corrected (AL2) for the measured $N_{min,ts}$ at the time of application (Table 1).

The application levels for F2 were 50 kg N ha^{-1} mid May and at the end of June in the year of planting and 60 kg N ha^{-1} mid May and at the end of June of the second growing season, not corrected (AL1) or corrected (AL2) for the measured $N_{min,ts}$ at the time of application. Nitrogen in IR1 and IR3 was applied as a row application. In IR2, N was applied through the drip irrigation over a period of 30 days. These scenarios were calculated for 30 cultures, using actual weather data from 1970 to 2000 of the Wageningen Agricultural University.

In the simulations, the initial soil mineral N content was set at 50 kg N ha^{-1} and evenly distributed over the soil profile (0-1.0 m deep). Simulations started at the day of planting (23 April) and ended one and a half year later (31 October).

Table 2. Total carbon (C, g kg^{-1}) and nitrogen (N, g kg^{-1}), measured C-release in 12 weeks incubation at 20 °C, the fitted apparent initial age (a, year) and the calculated amount of mineralized nitrogen ($N_{mineralized}$, kg ha^{-1}) for the entire cultivation (24 April 1998 – 30 October 1999) at measured soil temperatures at corresponding depths of three soil layers at the experimental site.

Depth (m)	C (g kg^{-1})	N (g kg^{-1})	C-release (%)	*a* (yr.)	$N_{mineralized}$ (kg ha^{-1})
0.0-0.4	16.7	0.82	3.03	5.8	143
0.4-0.6	14.9	0.80	1.01	13.9	23
0.6-0.9	4.0	0.21	0.59	15.9	8

Results of the scenario calculations pertain either to the first growing season (April-October), the winter period between the two growing seasons (November-March), the second growing season (April-October), or to the entire cultivation period. For the first and second growing season we considered N_{appl}, N_{shor} and N_{aue}. For the four periods we considered N_{loss} and N_{conc}. The parameters were analyzed by analysis of variance with the statistical package GENSTAT release 7.1 (GenStat, 2003).

Results and discussion

Laboratory experiment for potential mineralization rates

The measured C:N ratio of each layer was close to 20 (Table 2). The apparent initial ages for soil organic C in each soil layer, ranged from 5.8 to 15.9 year at 20 °C. The temperature corrected potential N mineralization rates ranged from 0.003 in the deepest layer in winter to 0.6 kg N ha^{-1} day^{-1} per layer of 0.3 m during the summer in the topsoil. For the entire cultivation (24 April 1998 – 30 October 1999), these potential mineralization rates correspond with 143 kg N ha^{-1} in the top layer to 8 kg N ha^{-1} in the deepest soil layer (Table 2).

Field trial for model calibration

No differences in leaf *DM* between treatments were found, but stem *DM* was increased by irrigation (Pronk *et al.*, 2004).

The N_{MFL} varied in time but no effect of treatment was found nor an interaction between time and treatment. Differences in N_{MFS} were related to treatment; N_{MFS} was significantly higher in treatment A than in the other three treatments in August and November 1998 but not in 1999. In spite of these differences, the total amount of N in the aboveground plant tissues did not differ between treatments. The measured N_{MFL} and N_{MFS} were all higher than previously reported as normal for *Thuja occidentalis* (Dyer, 1967; Young & Chase, 1965).

Table 3. Amounts of mineral nitrogen (kg ha⁻¹) in three soil layers (m) at the start and the end of each growing season and mid August of the first growing season.

	Treatment											
Year	A			B			C			D		
1998	0-0.3	0.3-0.6	0.6-0.9	0-0.3	0.3-0.6	0.6-0.9	0-0.3	0.3-0.6	0.6-0.9	0-0.3	0.3-0.6	0.6-0.9
19-May	50	42	17	50	42	17	50	42	17	50	42	17
25-Aug	126	59	50	151	59	50	92	50	42	42	25	25
01-Oct	8	25	34	8	34	34	8	17	17	8	8	8
1999												
11-May	7	6	3	5	4	0	5	5	0	13	8	5
30-Sep	12	17	11	5	4	5	3	0	4	4	0	7

The simulated amount of N in the leave (N_{ldm}, kg ha^{-1}) and stem (N_{sdm}, kg ha^{-1}) tissue of all treatments followed the measured N_{ldm} and N_{sdm} during the two-year growing period (Fig. 2) although the slope of the linear regression relating simulated to measured N_{ldm} was 0.93 (R^2 = 0.97) and significantly lower than 1 (p<0.001). This discrepancy between measured and simulated N_{ldm} may be due to discrepancies between measured and simulated leaf *DM* at different moments during the cropping period (see Pronk *et al.*, 2003b). The slope of the linear regression relating simulated to measured N_{sdm} was 1.03 (R^2 = 0.97) which was not significantly higher than 1. N_{ATOP} occasionally became lower than N_{MTOP} but never reached N_{CTOP} so that no reduction in growth due to N_{shor} occurred.

Soil mineral nitrogen

The measured N_{min} ranged from 0 to 151 kg N ha^{-1} in the topsoil and from 0 to 59 kg N ha^{-1} in the 0.3-0.6 m layer (Table 3). In general, high values were found in August and low values in the fall and mid May of the second growing season. The total N_{min} in the soil profile (0-0.9 m) ranged from 24 kg ha^{-1} in treatment D to 76 kg ha^{-1} in treatment B in October of the first growing season. At the end of September in the second growing season, N_{min} ranged from 7 to 40 kg ha^{-1}. The measured $N_{min,ts}$, used to determine N-application rates, was in the range with previously reported values found for *Thuja occidentalis* on sandy soils (Oele, 1994) and resulted in comparable application rates (Pronk & Challa, 2000).

The correspondence between measured and simulated N_{min} in the soil was generally good, with a few exceptions (Fig. 3).

Discrepancies between measured and simulated N_{min} occurred in August when measured N_{min} was high and simulated N_{min} was relatively low (Fig. 3). A much better correspondence was obtained when these extremes (the five highest measured values)

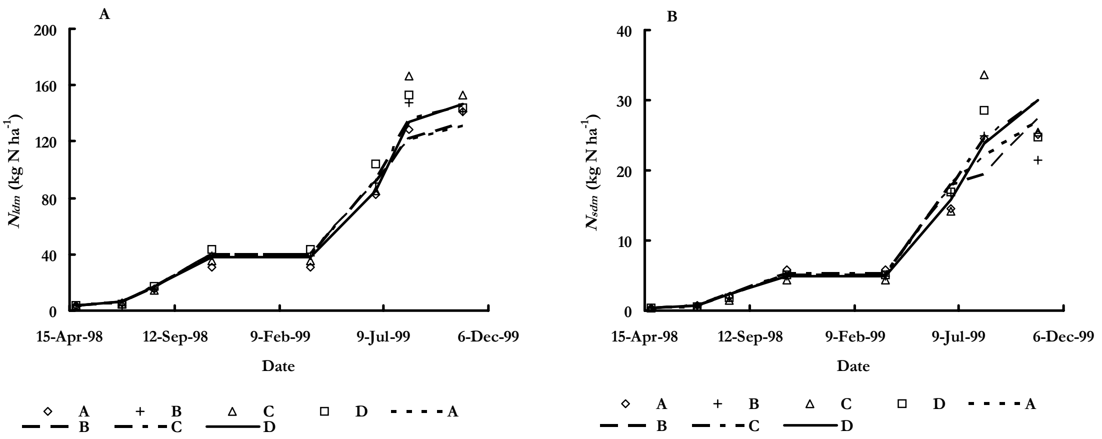

Figure 2. *Measured (symbols) and simulated (lines) nitrogen in leaf (N_{LDM}, A) and stem (L_{SDM}, B) dry mass (kg ha^{-1}) of the non and drip-irrigated treatments (A, B, C and D).*

are not taken into account (slope: 1.03, $R^2 = 0.72$). The measured N_{min} in the fall of treatments A and B was higher than of treatments C and D (Table 3). The model calculations underestimated measured N_{min} in August (Fig. 3) but adequately estimated N_{min} in the fall. This suggests that the actual N losses between August and the fall were even higher than predicted by the simulations.

