

Prediction of turf growth as a function of light and temperature under Nordic conditions

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Abstract

The aim of the project was to find a method to predict the potential growth and winter hardiness of three turf grass species as a function of different light and temperature conditions. Good knowledge of the potential growth is the basis for planning of a sound sustainable maintenance program, both regarding turf grass quality and economical and environmental concerns.

A simulation model for grass growth and winter mortality was used to estimate growth curves and winter survival for three different turf grass species (*Agrostis stolonifera*, *Festuca rubra* and *Poa annua*) for different climatic conditions. Four locations in the Nordic countries (Umeå, Västerås and Lund in Sweden and Særheim in Norway) were modeled. The three different places in Sweden represented different light and temperature conditions due to different latitudes. Særheim in Norway was selected to represent a more maritime climate. The effect of different climate change scenarios was also tested. Field data from Fullerö GK, Västerås was sampled during 2007 and 2008 to be used for calibration of the model.

The established model could reproduce growth pattern of turfgrass (*Agrostis stolonifera*) within the range of measurements several years when compared to independent data of grass clippings. However, there are still many uncertainties in the parameterization of the model, and especially with the winter mortality part, because the lack of physiological knowledge of the grass species studied and a lack of observations to test the model against.

The results on winter mortality showed very interesting results and identified the complexity between the two opposite processes of hardening and dehardening and the interaction with the climatic conditions during winter to determine the effects on plant mortality. The model showed that although a milder climate reduced the risk for temperatures below the minimum temperatures for grass tolerance at maximum hardening, mild autumns can lead to a less effective hardening so that maximum hardening never is reached. The weaker hardening made the grass more sensitive to low temperatures. A milder climate also decreased the number of days during winter with snow cover. The number of days with snow cover and the depth of snow are very important parameters for the soil surface temperature and thus for the survival of the turf.

Conclusions

- The established model could reproduce growth pattern of turfgrass (*Agrostis stolonifera*) within the range of measurements several years when compared to independent data of grass clippings.
- Winter mortality was the most important factor for the differences in the biomass pool when comparing Umeå (*Poa*), Västerås and Lund (*Agrostis*). However, when the same species were simulated for all sites the differences in winter mortality between the sites decreased. Actually, severe winter mortality was more frequent in both Västerås and Lund compared to Umeå for *Agrostis*, and almost as severe in Västerås as in Umeå for *Poa*.

- The model showed that a milder climate could lead to a less effective hardening during autumn so that maximum hardening never is reached, thus increasing the risk for winter kill during cold spells.
- A milder climate also reduced the period with snow cover during winter, which caused a more rapid dehardening to occur.
- As expected, the growth period lasted longer due to higher temperatures in the autumn for the coastal climate of Särheim compared to Västerås. However in spring the climatic conditions were more similar. The simulated growth at Särheim was much influenced by low radiation conditions during rainy periods during summer.
- The winter hardening/dehardening was much influenced by the climate change scenario, leading to a much weaker hardening and a more rapid dehardening, especially for the *Agrostis* turf in Västerås and Lund.

Introduction

Maximum plant growth is determined by the amount of solar radiation reaching the photosynthesizing part of the plant. Factors such as temperature, nutrients and water will limit the potential growth. It is a challenge for superintendents to find the optimum maintenance of the turf to meet the conditions due to the daily weather and wear, and at the same time strengthen it for coming weather conditions. Climatic conditions affect the turf status throughout the year. At our Nordic latitudes, temperature is normally the most limiting factor in spring for the onset of growth, while in autumn, light is the main factor that reduces growth. Plant respiration continues although no growth occurs. This maintenance respiration depends on temperature and the amount of accumulated biomass (Biscoe et al., 1975) and can cause a substantial loss of biomass during periods with low incoming radiation and relatively high temperatures (>5 °C) (Blombäck & Eckersten, 1997). A higher respiration rate in the autumn can cause problems for cold acclimation of the plants, thus reducing winter hardiness and enhancing the risk for winter kill (Junttila et al., 1990; Fowler et al., 1999). Generally, carbohydrate concentration is highly positively correlated with frost tolerance of plants (e.g. Pontis, 1989; Dalmansdottir et al., 2001). Both light and temperature dependent processes favouring net assimilation and accumulation of sugar in the basal parts of the shoot and in the roots are important. However, fertilization with nitrogen prior to cold acclimation has been found to decrease cold hardiness (e.g. Hetherington et al., 1990). Although hardened plants of cold temperate turf grass species have a low baseline temperature for winter hardiness (< -20 °C) (Gusta et al., 1980; Tompkin et al., 2000; Frank Rossi, personal communication), they are generally not winter dormant and lose hardiness easily (Tompkin et al., 2000).

Over the last 15 years the climate has changed in Sweden, with an increase in annual mean temperature of 0.9 °C, and during winter of up to 2.5 °C (SMHI, 2006a). In both 2005 and 2006 the autumns were very mild, with day temperatures up to 10 °C higher than average (SMHI, 2006b). In practice, superintendents normally have a well functioning empirically based knowledge of how much the turf grows at different times during the season in response to their maintenance program (fertilization, irrigation, other maintenance) and wear. But in a changing climate, maintenance practices must be adjusted to fit both the new growth dynamics of the turf and changes in playing intensity. To be able to evaluate, change or fine-tune the maintenance, the potential growth given by light and temperature at different times of the year must be known. Today, there is an ongoing discussion on how to fertilize during long, mild autumns to support a proper re-growth but without interfering with the winter hardening processes. An improved knowledge of the potential growth during low-light situations will make it easier to find a balance between wear and maintenance practices on the one hand and the potential re-growth on the other. To resolve this debate, one starting point would be to investigate how the turf actually behaves in the autumn at our Nordic latitudes, i.e. under low light conditions and variable temperatures. In this respect, simulation models can be powerful and cost-effective tools.

Simulation models for grass growth, based on plant physiological processes and calibrated for the different qualities of different grass species, can be used to estimate the potential growth for different light and temperature conditions throughout the year. From the potential growth curves it will be possible to

- Fine-tune fertilization in autumn to match the growth and estimate the turf re-growth potential and thereby the tolerance for wear
- Fine-tune fertilization during the season according to light, temperature and different stress factors.

Objectives

The aim of this study was to determine the potential growth of short-cut turf grass (*Agrostis stolonifera*, *Festuca rubra*, *Poa annua*, respectively) as a function of temperature and light at different Nordic latitudes, including hardening/dehardening processes and winter mortality.

Delivered results and practical implications

1. A growth model, including a module for simulation of winter survival, and parameter sets for the turf species *Agrostis stolonifera*, *Festuca rubra* and *Poa annua*.
Implication: The parameterised model is available for further studies on turf growth and winter survival.
2. Potential growth curves for the three studied grass species were established for different Nordic climatic conditions (Umeå, Västerås, Lund and Særheim) and for different time periods.
Practical implication: The growth curves can form a basis for improved fertilization practices.
3. Winter hardening/dehardening curves and winter survival under different climatic conditions were estimated.
Practical implication: Improved knowledge of the winter hardening and de-hardening processes will improve the recommendations for maintenance.
4. The effect of a warmer climate on turf growth and winter survival was estimated for different Nordic climatic conditions through climate change scenarios.
Practical implication: The scenarios indicate the sensitivity of the turf for changes in climatic conditions, and will thereby increase the awareness on different stress factors.

Materials and methods

A grass growth model (Eckersten et al., 2004, 2007; Torssell et al., 2007) developed from processes of the SOILN model (Blombäck & Eckersten, 1997; Blombäck et al., 1998) was used to simulate shoot and root biomass production and losses of the grass species *Agrostis stolonifera*, *Festuca rubra* and *Poa annua* used as golf green turf. The model was also developed to include a winter survival module. The model was parameterised according to available literature information on the plant physiology of the species *Agrostis stolonifera*, *Festuca rubra* and *Poa annua*, and further calibrated to measured data on clippings from an experiment located at the Fullerö Golf Club outside Västerås in central Sweden. The calibrated model was then run using weather data recorded for different time periods and different Nordic climatic conditions (1965-1987 for Umeå, Västerås and Lund in Sweden; 2001-2008 for Fullerö GC in Västerås; 2006-2008 for Særheim in Norway). Climate change scenarios were also simulated for the different sites.

Experimental data

Growth of three different grass species (*Agrostis stolonifera*, *Festuca rubra* and *Poa annua*) was measured during 2007-2008 at the experimental greens established at Fullerö Golf Club outside Västerås in central Sweden to be used for calibration of the model. The experimental site was originally designed to test different fertilization strategies for the different grass species (Blombäck et al., 2007). For this study the treatment with maximum fertilization (100% of demand) was used to avoid reduced growth due to nutrient stress. The greens were fertilized weekly. *Agrostis* was fertilized with a total amount of 2.1 kg/100 m², *Poa* with 2.3 kg/100 m² and

the *Festuca* with 1.0 kg/100 m². Irrigation was applied when needed to avoid growth reduction due to drought. The experimental greens were used as chipping greens (*Agrostis* and *Festuca*) and as an ordinary green at the golf course (*Poa*) to get a natural wear of the turf by foot tramp and machinery.