The processes of the simulated N balance include the inputs via N fertilizers and mineralization and the outputs via N uptake by the crop and N losses due to leaching and denitrification. Each of these processes may contribute to the discrepancy between simulated and measured $N_{min,ts}$ in August. The N uptake however, was simulated in agreement with the measurements indicating that this was of little or no consequence to the discrepancy. The leaching of N largely depended on the soil water balance of the FUSSIM2 model. The soil water balance of FUSSIM2 was found to perform adequately under non and drip-irrigated conditions for field-grown *Thuja occidentalis* (Pronk *et al.*, 2004) indicating that N leaching was estimated satisfactorily. The simulated denitrification ranged from 13.5 to 19 kg N ha^{-1} from planting to 31 December 1998 and was just a few kg in the second part of the cultivation (January-October). The low values for denitrification suggest that this was also of little consequence to the N balance. The simulated mineralization however, is a major component in the N balance. Mineralization as input in the N balance was included in a relatively simple way. The potential mineralization rates were corrected for temperature but not for other soil conditions. Mineralization rates are reduced when the soil water content falls below 20% (Paul *et al.*, 2003).

In the period between the end of June and mid August 1998, the simulated water content of treatments A and B reached these dry conditions in the top layer (0-0.05 m) and for a short period of time (3 days) at 0.15 m depth. These dry conditions most likely reduce mineralization rates and thereby increasing the discrepancy. The effect of an additional soil condition may have contributed to the discrepancy. Fertilizer applications can increase mineralization rates considerable (Bhogal *et al.*, 1999).

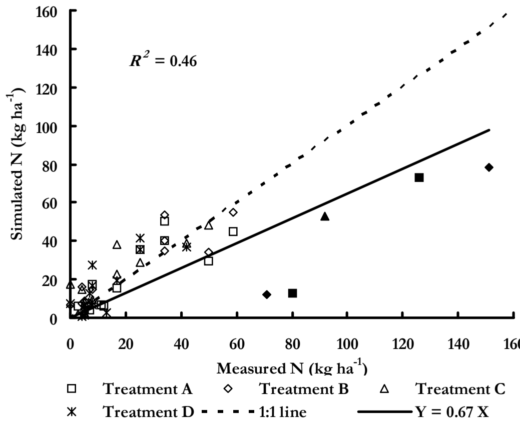

Figure 3. Measured versus simulated nitrogen content of the soil (kg N ha^{-1}) at different depths of the non-irrigated, drip-irrigated according to local practices, drip-irrigated with 0.25 L and 0.5 L per plant per day (treatments A, B, C and D, respectively). Solid line indicates regression line; solid symbols indicate August measurements of treatments with open symbols.

High values of mineral N contents were found 6 weeks after fertilization in treatments A and B but not in C and D. There may have been high mineralization rates in treatment C and D as well, but nitrate is probably leached or the fertilizer application through drip irrigation may not initiate increasing mineralization rates. However, increased mineralization rates due to fertilizer applications were not implemented in the model.

Scenario calculations

The mean difference between potential and actual N uptake, N_{shor} (all scenarios) was 5 kg N ha^{-1} and ranged from 0 to 52 kg N ha^{-1} (Fig. 4). In most cases (67%), N_{shor} ranged between zero and 5 kg N ha^{-1} for each growing season.
Interactions were found between irrigation and fertilizer application method and irrigation and application levels for N_{shor} in the first growing season (Table 4).
N_{shor} was lowest for IR1 and highest for IR2 and within IR2 highest for F1. In other words, the highest N_{shor} was found for the daily drip-irrigated treatment with one fertilizer application. In the interaction with application levels, N_{shor} was found highest for the daily drip-irrigated strategy with $N_{min,ts}$ subtracted from the application rate (IR2 x AL2).
In the second growing season, an interaction was only found for irrigation and fertilizer application method, showing high values for N_{shor} in the daily drip-irrigated strategy with one fertilizer application (IR2 x F1). In addition, subtracting $N_{min,ts}$ from the application level increased N_{shor}. The increased N_{shor} in the daily drip-irrigated strategy (IR2) was caused by a combination of 1) an increased *DM* production (Pronk *et al.*, 2004) followed by an increased N_p which could not be fulfilled and 2) an increased N_{loss} due to irrigation.

Table 4. The nitrogen shortage (N_{shor}, kg ha⁻¹) and nitrogen utilization (N_{util}, %) for irrigation strategies (IR) and fertilizer application methods (F) and application levels (AL) of both growing seasons in the scenario calculations for 30 cultures.

Factor	First season		Second season	
	N_{shor}	N_{util}	N_{shor}	N_{util}
IR1 (n=240) [1]	1.8	32	0.1	66 a[1]
IR2	1.0	28	10.1	71 b
IR3	0.4	32	6.3	70 b
AL1 (n=360)	2.9	27	4.3 a	65
AL2	7.1	34	6.6 b	72
F1 x AL1 (n=180)	4.2	29 b	7.8	69 b
F1 x AL2	6.4	32 c	10.7	72 bc
F2 x AL1	1.5	26 a	0.5	62 a
F2 x AL2	7.8	35 d	2.5	73 c
IR1 x F1 (n=120)	1.5 a	32	0.2 a	68
IR1 x F2	2.2 ab	31	0.0 a	63
IR2 x F1	11.1 e	28	17.6 c	72
IR2 x F2	8.1 d	28	2.7 a	70
IR3 x F1	3.2 b	33	10.2 b	71
IR3 x F2	3.8 bc	32	1.9 a	69
IR1 x AL1 (n=120)	0.6 a	28 ab	0.0	61
IR1 x AL2	3.1 b	36 d	0.2	80
IR2 x AL1	6.8 c	26 a	8.4	68
IR2 x AL2	12.5 d	30 c	11.9	74
IR3 x AL1	1.3 a	29 bc	4.4	66
IR3 x AL2	5.7 c	36 d	7.7	73

[1] *For a description of the abbreviations, see Table 1*

[2] *Means within the same column followed by different letters are significantly different at p = 0.05*

The distribution of N_{shor} showed that the median was increased in the daily drip-irrigated strategy compared to the non-irrigated strategy for both growing seasons (Fig. 4). Furthermore, the variability increased due to irrigation (threshold and daily drip irrigation, both growing seasons) although in the threshold-irrigated strategy the median was close to zero.

Although N_{ATOP} became lower than N_{MTOP} (whenever $N_{shor} > 0$), N_{ATOP} never approached N_{CTOP}, indicating that *DM* production was not limited due to N deficiency. The average N_{aue} was 31% in the first and 69% in the second growing season. However, N_{aue} ranged from 17% to 97%. In the first growing season, interactions for N_{aue} were found between irrigation strategy and application level and between fertilizer application method and application level (Table 4).

Table 5. The average nitrogen applied (N_{appl}, kg ha^{-1}) for the different irrigation (IR), fertilizer application (F) strategies and application levels (AL) of both growing seasons in the scenario calculations for 30 cultures (n=30).

Irrigation	IR1[1]				IR2				IR3			
Fertilizer application	F1		F2		F1		F2		F1		F2	
Application Level	AL1	AL2	AL1	AL2	AL1	AL2	AL1	AL2	AL1	AL2	AL1	AL2
First season	70 d[2]	49 c	100 e	31 a	70 d	49 c	100 e	40 b	70 d	49 c	100 e	31 a
Second season	90 b	82 a	120 d	80 a	90 b	82 a	120 d	97 c	90 b	82 a	120 d	91 b

[1] *For a description of the abbreviations, see Table 1*

[2] *Means within the same row followed by different letters are significantly different at p = 0.05*

The lowest N_{aue} was found for the daily drip-irrigated strategy, not corrected for $N_{min,ts}$. The highest N_{aue} was found when $N_{min,ts}$ was subtracted from the application level. From the interaction between fertilizer application method (F) and application level (AL) it became clear that subtracting $N_{min.ts}$ improved N_{aue}. In the second growing season only an interaction between fertilizer application method (F) and application level (AL) was found and a main effect of irrigation (IR). Again, correcting for $N_{min,ts}$ improved N_{aue}. The split fertilizer application without subtracting $N_{min,ts}$ (F2 x AL1) had the lowest N_{aue}. Also, irrigation, daily drip irrigation or threshold irrigation, improved N_{aue}.