Grass clippings were sampled at four occasions (June, July/August and September 2007 and April 2008) for the *Agrostis* and *Festuca* species and at three occasions (July/August and September 2007 and April 2008) for *Poa*. At each occasion, clippings were collected daily or every second day for a period of 3 to 5 days to get a value for the daily shoot growth. The maximum fertilization treatment had three replicates for each grass species, and each replicate was sampled and treated separately. The plant material was dried at 60 °C for three days and weighed to determine the biomass content. The plant material was also combusted to adjust for sand content in the samples. The total nitrogen content of the plant material was determined (Leco).

Standing biomass above ground, i.e. turf biomass below clipping height, was determined at one occasion in April 2008. Three cores (Ø 22mm) were taken in each replicate immediately after mowing of the grass and the grass was sampled by cutting close to the soil surface. The same procedure as for the grass clippings was used to determine the dry weight of the standing biomass.

For validation of the model simulations, measured data on grass clippings from an earlier experiment at Fullerö GK in Västerås (Blombäck et al., 2003) was used. Grass clippings from the experimental green with *Agrostis stolonifera* turf was sampled daily during three monitoring campaigns in the summers 2001-2003. Clippings were collected from four different treatments with different soil organic matter content (2, 3 and 4%), but managed in the same way (i.e. fertilization, irrigation, aeration, sand dressing etc.). Weather data from Uppsala was used to run the simulations for validation.

Model description

The model (Fig 1.) is based on the concept of radiation use efficiency, and where growth is a function of intercepted light and temperature. The model simulates shoot and root growth and maintenance respiration on a daily basis, including re-growth after mowing. Plant biomass is represented by three state variables, leaves, stems and roots, respectively. The development of plant biomass is simulated as a function of daily values for air temperature and solar radiation. The mass balance of the plant is simulated as function of processes for growth, allocation, re-growth and losses and is updated daily. To simulate frost damage, a winter hardiness model was coupled to the growth model. The winter hardiness model was originally developed for North American continental conditions (Fowler et al., 1999) and then later adapted and applied to winter wheat grown under Norwegian conditions (Bergjord et al., 2008). The model calculates daily low-temperature tolerance values in terms of LT₅₀ (minimum temperature that causes 50% plant mortality) according to:

$$LT_{50} = LT_{50(t-1)} - RATEH + RATED + RATES + RATER . \quad (1)$$

Low temperature acclimation, or hardening (RATEH), occurs during the vernalization period in the autumn and early winter when plants are exposed to temperatures below 10 °C. Dehardening (RATED) occurs when the plants are exposed to warmer temperatures, during prolonged exposure to near lethal temperatures (RATES), or due to respiration stress when covered by a thick layer of snow (RATER). Once the vernalization period is complete, LT tolerance is maintained within a certain range of temperatures and dehardening occurs when the plants are exposed to warmer temperatures. Once dehardening occurs the plants have limited ability to reharden if exposed to cold temperatures again (see equations 17-20 in Appendix 1 for details). When temperatures approach LT₅₀, mortality occurs. Biomass is also lost through root turnover and leaf senescence. The growth model can be coupled to a soil sub-model to include the effects

of nitrogen and water as an option. However, this option was not used in this experiment since optimum water and nutrient status was assumed. Recorded weather data is used as driving variables for the model. More detailed information about the model is referred to Appendix 1.