The N_{appl} was reduced when anticipated for N_{min} in both seasons (compare AL1 with AL2, Table 5). Irrigation started on the same day as the first N-application occurred, namely mid May (first and second growing season). At that time, no differences due to irrigation strategies could be found for N_{appl} when one, $N_{min,ts}$ corrected fertilizer application was applied (compare IR1 x F1 x AL2 with IR2 x F1 x AL2 or IR3 x F1 x AL2) because irrigation had not affected $N_{min,ts}$ at that time. The largest reductions were found when the split fertilizer applications were corrected for $N_{min,ts}$ (compare F2 x AL1 with F2 x AL2). A maximum reduction of 69 kg N ha^{-1} was found in the first growing season for the non and threshold-irrigated strategy and of 40 kg N ha^{-1} in the second growing season for the non-irrigated strategy.

That young trees require little or no fertilizers in the year of planting was also found by Ledin (1986) and by Millard and Neilsen (1989) for transplanted apple rootstocks. Both authors indicated that this was due to the 'not yet established root system'. Our study suggests that N demand was relatively small while mineralization from soil organic matter supplied a considerable part of that demand.

Two significant main effects were found for N_{loss} in the first growing season, namely irrigation strategy and application level (IR and AL, Table 6). Daily drip irrigation (IR2) had the highest N_{loss} whereas the lowest N_{loss} was found for the non-irrigated strategy (IR1). N_{loss} was reduced when corrected for $N_{min,ts}$.

Table 6. The amount of nitrogen lost (N_{loss}, kg ha^{-1}) and the nitrogen concentration (N_{conc}, mg L^{-1}) calculated as N_{loss} divided by the total water loss for the different irrigation (IR), fertilizer application (F) strategies and application levels (AL), of both growing seasons, the winter period and the entire cultivation period in the scenario calculations for 30 cultures.

	First season		Winter period		Second season		Cultivation period	
Factor	N_{loss}	N_{conc}	N_{loss}	N_{conc}	N_{loss}	N_{conc}	N_{loss}	N_{conc}
IR1 (n=240)[1]	31 a[2]	20	91	39 c	19 a	22 b	142 a	30
IR2	74 c	26	66	26 a	48 c	19 a	189 c	23
IR3	43 b	23	89	35 b	32 b	20 ab	164 b	27
AL1 (n=340)	52 b	23	94	32	33	23	162	30
AL2	47 a	22	70	34	34	18	168	24
IR1 x AL1 (n=120)	32	20 a	105 c	45	22	159	159	33 e
IR1 x AL2	30	19 a	78 b	33	17	125	125	26 c
IR2 x AL1	80	27 d	74 b	30	53	207	207	26 c
IR2 x AL2	69	24 c	57 a	24	44	170	170	21 a
IR3 x AL1	45	23 c	103 c	40	36	183	184	30 d
IR3 x AL2	41	22 b	75 b	29	29	145	145	24 b
F1 x AL1 (n=180)	52	23 b	85 c	35 c	35 b	21 b	171 c	28 c
F1 x AL2	48	22 a	74 b	30 b	31 ab	19 ab	153 b	25 b
F2 x AL1	53	24 b	103 b	42 d	39 c	24 c	195 d	32 d
F2 x AL2	46	21 a	66 a	27 a	28 a	17 a	141 a	23 a

[1] *For a description of the abbreviations, see Table 1*

[2] *Means within the same row followed by different letters are significantly different at p = 0.05*

This suggests that over-irrigation enhances N losses during the growing season as was also found by many other researchers (Pionke *et al.*, 1990).

In the second growing season, again irrigation significantly affected N_{loss}, but an interaction between fertilizer application method (F) and application level (AL) was found. The split fertilizer application with no correction for $N_{min,ts}$ (F2 x AL1) had the highest N_{loss} whereas correcting for $N_{min,ts}$ (F2 x AL2) had the lowest N_{loss}. When one fertilizer application was applied, N_{loss} was not affected by subtracting $N_{min,ts}$. An interaction was found in the winter period between irrigation strategy and application levels, and fertilizer application method and application levels for N_{loss}. Now the lowest N_{loss} was found for the daily drip-irrigated strategy and subtracting $N_{min,ts}$ (IR2 x AL2). This result is not surprising because most N was already lost during the preceding first growing season.

The highest N_{loss} was found for the non-irrigated strategy and the threshold-irrigated strategy, not correcting for $N_{min,ts}$ (IR1 x AL1 and IR3 x AL1). This shows that N is lost after all during the winter. The N_{loss} for the whole cultivation period ranged from 118 kg ha^{-1} to 218 kg ha^{-1}.

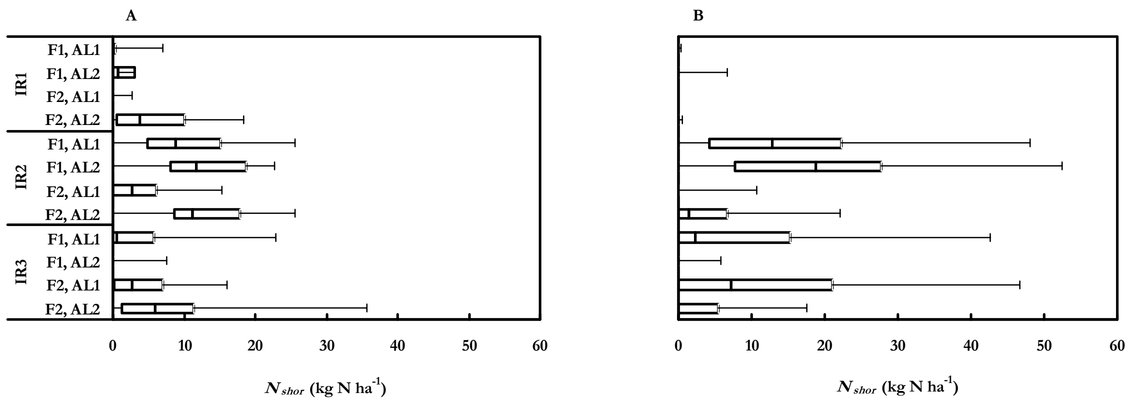

Figure 4. *Distribution of nitrogen shortage (N_{shor}, kg N ha^{-1}) for 30 cultures in a box plot for the first (A) and second (B) growing season for the different irrigation strategies (IR), fertilizer application method (F) strategies and application levels (AL). The box spans the interquartile range of the values in N_{shor}, so that the middle 50% of the data lie within the box, with a line indicating the median.*

An interaction between fertilizer application method (F) and application level (AL) was found and again a main effect of irrigation (IR). Subtracting $N_{min,ts}$ lowered total N_{loss} when one or a split fertilizer application was applied. The reduction however, was much higher for the split application.

Irrigation increased total N_{loss} although the increase was smaller for the threshold based irrigation strategy compared to the daily drip-irrigated strategy. Annual N_{loss} (calculated as N_{loss} of the cultivation period divided by two) was comparable with N_{loss}'s found for common arable crops (Haas *et al.*, 2000; Van Dijk & Smit, 2004).

The N_{conc} in the percolating soil solution at 1 m depth varied between 7 and 78 mg N L^{-1}. The low concentrations were found in the second growing season, 2 times 7 mg N L^{-1} and 2 times 9 mg N L^{-1}. The highest concentration was found in the winter period when no irrigation was applied, a split fertilizer application and no correction for $N_{min,ts}$. The low concentrations comply with the limit of 11.3 mg NO_3-N L^{-1} but this was found for only 1% of all calculations of the second growing season. N_{conc} depends on available NO_3-N but also on the irrigation and precipitation surplus. On average, calculated concentrations are in agreement with measured concentrations in intensively cropped systems on sandy soils (Fraters *et al.*, 2004), including nursery stock (McLaughlin *et al.*, 1985).