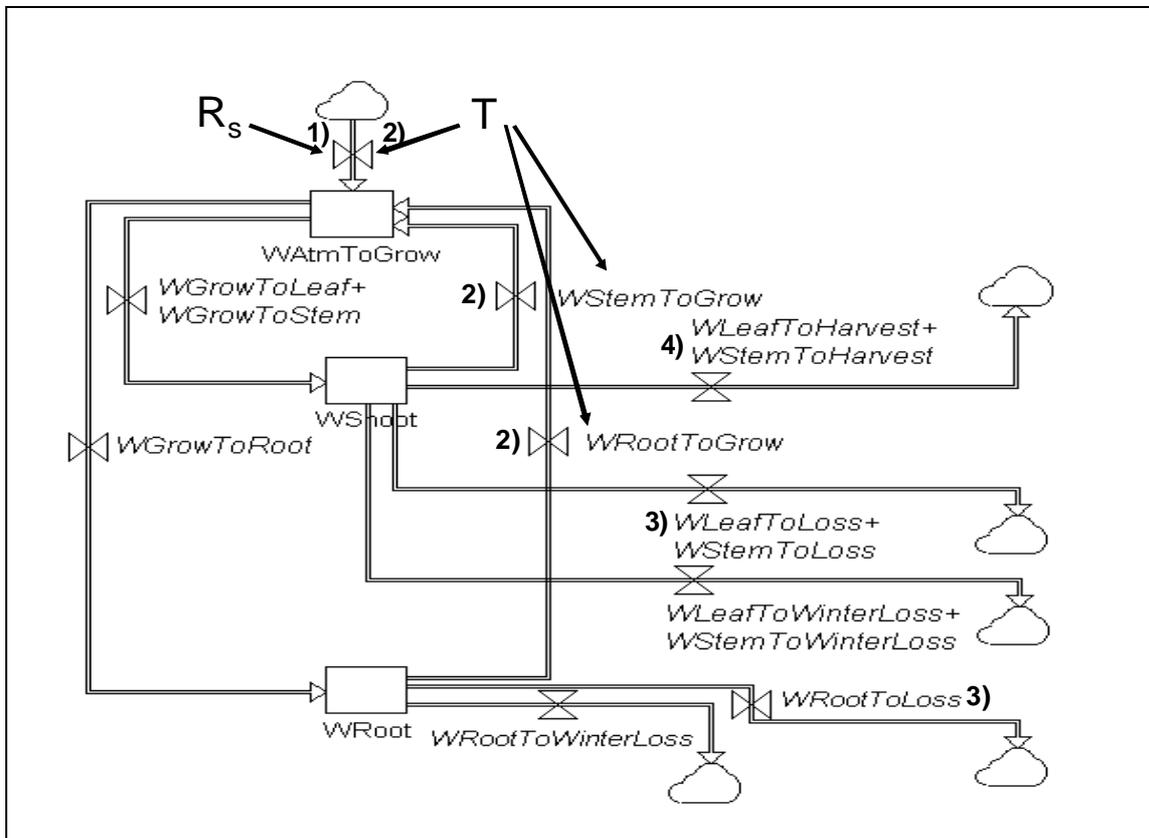


Figure 1: Schematic description of state variables (boxes) and flows of biomass. WShoot is the sum of leaf and stem biomass, and WAtmToGrow is the daily assimilation that is allocated to roots, leaves and stems. Notations 1) - 4) refer to flows that were directly influenced by the calibration steps one to four, i.e calibration of ϵ , T_{Max} , m and ΔW_{LSMin} , respectively (see Table 1).

Input variables

Daily values of mean air temperature (Table 1) and global radiation sum reported by SMHI (Swedish Meteorological and Hydrological Institute) and by Bioforsk in Norway were used for the simulations. For Västerås, the climate variables were interpolated values, whereas for the other sites they were measured. Climate change scenarios as predicted by the Intergovernmental Panel on Climate Change (IPCC) scenario A2 for ~2085 reported by SMHI (Table 1 and 2) was used for estimation of the effects of a warmer climate on turf growth and winter survival.

Botanical observations used as targets for calibration were above ground daily growth of dry matter and above ground biomass below clipping height.

Table 1. Monthly mean temperatures (°C) for present (1965-87) climate in central Sweden and temperature changes in accordance to climate change scenarios for 2071-2100 (~2085; SMHI).

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean temperature 1965-87:												
Umeå	-9.8	-9.5	-4.4	0.9	6.8	13.0	15.2	13.7	8.7	3.7	-2.4	-6.4
Västerås	-4.9	-5.1	-0.9	3.7	10.1	15.2	16.6	15.7	11.3	6.8	1.7	-2.2
Lund	-1.1	-1.1	1.7	5.5	11.1	15.2	16.8	16.7	13.1	9.1	4.7	1.3
20060101-20080731:												
Västerås	-1.0	-2.4	-0.5	5.2	10.3	15.0	17.6	17.4	12.9	7.3	2.6	1.9
Saerheim	3.1	2.5	2.6	6.1	9.7	13.2	15.7	15.3	13.1	10.5	6.1	5.3
Increase in temperature by ~2085:												
Umeå	6.1	6.3	6.2	5.0	4.0	3.5	3.5	4.0	3.9	4.5	4.5	4.8
Västerås	5.3	5.8	5.8	4.8	2.8	2.8	2.8	3.3	3.3	3.8	3.3	3.8
Lund	4.9	5.0	5.5	4.5	2.0	3.5	3.8	4.5	4.0	4.5	4.5	4.2
Saerheim	4.0	4.0	4.5	3.6	2.0	2.8	2.0	3.0	3.5	3.8	3.8	3.5

Parameterisation and initial states

Independent parameter values were taken from original studies on winter wheat with the SOIL-SOILN models (Eckersten & Jansson, 1991) and applications of a detailed version of this model to a large data set on grass leys (Eckersten et al., 2004; see also Torssell et al., 2007). Values used are given in the Appendix 2 (Table A1). A few parameters as well as initial states of the shoot biomass were calibrated to fit model output to the observed standing shoot biomass and growth rates (Table 3). The winter hardiness model was initially parameterized according to Bergjord et al. (2008) and then one parameter was used for calibrating against winter mortality observations, see the Results section for further details.

Results

Calibration – Parameter sets for the different grass species

Different parameter sets were established for the different species through calibration against the measured data on grass clippings and standing biomass 2007-2008 (Table 2). *Agrostis* and *Festuca* were similar in their parameterisation, whereas *Poa* differed. To adjust the model outputs to the observed values the initial values of the biomass pools were set to 200 g m⁻² for roots and 75 g m⁻² for leaves and stems respectively for *Agrostis* and *Festuca*. For *Poa* the values were set 50% higher (Table 3). For the shoot biomass (leaf plus stem) these values were similar to the observed.

The first calibration step was to adjust the utilisation efficiency of solar radiation (ϵ) for total plant growth to fit simulated daily growth rates to a similar range as those observed in terms of the frequent cuts. The value of ϵ was 0.5 gMJ⁻¹ for *Agrostis* and *Festuca* and 0.7 gMJ⁻¹ for *Poa*. These values are very low in comparison with young grass leys and agricultural crops. Secondly, to simulate the reduction in growth rates properly during autumn the lower temperature limit for optimal growth was adjusted. Especially for *Poa* this value had to be set fairly low (10 °C) to achieve a relatively high growth rate late in the autumn. This temperature value also influenced the rate of re-growth in spring (Fig. 1). Thirdly, the losses of biomass (root turnover and leaf senescence) was adjusted to give stable biomass pools, i.e. having the same value each spring, of roots, stems and leaves over several years of similar weather. Finally the minimum growth rate needed to activate the automatic harvest routine was set to 0.05 g m⁻² d⁻¹ which stopped the harvest in proper time in autumn.

Table 2. Initial states and calibrated parameter values for *Agrostis stolonifera*, *Festuca rubra* (values outside brackets) and *Poa annua* (values within brackets). ($W_{\text{Shoot}} = W_{\text{Stem}} + W_{\text{Leaf}}$)

Parameter	Symbol	Value	Unit	Source
Initial biomass	$W_{\text{Root}}(t_0)$	200 (300)	g/m^2	t_0 is 2007-01-01
	$W_{\text{Stem}}(t_0)$	75 (110)		Set to fit observed W_{Shoot}
	$W_{\text{Leaf}}(t_0)$	75 (110)		
Radiation use efficiency	ϵ	0.5 (0.7)	g/MJ	Calibrated vs $\Delta W_{\text{Shoot}} / \Delta t$
Lower temperature limit for optimal growth	T_{Max}	15 (10)	$^{\circ}\text{C}$	Blombäck and Eckersten (1997); (cal vs $\Delta W_{\text{Shoot}} / \Delta t$ and W_{Shoot})
Fraction of root, stem and leaf biomass lost by respiration	m	0.005	d^{-1}	Calib. vs stable W_{Shoot} over years
Minimum growth for harvest	ΔW_{LSMin}	0.05	$\text{g m}^{-2} \text{d}^{-1}$	Calib. vs last harvest date within season
Temperature for 50% mortality	LT_{50c}	-17 (-10)	$^{\circ}\text{C}$	Calib. mortality frequency over years

The calibrated simulations were compared to the measured values of grass clippings (Fig. 2). The daily shoot growth rate in the autumn 2007 and the spring 2008 was well estimated by the model, whereas during summer 2007, and especially in July/August, the model overestimated the growth rate compared to measurements. On the other hand, the measured values of clippings were very low in July/August. This could probably partly be explained by the sampling technique, where the dew moistened the grass during a great time of the day and caused clippings to get caught in the mower. This problem is probably also the reason for the large variation in the measured values for the summer samplings (Fig. 2).

For both *Festuca* and *Poa* it was possible to simulate a stable biomass pool for the shoot biomass (stems plus leaves) of the same size as the measured standing biomass below clipping height (Fig. 2, below) and at the same time fairly well simulate the daily growth during 2007-08. For *Agrostis*, the stable biomass pool had to be underestimated to not overestimate the simulated daily growth severely.