Conclusions

The soil process mineralization was an important factor in the modelled N balance. Mineralization was implemented in the model in a relatively simple way and the measured increase of $N_{min,ts}$ between the end of June and mid August under non-irrigated conditions was not well simulated. The priming effect of fertilizer applications may explain the suggested increased mineralization and the high measured $N_{min,ts}$

(Bhogal *et al.*, 1999) but to the best of our knowledge no validated models are available yet to account for this phenomenon.

The recommended N fertilizer application levels were adequate for unconstrained N uptake for all three irrigation strategies on the moderately fertile sandy soil. However, simulation results indicated that N concentrations in the shallow groundwater will most likely exceed the EU nitrate-N limit of 11.3 mg NO_3-N L^{-1}. To reduce N_{loss} it was imperative to correct recommended application levels for measured $N_{min,ts.}$ Our optimized irrigation and fertilization strategies, however, did not result in drastically reduced N leaching. The low N uptake by nursery stock in the year of planting and the 'not yet established root system' (Ledin, 1986; Millard & Neilsen, 1989) contributed to high N_{loss} on this moderately fertile sandy soil in a temperate climate with precipitation surpluses in the winter time. The relatively high mineralization rates provided too much mineral N to the young trees with respect to the crop N demand especially during the year of planting. Similar results were found for short rotation intensively cultured poplar (McLaughlin *et al.*, 1985).

Other researchers indicate that application rates up to 150 kg N ha^{-1} will not propose a threat for the groundwater (Bergström & Johansson, 1992). Our study indicates that additional actions are necessary for field-grown conifers on sandy soils to meet the limit for nitrate in the groundwater. Possible solutions may involve the use of catch crops (Calkins & Swanson, 1996; Hanninen, 1998; McLaughlin *et al.*, 1985) which can be sown mid August in the year of planting and further reduced fertilizer application rates because caught N is released in the next growing season. Our tool could be used to explore the effects of reduced fertilizer application rates. With moderate modifications this tool may explore the effects of catch crops as well.

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CHAPTER 7

General discussion

Introduction

Agricultural and horticultural production systems increasingly face the challenge to optimize yields within environmental and social-cultural constrains. Ornamental nurseries on sandy soils in the Netherlands encounter two main environmental constraints which may affect yields, namely restricted use of groundwater for irrigation purposes (VenW, 1989) and restricted use of (fertilizer) N (Anonymous, 1999). The two production factors water and N are of major importance for dry mass production, and restrictions on its use may limit crop yields, especially on sandy soils (Averdieck & Bohne, 1994; Curtius & Bohne, 1996; Pronk & Ravesloot, 1998). Irrigation and N application also play a key role in determining the concentration of nitrate in the groundwater below the cropped area (Pionke *et al.*, 1990).

The majority of nursery stock (57 %, 7437 ha) is grown on the sandy soils in Noord Brabant and Limburg (LEI & CBS, 2004). Conifers are grown on about 19% of the area (1425 ha), where shrubs cover only 9% (704 ha). Most conifers have comparable growing features when it comes to physiological processes like bud burst and leaf area. The trees are planted in rows in the spring and grown for two growing seasons. In this study white cedar (*Thuja occidentalis*) was chosen as a model crop for ornamental conifers. The estimated surplus N input via fertilizers and manure relative to the output via harvested crops for conifers is 129 kg N ha^{-1} jr^{-1} and relatively low compared to the surplus of seedlings of forest and hedges (263 kg N ha^{-1} jr^{-1}) and that of shrubs (202 kg N ha^{-1} jr^{-1}) (Alt *et al.*, 1989). Large areas of the sandy soils of Noord Brabant and Limburg are dry and nitrate losses through leaching are expected to be much higher on dry soils compared to wet soils (Boumans *et al.*, 2004).
Irrigation is restricted in areas with sandy soils and deep groundwater tables, because large-scale water extraction for irrigation purposes may contribute to the lowering of the groundwater table at regional scale and that may induce loss of biodiversity in local nature conservation areas. Local administrators increased taxes on groundwater extraction to decrease extraction. However, growers can be reimbursed for the increased taxes when they use a decision support irrigation tool to optimize the irrigation efficiency.
Growers also face constraints on N inputs, so as to protect the groundwater quality from contamination by nitrate through leaching. Nitrate-N concentrations in the shallow groundwater should not exceed 11.3 mg L^{-1} (Anonymous, 1991). These

restrictions force growers to carefully decide where and when to apply water and N within the crop rotation to maximize the recovery of both inputs.

The aim of this study was to increase the understanding of the effects of irrigation and N fertilizer application on dry mass production of white cedar, and on the irrigation and N use efficiency. The focus was on the relationship between inputs (water and N) and outputs (dry mass production, water and N) in the crop-soil system. A specific aim of this study was to integrate this knowledge into a model to forecast the effects of irrigation and fertilization strategies on dry mass production, the irrigation and N use efficiency and on N leaching losses on a sandy soil. Such a model may be used subsequently by policy makers and growers to evaluate measures on N input restriction. It might also be used to select irrigation and fertilization strategies which increase the irrigation and N use efficiency, and to develop simple but applicable guidelines for irrigation and fertilization practices. The model may also be used by private companies and growers as a basis for a decision support tool for irrigation practices on a daily basis.

The study included five topics, namely:

1. radiation interception by small, field-grown conifers,
2. calibration and validation of the concept of the radiation use efficiency and the distribution of dry mass between the various sinks of *Thuja*,
3. root growth and development of *Thuja*, in this study described by a two-dimensional diffusion process,
4. effects of drip irrigation on dry mass production of *Thuja* and water losses, compared with non-irrigated strategies on a sandy soil,
5. effects of irrigation, split fertilizer N application and different levels of fertilizer N application on the N use efficiency and on N leaching losses of *Thuja* on a sandy soil.

Container and field trials were conducted to assess radiation interception, dry mass production of both aboveground and below ground plant parts, and water use efficiency of one-year old cuttings of the ornamental conifer *Thuja occidentalis* in the nursery stage. The experimental data were then used to develop, calibrate and validate the conifer-growth model CONGRO (CONifer GROwth model) and to validate the two-dimensional soil water balance model FUSSIM2 (Heinen, 2001; Heinen & De Willigen, 1998), for conifers grown on sandy soils.

The next paragraph (paragraph 'Major findings') discusses the major findings of this study. Paragraph 'The model as a tool to evaluate effects of measures on N leaching' discusses the use of the model as a tool to evaluate the effects of measures on N leaching and paragraph 'The model as a decision support tool for growers' discusses the model as a decision support tool for growers. Finally, paragraph 'Subjects for further research' discusses some topics for further research.

Major findings

Radiation interception

It was concluded that interception of radiation by the stem area of *Thuja occidentalis* was very small and that no corrections were necessary for grouped foliage, to adequately estimate the fraction of radiation interception by the leaves. This result made it possible to modify the standard equation for radiation interception of row crops to rows of cuboids without additional corrections for radiation interception by non-leaf area.

The fraction radiation intercepted by the rows of cuboids method was considerable lower than by the row crop method (8% for $LAI = 1$). Planting row and intra-row distances of conifers may vary in practice and tree characteristics as height and width may vary with crop species. This simple but generic method is able to estimate radiation interception of all planting orders and plant shapes.

Dry mass production contribution to soil organic matter balance

Results on dry mass partitioning between aboveground and below ground sinks revealed that in the two-year cropping period, *Thuja* partitioned about 50 % of the dry mass to the below ground sinks. With root pruning and subsequently harvesting of root balls of 5 to 6 liter per plant, only about 1/3 of the root biomass is removed, leaving 2/3 as root residue in the soil. This residue consists of coarse and fine roots and contributes to the organic matter balance of the soil. An amount of aboveground dry mass of 16 tons ha^{-1} after two years, as found in this study, equals 16 tons of root dry mass and suggests that about 11 tons ha^{-1} will stay in the field after harvesting the crop with root balls. Assuming an organic matter content of 90% and a humification coefficient of the roots of 45% (Yang, 1996) this contributes 4.3 tons ha^{-1} of effective organic matter per two years.

Root growth and development

Field measurements on root length density of white cedar grown for two years on a sandy soil, demonstrated that a rootless area existed between root systems of adjacent plants for the majority of the cultivation period. A closed rooting area, in analogy of closed canopy, was obtained in the second growing season only. The horizontal exploration of the soil by the roots needed to be included in the simulations on root growth. In addition, drip irrigation also affected root growth and proliferation. The convective diffusion model includes the horizontal exploration of roots and was also able to describe affects of drip irrigation on root growth and proliferation satisfactorily. For *Thuja*, planted at low plant densities, it was necessary to describe root growth and proliferation as a two-dimensional diffusion process and thereby accounting for the rootless area between plants when simulating root water and N uptake. Leaching losses and drought stress will be underestimated when roots are assumed to be evenly distributed between plants. The assumed available water for crop uptake in a model with a uniformly distributed root system is much larger than when only half or less of the soil profile is rooted. Subsequently, the model overestimates water uptake at dry conditions. Leaching losses of N are expected to be larger from the rootless soil areas at precipitation surpluses because there is no uptake.

Effects of irrigation

Thuja responded to irrigation in the second growing season by producing more structural biomass; *i.e.* more stem dry mass and more coarse root dry mass. The light interception capacity, expressed as leaf area index, as well as the water and nutrient uptake capacity, expressed as length of the fine roots, were not different for the non and drip-irrigated treatments. In general, leaf area is reduced under dry conditions (El Sharkawy & Cock, 1987), but the difference in drought stress between the non and drip-irrigated treatments was most likely not large enough or the dry period may have been too short to create differences in leaf area. Difference in soil pressure head measurements between the non and drip-irrigated treatments were not found for the first growing season and subsequently no differences in dry mass production. The weather data in that year diminished the effects irrigation.
The differences in soil moisture tension however, had an effect on the distribution of fine roots in the soil profile. The non-irrigated trees rooted deeper compared to the drip-irrigated trees. It is possible that fine roots were present in the topsoil in the non-irrigated treatment, but that they died during the growing season due to dry conditions (Espeleta & Eissenstat, 1998).
The results led to the conclusion that dry mass production of white cedar is not always increased due to irrigation in a moderate climate as the Netherlands.

The COnifer GROwth model CONGRO

Simulation of dry mass production, leaf area development and distribution of dry mass to the various plant parts of the nursery stock crop *Thuja occidentalis* could be done successfully, combining techniques commonly used for agricultural crops and for forests with minor modifications. The Light INTerception and UtiLization (LINTUL) model uses a linear relationship between biomass production and the amount of radiation intercepted by the crop canopy (Monteith, 1977). This relatively simple concept had to be modified to describe the radiation interception by small, transplanted *Thuja* and to describe dry mass production of perennial crops. Temperature sum to simulate bud burst in the spring of perennial crops (Thomson & Moncrieff, 1982) is a common technique in forest growth models and this was successfully incorporated into the LINTUL model for CONifer GRowth CONGRO.

FUSSIM2 for cylindrical coordinates

The system under consideration included drip irrigation and the irrigation was applied through a pressure compensated emitter at the stem base of the tree. The measurements on soil moisture tension showed that there was a difference between the soil moisture tension below and near the tree. This indicated a significant horizontal gradient of the soil moisture tension and a one-dimensional model is not able to simulate that. Therefore, a two-dimensional soil water balance was used. The irrigation application placed at the stem base initiates a wetting front at the time of application. Because the intra-row and row distance of the trees are almost the same (0.4 and 0.5 m respectively), the wetting fronts did not overlap to a wetted perimeter. The application time was also not long enough to overcome the intra-row distance of 0.4 m as soil hydraulic properties of a sandy soil conveyed the 20 minutes irrigation application only about 0.1 meter from the emitter (Clark, 1992). The two-dimensional soil water balance model was therefore modified to cylindrical coordinates.

Scenario studies on irrigation and N use efficiency

Model calculations on irrigation and N fertilization strategies showed that the standard N application rate could be greatly reduced when corrections were made for mineral N in the topsoil. This was true for both the first and the second growing season on this moderate fertile soil.

In this study we assumed that dry mass production was not decreased due to N deficiencies when the N concentration of the aboveground dry mass stayed above a predefined critical concentration. This concept has not been validated for white cedar but is used for several agricultural crops (Godwin & Jones, 1991). In the scenario calculations, the N shortage (calculated as the difference between the potential and actual N uptake) was occasionally simulated. In those cases, the actual N uptake became lower than the potential N uptake. However, the N concentration of the aboveground dry mass never reached the critical concentration and was assumed that dry mass production was not affected by N deficiency.

This leads to the conclusion that N was not a factor that reduced dry mass production under the applied N fertilization strategies. N applications might even be reduced further. It is recommended to explore when dry mass is affected by N deficiency and to explore what N losses might be within reach with high biomass production.

This study showed that the N use efficiency was increased when N applications were split and corrected for the mineral N in the topsoil. The effectiveness of irrigation was increased when irrigation was based on a threshold value in the rooting environment. In spite of all these increased efficiencies, the percolating soil solution below the rooting zone still exceeded the limit of 11.3 mg nitrate-N L^{-1}. High nitrate concentrations in the shallow groundwater are also found for other nursery stock crops such as poplar (McLaughlin *et al.*, 1985) and agricultural and horticultural cropping systems on sandy soils in the Netherlands (Fraters *et al.*, 2004).

The N leaching losses were highest in the year of planting, although N application rates were low, 49 kg N ha^{-1} yr^{-1}. Apparently, the transplanted conifers required little nitrogen. This was also found by Ledin (1986) for nursery stock crops and by Millard & Neilsen (1989) for apple root stocks. These authors suggested that the low N requirement was related to the 'not yet established root system', with relatively large areas without roots. Moderate and fertile soils release substantial amounts of mineral N and this N may be easily leached from these rootless areas in periods when precipitation surpluses occur. Placement and split applications of reduced amounts of fertilizer N may increase the chance of acceptable N concentrations in the percolating soil solution in the year of planting and at the same time maintain high biomass production.

The relatively high fertility of the sandy soil used in this study probably is a result of the high organic amendments when N application rates were not restricted. Application rates of solid manure for field-grown nursery stock in Germany ranged from 65 to 85 tons fresh material ha^{-1} annually (115 to 203 kg N ha^{-1} yr^{-1}) in the late eighties (Alt *et al.*, 1989) and although no specific data are available for Dutch nurseries, application rates are likely to resemble the German application rates. Application rates had no bearing on N uptake by the crop. Although the effect of high soil fertility will cease when application rates are reduced, mineralization rates might not decrease enough to meet the N limit. A sandy topsoil (0-0.3 m) with 2% organic matter, a decomposition rate of 2%, a C:N ratio of 10 and a C- content of organic matter of 54%, releases 65 kg N ha^{-1} yr^{-1}. Annual deposition of N is 54 kg yr^{-1} (Boumans *et al.*, 2004) and uptake by conifers in the year of planting is approximately 50 kg N ha^{-1} at standard planting distances (this study, Alt, 1998; Dierend, 1992; Oele, 1994). The surplus of this simplified N balance is 69 kg N ha^{-1} in the year of planting. With an average precipitation surplus of 250 mm yr^{-1} estimated using the reference evapotranspiration (Boumans *et al.*, 2004) and no denitrification, this leads to a concentration of approximately 30 mg N L^{-1}. The precipitation surplus for conifers will most likely be larger than estimated for the reference evapotranspiration. Subsequently this will lead to lower nitrate concentrations with the same N losses. When 50% is denitrified before reaching the shallow groundwater, the concentration drops to 15 mg N L^{-1}. However, in both cases the limit is not met and growers have not even applied any organic materials or additional N fertilizers.
In conclusion, if conifers grown on high and may be even moderate fertile sandy soils with relatively low groundwater tables have to comply with the N limit for groundwater, additional actions are needed to reduce N losses (see next paragraph).