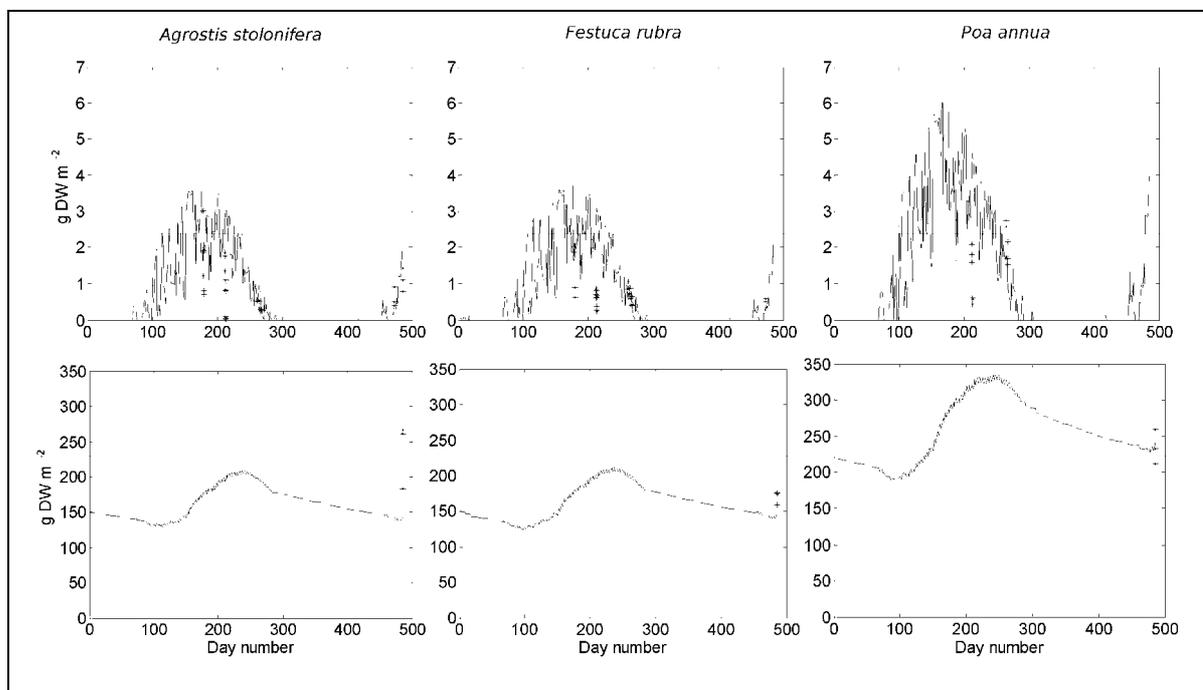


Figure 2. Simulated (line) and measured (dots) above ground daily growth ($\text{g DW m}^{-2} \text{d}^{-1}$) (above) and above ground biomass (g DW m^{-2}) (below) for the period January 2007 until April 2008. From left to right: Krypven, Rödsvingel and Vitgröe.

Of the accumulated input of biomass during the simulated period almost half was lost through respiration. The other half, or slightly more, was lost in equal proportions between root turnover and harvest output. The accumulated biomass production was about twice as high for *Poa* as for *Agrostis* and *Festuca* (Fig. 2).

During the calibration period 2007-2008 no winter mortality of plant was simulated. The winter mortality parameter LT_{50c} (maximum obtainable frost tolerance) was calibrated for the period, 1965 to 1987. LT_{50c} was adjusted for each site so the frequency of winter mortality in the simulations matched observations (personal communication: Agronomists from the Swedish Golf Federation and greenkeepers). *Poa* cultivated in Umeå (northern Sweden), is known to be severally killed almost every winter. Using the growth parameters for *Poa* (Table 2), LT_{50c} (minimum obtainable LT_{50} of a cultivar) was adjusted to $-10\text{ }^{\circ}\text{C}$ to achieve a near annual winter mortality rate in Umeå, i.e. an above ground biomass below 50 g m^{-2} in the end of winter. For the Umeå simulation the initial biomass was decreased to a third of that for Västerås. In Västerås *Agrostis* was cultivated and generally known to be killed about 20-30% of the years. Introducing the *Agrostis* growth parameters (Table 2), and adjusting LT_{50c} to $-17\text{ }^{\circ}\text{C}$ achieved a strong winter mortality in 6 out of 22 winters. For Lund the same LT_{50c} value as for Västerås was used and resulted in lower winter mortality rates (3 winters out of 22) in accordance to observations.