The model as a tool to evaluate effects of measures on N leaching

This model can be used to evaluate the effects of increased governmental restrictions of N inputs on dry mass production and N losses. The measures will be designed to reduce the N concentration of the percolating soil solution. The model will also indicate effects on dry mass production. With only small modifications the model can also evaluate effects of the application of organic materials on dry mass production and N losses.

The model can be used to evaluate the effect of increased plant density on N leaching. Plant densities of 15 plants per m^2 for *Thuja* as practiced on the very favorable peat soils (high water holding capacity, high mineralization rates, low bulk densities for easily rooting) in the Boskoop area might reduce N losses to acceptable levels. This high plant density does not affect plant quality on this peaty soil. Model calculations can indicate if N concentrations drop below critical N concentrations and how irrigation and N fertilizer application might need to be adapted to ensure high biomass production. This model can also be used to develop advanced N application strategies like placement of N fertilizer applications and the model may find out when the application is best to be carried out. Results might be implemented in fertilizer recommendations. It can also be used to evaluate effects of catch crops on N leaching. Using catch crops seems a promising technique to reduce nitrate concentrations below the system (Hanninen, 1998; McLaughlin *et al.*, 1985). Winter hardy catch crops like rye and oats, can be sown as groundcover from mid August on in the year pf planting, when N uptake slows down and N accumulates in the soil profile. These catch crops carry the N over the winter period. They can be mowed and incorporated with a shallow soil operation in May or killed by pesticides. The N mineralized from the catch crop residue can be used by the nursery stock crops.

The model as a decision support tool for growers

A decision support tool to increase the irrigation and N use efficiencies provides support to decision making on a short time scale. The support systems need to answer questions like:
is irrigation necessary now or can it wait and is N fertilization necessary and if yes, how much? The requirements for such systems are high. From a growers point of view they need to be easy to use and reliable.

At this moment, there are two major concerns when using the model in practice at this stage of development, one for the use as a decision support tool for irrigation scheduling and one for N fertilizer application.
With respect to scheduling irrigation, the model is a complicated software tool with a high demand for information on specific growth conditions: soil type, soil characteristics, water retention curves, organic matter dynamics, physiological tree characteristics such as the water use efficiency or the transpiration reduction function, initial tree weight and initial leaf area index. When the model is parameterized for a specific field it requires the weather data on a daily basis. The model is sensitive for information on precipitation. The best approach would be to involve private companies, as promising examples exist for decision support systems on irrigation for fruit tree (Boshuizen & Van Der Maas, 1999).

With respect to the support of N fertilizer applications, the model has a relatively simple approach on N mineralization. Although the mineral N content in the topsoil was nicely predicted mid May and at the end of June, the mineral N content was underestimated in August in the treatments where no or hardly any irrigation was applied. The fertilizer recommendations are based on the mineral N content mid May and at the end of June, but because of the large discrepancies in August the mineralization should be investigated and validated before the model can be used as a decision support tool for N fertilizer applications.

Subjects for further research

1. Growth of the tree is initiated at bud burst and bud burst is based on a visual assessment of the first leaf growth in the spring. It is suggested by Atkinson & Wilson (1980) that root growth and N uptake may precede budburst. Knowledge on root growth and N uptake in relationship to bud burst can increase N use efficiency because the time of application can be adjusted to the moment N uptake occurs. This aspect should be explored further.

2. No symptoms of N deficiencies were found in the field trial on the moderately fertile sandy soil. It is therefore not clear when dry mass production will be affected by N deficiencies. As leaching of nitrate N occurs due to high mineralization rates, one measure to meet the N limit might be to reduce the mineralization rate. This is done by reduced soil fertility. To balance between reduced soil fertility and maintaining a sufficient N supply to the crop, we need to know what the critical N concentrations in the different plant parts are and at which N supply these critical concentrations occur. With both aspects combined, critical concentrations and uptake efficiency, guidelines on organic matter fertilization can be developed which meet the N limit and the N demand of the crop.

3. The model should be used to explore fertilization strategies involving placement of fertilizers and time of application in the spring. With only small modifications, it can also be used to explore effects of the use of manure or composted products. In addition, the use of catch crops on N losses and N concentrations need to be explored.

4. This study clearly indicates that the EU limit for nitrate in the groundwater is a real challenge for field grown conifers on moderate fertile sandy soils with a relatively low groundwater table. Research should focus on the development of culturing practices which reduce N losses from the system. The benefits of a winter hardy catch crop sown in the year of planting should be quantified. Perhaps a more acceptable strategy fro growers will be an increased plant density.

6. The water use efficiency was assumed to be constant during the cultivation period of field grown *Thuja*. However, this might not be the case for a crop of which the leaf area index increases from 0.1 at planting to 4 or 5 at harvest and the leaf area density within the cone increases when crop age. The model was very sensitive for the water use efficiency. Because of this sensitivity and the assumption, the water use efficiency needs to be further investigated.

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Summary

Governmental regulations on inputs of nutrients and irrigation in agricultural production systems are increasingly restrictive and sometimes banning conventional cultivation practices in nursery stock cropping systems in the Netherlands. Restrictions in nitrogen (N) input are enforced to meet the nitrate-N limit in groundwater of 11.3 mg N L^{-1}. Restrictions in irrigation practices in the summer are enforced to prevent groundwater tables from falling. Consequently, growers face problems with N fertilizer applications and irrigation. The effects of the restrictions on dry mass production and emissions to the environment of nursery stock are not yet known. The aim of this study was therefore, to increase the understanding of the effects of irrigation and N fertilizer applications on dry mass production of conifers on sandy soil and on water and N losses to the groundwater. The study focused on the relationship between inputs (water and N supply) and outputs (dry mass production, water and N leaching) in the crop-soil system. The specific output of this study was a field-based model to explore the effects of irrigation and fertilizer strategies on dry matter production and on N losses. The model was used to evaluate irrigation strategies aimed to increase the effectiveness of irrigation. Also the impact of fertilizer application methods and application levels on N (leaching) losses within the framework of the EU nitrate-N limit was assessed.

Light interception is one of the basic processes for plant production and a simple method was developed to estimate the fraction of the total radiation intercepted by small *Thuja occidentalis* (Chapter 2). The row crop method to intercept radiation was modified to describe radiation interception of the crop canopy presented as rows of cuboids. Radiation interception estimated with the rows of cuboids method was compared with methods used for estimating radiation interception by crops with homogeneous canopies and crops grown in rows. To perform these calculations, the radiation extinction coefficient was determined, using different plant arrangements of *Thuja*. An average k value of 0.48 ± 0.03 (R^2 = 0.89) was found and used in the estimations of the fractions of intercepted radiation. Effects of changing plant characteristics and inter- and intra-row plant distances were explored. The fraction intercepted radiation that was estimated with the method for rows of cuboids and for row crops was up to 20% and 8% lower than estimated with the method for homogeneous canopies at low plant densities and a leaf area index of 1. The fraction radiation intercepted by small plants of *Thuja occidentalis* was best estimated by the simple method for rows of cuboids.

Light interception results in dry mass production. The concept of a constant radiation use efficiency was combined with the method for radiation interception of a row of cuboids (Chapter 3). A dynamic simulation model of dry mass production and leaf area development of ornamental conifers, CONGRO, was developed. A field trial was used

to calibrate the radiation use efficiency and the dry mass partitioning as well as to obtain the specific leaf area. The increase of the leaf area was simulated through leaf dry mass increase and the specific leaf area. Ten independent trials (1991-1999) were used for validation. Predicted aboveground dry mass agreed well with measured data (R^2 = 0.94). The predicted leaf area index agreed less with experimental field data (R^2 = 0.90). The sensitivity analysis showed a large positive and sometimes more than proportional effect of the radiation use efficiency, the specific leaf area and partitioning into the leaf dry mass on the simulated total dry mass, the leaf dry mass, the leaf area index and the intercepted radiation.

In Chapter 4 two-dimensional diffusion parameters for dynamic root growth under wet and dry conditions were estimated based on the dry mass production partitioned to the fine roots and the concept of a convective-diffusion model of cylindrical root growth and proliferation. To achieve this, aboveground dry mass, total root dry mass and root length density of the fine roots of *Thuja occidentalis* were determined under non and drip-irrigated field conditions. Drip irrigation increased both aboveground dry mass and the shoot:root ratio compared to those with no irrigation. Dry mass of the coarse roots increased as well, due to drip irrigation. No effect on total or fine root dry mass was found. Drip irrigation decreased root proliferation in depth by 27%, whereas proliferation in the horizontal direction was not altered. Simulated root length densities with the two-dimensional diffusion parameters overestimated measured root length densities by 6 to 21% ($0.68 < R^2 < 0.92$).

The 'row of cuboid' method to estimate light interception and the two dimensional root growth were implemented in the model for dry mass production of conifers CONGRO. To simulate drip-irrigated systems, CONGRO was combined with the two-dimensional soil-water balance model FUSSIM2, which was modified to cylindrical coordinates, parameterized and validated in Chapter 5. The combined model was used to investigate dry mass production and water use of *Thuja occidentalis* in a field trial under non-irrigated and drip-irrigated conditions. Measured leaf dry mass and leaf area index were not affected by irrigation but irrigation increased stem dry mass and the specific leaf area. Simulated dry mass and leaf area index were in good agreement with the measurements. Often simulated pressure head in the soil followed the measured pressure head, although the model performance was better under dry than under wet conditions. Simulation experiments indicated that increasing irrigation threshold levels (resulting in more irrigation) increased dry mass production and leaching relative to no irrigation.

In Chapter 6 N uptake of *Thuja* was included in the conifer growth model CONGRO and nitrogen was included in the two-dimensional soil water model FUSSIM2 for cylindrical co-ordinates. The model was calibrated and used to explore effects of three irrigation strategies in combination with split-fertilizer application strategies and two application rates for 30 cultivations on selected model output parameters. The output parameters included N use efficiency (calculated as the N uptake by the crop divided by total N supply through fertilization and mineralization), N application rate corrected

for the mineral N content of the topsoil and N loss. Irrigation strategies included no irrigation and daily drip irrigation, as well as irrigation triggered by a soil water pressure head threshold value. Fertilizer application strategies consisted of a single application and split-applications. Application rates included a standard rate and a standard rate corrected for the actual mineral N content in the topsoil. The model was calibrated successfully although discrepancies were found between the simulated and measured mineral N content of the soil, mainly during the first growing season. The average simulated N use efficiency was 31% in the first and 69% in the second growing season. Correction for the mineral N content of the topsoil reduced the N application rate compared to no correction. The reduction was highest for the non and threshold-irrigated strategies. Simulated N losses ranged from 118 kg N ha^{-1} in the non-irrigated strategy with split-applications and correcting for the mineral N content of the topsoil, to 218 kg N ha^{-1} in the daily drip-irrigated strategy with split-applications during the two-year cultivation. Simulated N concentrations in the percolating soil solution at 1 m depth exceeded the nitrate-N limit of 11.3 mg L^{-1} in almost all cases.

The main results and limitations of this study are discussed in Chapter 7 and suggestions for further research are given.
This study demonstrated that potential dry mass production under optimized irrigation and N applications reduced the N concentration in the percolating soil solution but the concentration still exceeded the nitrate-N limit of 11.3 mg L^{-1}. Additional measures are necessary to improve the N use efficiency to reduce N losses and to develop conifer-cropping systems on sandy soil, which meet the policy constrains for nitrate in groundwater.

Samenvatting

De laatste jaren is het mineralenbeleid van de overheid erop gericht om de emissie van stikstof en fosfaat vanuit de landbouw terug te dringen. De aanvoer van dierlijke mest en kunstmest zijn daardoor per bedrijf genormeerd. Deze maatregelen zijn er mede op gericht om de limiet gesteld aan de grondwaterkwaliteit van 11.3 mg nitraat stikstof per liter te halen. Het overheidsbeleid is er tevens op gericht om verdroging in bepaalde delen van Nederland terug te dringen. Op de droge zandgronden wordt grondwater gebruikt voor beregening tijdens droge perioden. De lokale overheden voeren een beleid uit om onttrekking van grondwater te verminderen en stellen daarbij beperkingen aan de beregening van akker- en tuinbouwgewassen in de desbetreffende regio's. Belastingen op grondwateronttrekking kunnen door ondernemers terug ontvangen worden als ze gebruik maken van beslissingsondersteunende systemen voor de beregening. De onttrekking moet tevens geregistreerd worden met gecertificeerde watermeters. Ook de boomkwekerijsector wordt geconfronteerd met deze toenemende regelgeving op het gebied van bemesting en beregening. De regels beperken in toenemende mate de inzet van deze productiefactoren. Het effect van deze beperkingen op de gewasgroei van boomkwekerij producten en de vermindering van de emissies naar het milieu zijn echter niet bekend. Tevens zijn er weinig geschikte beslissingsondersteunende beregeningssystemen voor boomkwekerijgewassen beschikbaar.

In deze studie staat het effect van de beperkingen van de productiefactoren water en stikstof op de gewasgroei van boomkwekerijgewassen en de emissies van stikstof en water centraal. Het doel van deze studie was om de effecten van beregening en stikstofbemesting op de gewasgroei van *Thuja occidentalis*, modelgewas voor de boomkwekerij, en op de verliezen van water en stikstof naar het bovenste grondwater beter te begrijpen. De studie was vooral gericht op de relatie tussen water en stikstof in het plant-bodem systeem. De kennis die nodig was om deze relatie goed te beschrijven is geïntegreerd in een model. Dit model was geschikt om verschillende beregeningsstrategieën te evalueren in combinatie met verschillende bemestingsstrategieën en verschillende doseringen stikstof. In de evaluatie stonden de drogestof productie, de beregenings- en stikstofefficiëntie en de stikstofverliezen centraal. De studie is uitgevoerd voor *Thuja occidentalis*, geteeld gedurende twee jaar op een droge zandgrond. Het ontwikkelde model kan gebruikt worden om beleidsmaatregelen te evalueren op de beoogde effecten. Tevens is dit model, na enige aanpassingen, geschikt om als een beslissingsondersteunende begereningswijzer te dienen voor de praktijk voor de teelt van *Thuja*.

Voor de ontwikkeling van dit model was het nodig om vijf aspecten van het plant-bodem systeem verder te onderzoeken. Dit resulteerde in vijf studies die ieder in een hoofdstuk van dit proefschrift beschreven worden.

In hoofdstuk 2 staat de lichtonderschepping door *Thuja occidentalis* centraal. Hoewel deze lichtonderschepping in eerste instantie beschreven werd door het bladerdek van

het gewas in rijen op te delen, was een verdere verfijning noodzakelijk. De open ruimte tussen de planten in rij is namelijk bijna net zo groot als de open ruimte russen de rijen. De lichtonderschepping is daarom beschreven als de onderschepping door het bladerdak te beschouwen als losstaande rechthoeken: de rij is opgedeeld in kleine rijtjes met de vorm van een rechthoek. Hierdoor is er rekening gehouden met de gewasloze ruimte in de rij. De verschillende berekeningsmethoden om de lichtonderschepping te schatten, de rijbenadering en de rechthoekbenadering, zijn vergeleken met de standaardmethode voor een homogeen bladerdek. Om deze berekeningen te kunnen uitvoeren was het nodig om de uitdovindscoefficiënt in het bladerdek van *Thuja* te bepalen. Hiervoor zijn lichtonderscheppingsmetingen uitgevoerd aan planten met verschillenden hoeveelheden bladeren en bij verschillende plantdichtheden. De uitdovingcoëfficiënt was 0.48 ± 0.03. De fractie onderschept licht, berekend met de methode voor rechthoeken bij een bladoppervlakte-index van 1 bladlaag per m^2, was 20% lager dan met de standaardmethode voor een homogeen bladerdek. De lichtonderschepping berekend met de rijenmethode was 8% lager t.o.v. de standaardmethode. Het was daarom noodzakelijk om de lichtonderschepping van *Thuja* te berekenen met de methode waarin het bladerdek van het gewas beschouwd wordt als een rij van individuele rechthoeken.