Potential growth curves for the three studied grass species for five different climatic conditions.

Validation of the model on independent data

When the model was validated on the independent data set on *Agrostis stolonifera* from 2001-2003, the simulation fitted fairly well to the observed values in 2001 and 2002, and also in the summer and autumn of 2003 (Fig. 3). However, for May in 2003 the simulated growth was too low. The low growth was due to a small assimilating biomass pool in spring due to strong winter mortality in the model. This was however not reflected in the measurements.

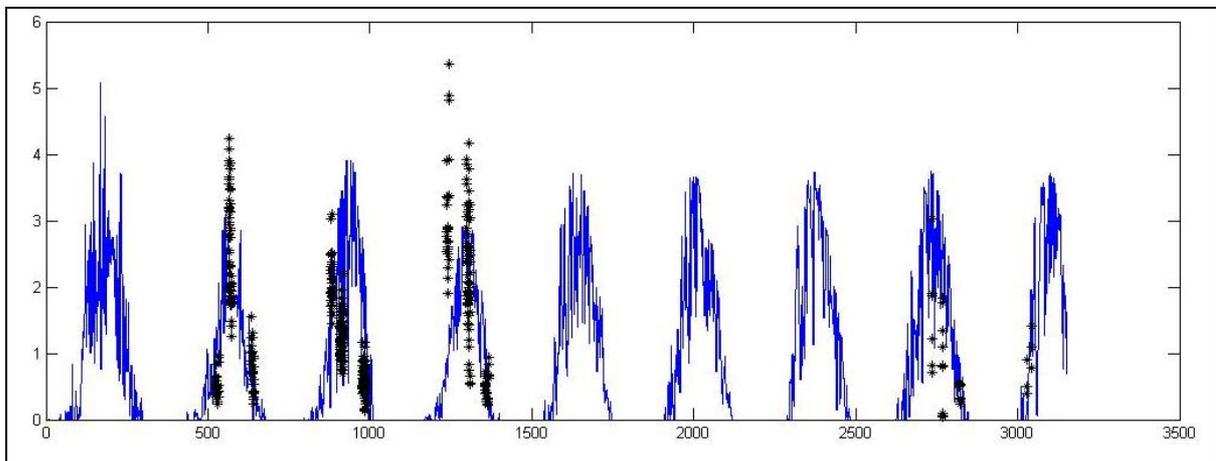


Figure 3. Simulated (line) and measured (dots) above ground daily growth ($\text{g DW m}^{-2}\text{ d}^{-1}$) for the period January 2001 until April 2008, for *Agrostis stolonifera* from an experimental green at Fullerö GK in Västerås, Sweden. The observed values of 2007 and 2008 are the same as used in the calibration (Fig. 2)

Estimation of biomass and growth curves for different climatic conditions

The biomass of green turf (*Poa annua* for Umeå and *Agrostis stolonifera* for Västerås and Lund) simulated for the period 1965-1987 showed great differences between the three Swedish sites, Umeå, Västerås and Lund (Fig. 4). Winter mortality was the most important

factor for the differences in the biomass pool (below clipping height) between the sites, whereas differences in root turnover, senescence and respiration only had minor effects. In Umeå, biomass of *Poa* was severely reduced by winter mortality almost every winter. In Västerås, biomass of *Agrostis* was severely reduced 7 winters out of 22, whereas in Lund the winter mortality was severe 3 winters out of 22. Winters with severe reduction in biomass caused a weak growth rate in spring, due to low leaf area index and absorbing capacity of radiation. Due to the 40% higher radiation use efficiency of *Poa* compared to *Agrostis* the growth rate of *Poa* in Umeå exceeded the *Agrostis* in Västerås and Lund from mid-summer all years, as exemplified in Fig. 5.