Het onderschepte licht wordt in een gewas omgezet in drogestof. In hoofdstuk 3 is in een veldproef de hoeveelheid drogestofproductie per onderschepte hoeveelheid straling bepaald, de 'Radiation Use Efficiency'. Deze gegevens zijn gebruikt om het CONiferen gewasGROei model CONGRO te kalibreren. Het model is gevalideerd met 10 onafhankelijke proeven en de gesimuleerde drogestofproductie kwam goed overeen met de gemeten drogestofproductie (R^2 = 0.94). De gesimuleerde bladoppervlakte-index kwam iets minder goed overeen met de gemeten bladoppervlakte index, (R^2 = 0.90). De modeluitkomsten 'totale drogestofproductie', 'bladmassa', 'bladoppervlakte-index' en de 'fractie onderschept licht', waren erg gevoelig voor kleine veranderingen in het model van de invoerparameters 'Radiation Use Efficiency', het specifiek bladoppervlak en de verdeling van drogestof over de verschillende gewasdelen.
De wortelgroei is beschreven als een tweedimensionaal diffusieproces door de fractie drogestof verdeeld naar de fijne wortels te combineren met de wortelverdeling van *Thuja* tijdens de teelt (hoofdstuk 4). De gefitte diffusieparameters waren verschillend voor natte en droge omstandigheden in het tweede teeltjaar. De diffusieparameters zijn in het gewasgroeimodel CONGRO geïmplementeerd.
De koppeling van het gewasgroeimodel CONGRO aan het model FUSSIM2 is beschreven in hoofdstuk 5. Het model FUSSIM2 beschrijft de waterbalans in twee dimensies maar omdat in deze studie gewerkt is met druppelbevloeiing, is het model aangepast aan radiale co-ordinaten. Hierdoor wordt het watertransport over de r-as (radiaal) en de z-as (verticaal) gesimuleerd. Het gecombineerde model is geparametriseerd voor een droge zandgrond in Nederland. Het model voorspelde de drogestofproductie onder natte en droge omstandigheden goed. De gesimuleerde drukhoogten vertoonden hetzelfde patroon als de gemeten drukhoogte. De correlatie tussen gesimuleerde en gemeten drukhoogten was echter onder droge omstandigheden

beter dan onder natte omstandigheden. Met het gecombineerde model, zijn verkennende berekeningen uitgevoerd, om de strategie voor de maximale benutting van de beregening te bepalen. *Thuja* kan het beste beregend worden als een drukhoogte van –25 kPa op 0.25 m diepte recht onder de stam bereikt wordt. Bij deze strategie wordt de drogestofproductie benaderd en treden de minste verliezen van water op.

Verliezen van water gaan doorgaans gepaard met verliezen van stikstof. Stikstof is het laatste aspect dat in deze studie onderzocht is (hoofdstuk 6). De opname van stikstof door het gewas is gebaseerd op metingen in een veldproef met *Thuja* met vier beregeningsstrategieën. *Thuja* was bemest volgens het bemestingsadvies. Daardoor is er bij het modelleren van stikstofopname door het gewas vanuit gegaan is dat er geen groeireductie is opgetreden door stikstoftekorten. Het gewasgroeimodel is aangepast om de stikstofvraag te berekenen. FUSSIM2 is uitgebreid met modules die de stikstofprocessen in de bodem simuleren en is gekalibreerd op veldmetingen. De gesimuleerde stikstofopname door het gewas was in overeenstemming met de gemeten waarde, zodat de kalibratie goed was uitgevoerd. Echter, de gesimuleerde stikstofhoeveelheid in de bouwvoor bij de behandelingen met weinig beregening bleef in augustus bleef fors achter bij de gemeten hoeveelheden. Toch is het model vervolgens gebruikt om verschillende scenario's door te rekenen voor 30 teelten van *Thuja*, iedere teelt startend in een ander jaar. De scenario's bestonden uit drie beregeningsstrategieën (geen beregening; dagelijkse hoeveelheid via druppelbevloeiing; druppelbevloeiing als een bepaalde drukhoogte bereikt wordt) gecombineerd met twee stikstoftoedieningsstrategieën (1 gift; gedeelde gift) en twee doseringen (de standaarddosering; standaarddosering verminderd met de minerale hoeveelheid stikstof in de bouwvoor op het moment van toediening). Er is gekeken naar effecten op de stikstofefficiëntie (berekend als de opname door het gewas gedeeld door het totale aanbod via bemesting en mineralisatie), de totale stikstofgift na correctie voor de minerale N voorraad in de bouwvoor en de stikstofverliezen. De gemiddelde benutting van stikstof was 31% in het eerste en 69% in het tweede groeiseizoen. De stikstofgift was aanzienlijk kleiner dan de standaardgift, als er rekening gehouden werd met de minerale stikstofhoeveelheid in de bouwvoor. Niet beregenen en beregenen m.b.v. een drempelwaarde, leverde de grootste 'winst' op. Het berekende stikstofverlies was 118 kg N ha^{-1} tijdens de gehele teeltperiode als er niet beregend werd, de bemesting gedeeld en er rekening gehouden werd met de minerale hoeveelheidstikstof in de bouwvoor. Het grootste verlies werd gevonden bij een dagelijkse beregening en een gedeelde standaardbemesting en bedroeg 218 kg N ha^{-1}. De gesimuleerde stikstofconcentratie in het lekwater beneden de wortelzone (1 meter diepte), was in bijna alle berekeningen hoger dan de gestelde limiet van 11.3 mg nitraat-N L^{-1}.
In hoofdstuk 7 worden de belangrijkste resultaten en beperkingen besproken en staan er aanbevelingen voor toekomstig onderzoek.

Curriculum vitae

Annette Pronk werd geboren op 14 juni 1964 te Amsterdam. Na het doorlopen van de Vrije School, eerst in Haarlem, daarna in Zeist, heeft zij in 1984 op het Eemland College (Amersfoort) het VWO-diploma behaald. Aan de toenmalige Landbouw-universiteit in Wageningen studeerde zij van 1984 tot 1990 Landbouwplantenteelt, oriëntatie Akkerbouw. Tijdens de doctoraalfase heeft zijn drie afstudeervakken gedaan. Voor haar stage Alternatieve Landbouw bracht ze 3 maanden door aan Cornell University (USA).Na haar afstuderen wekte ze een jaar in de Verenigde Staten op het biologische onderzoeksinstituut Rodale Institute Research Center. Hier werkte zij mee aan verschillende langjarige proeven zoals the Farming System Trial, the Compost Utilization Trial en the Low Input Reduced Tillage Trial. Na terugkomst in Nederland heeft zij verschillende functies vervuld bij het toenmalige Proefstation voor de Boom-kwekerij. In 1996 kreeg ze een 4 jarig contract aangeboden als wetenschappelijk onderzoeker bemesting en hierbij deed zich de gelegenheid voor een voorstel voor een promotieonderzoek te formuleren. In 1998 is gestart met het experimentele werk. In 1999 werd het toenmalige contract omgezet in een vaste aanstelling. Daarmee kwam het onderzoek naar geïntegreerde en biologische bedrijfssystemen bij haar terecht, het onderzoek naar beregenen in de vollegrond en het voorzitterschap van de werkgroep biologische Boomteelt. Bij de fusie van PPO en DLO in het najaar van 2001 heeft zij de overstap gemaakt naar Agrosysteemkunde bij Plant Research International in Wageningen. Daar is zij tot op heden werkzaam als wetenschappelijk onderzoeker landbouwbedrijfssystemen.