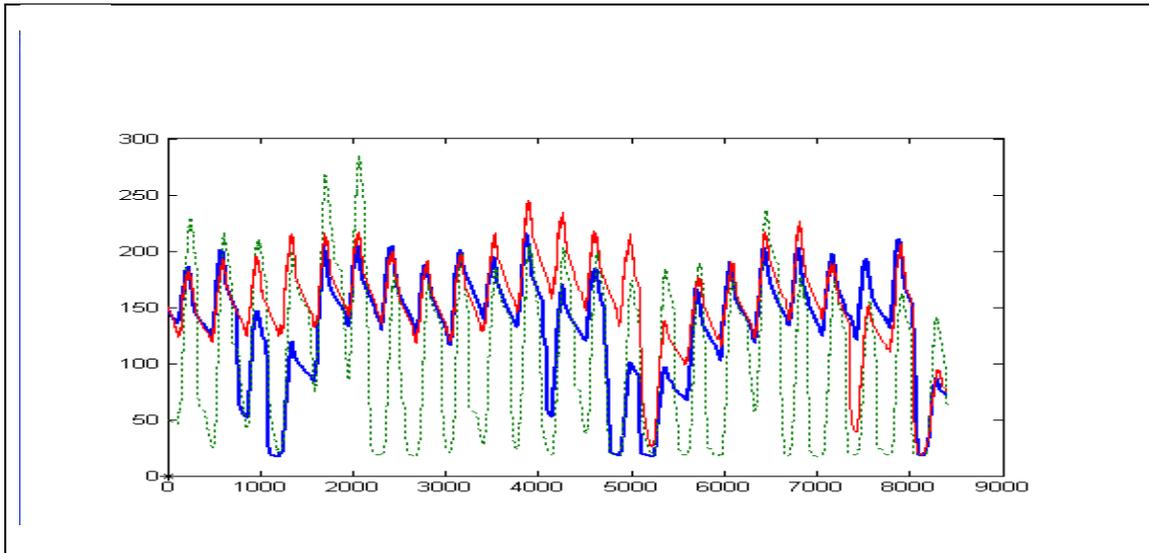


Figure 4: Simulated above ground biomass (below clipping height) of green turf in Umeå (green), Västerås (blue) and Lund (red) for the period 1965-1987. For Umeå *Poa pratensis* was assumed as green turf, and in Västerås and Lund *Agrostis stolonifera* was assumed.

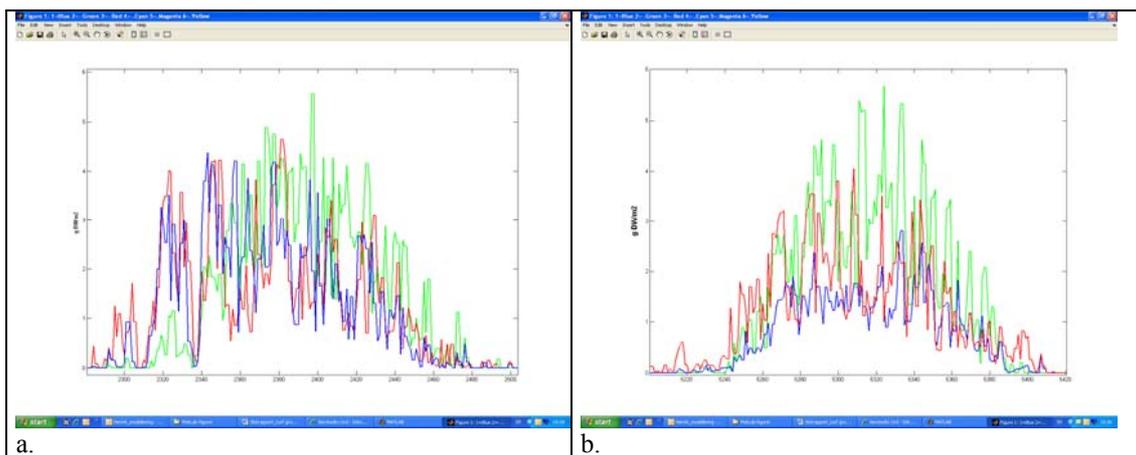


Figure 5. Simulated daily biomass production in Umeå (green), Västerås (blue) and Lund (red) in **a.** 1971 after low winter mortality in Västerås and Lund and sever mortality in Umeå, and **b.** 1979 after sever winter mortality at all sites.

When *Agrostis* was simulated also for Umeå, the differences in winter mortality between the sites decreased since *Agrostis* was parameterized to be more tolerant to low temperatures ($LT_{50c} = -17\text{ °C}$) compared to *Poa* ($LT_{50c} = -10\text{ °C}$) (Fig. 6a). Actually, severe winter mortality

was more frequent in both Västerås and Lund compared to Umeå. This effect was caused by a less effective hardening process in Västerås and Lund compared to Umeå, which caused the turf to be more sensitive to low winter temperatures. The higher mortality was also caused by the more frequent lack of snow cover at the southern latitudes. When *Poa* was simulated also for Västerås and Lund, the winter mortality increased due to the high LT_{50c} -value for *Poa* (Fig. 6b). In Västerås the mortality was almost as severe as in Umeå.

When the same species were compared, less biomass was produced in Umeå during the summers due to the shorter growing season with lower temperatures compared to Västerås and Lund.

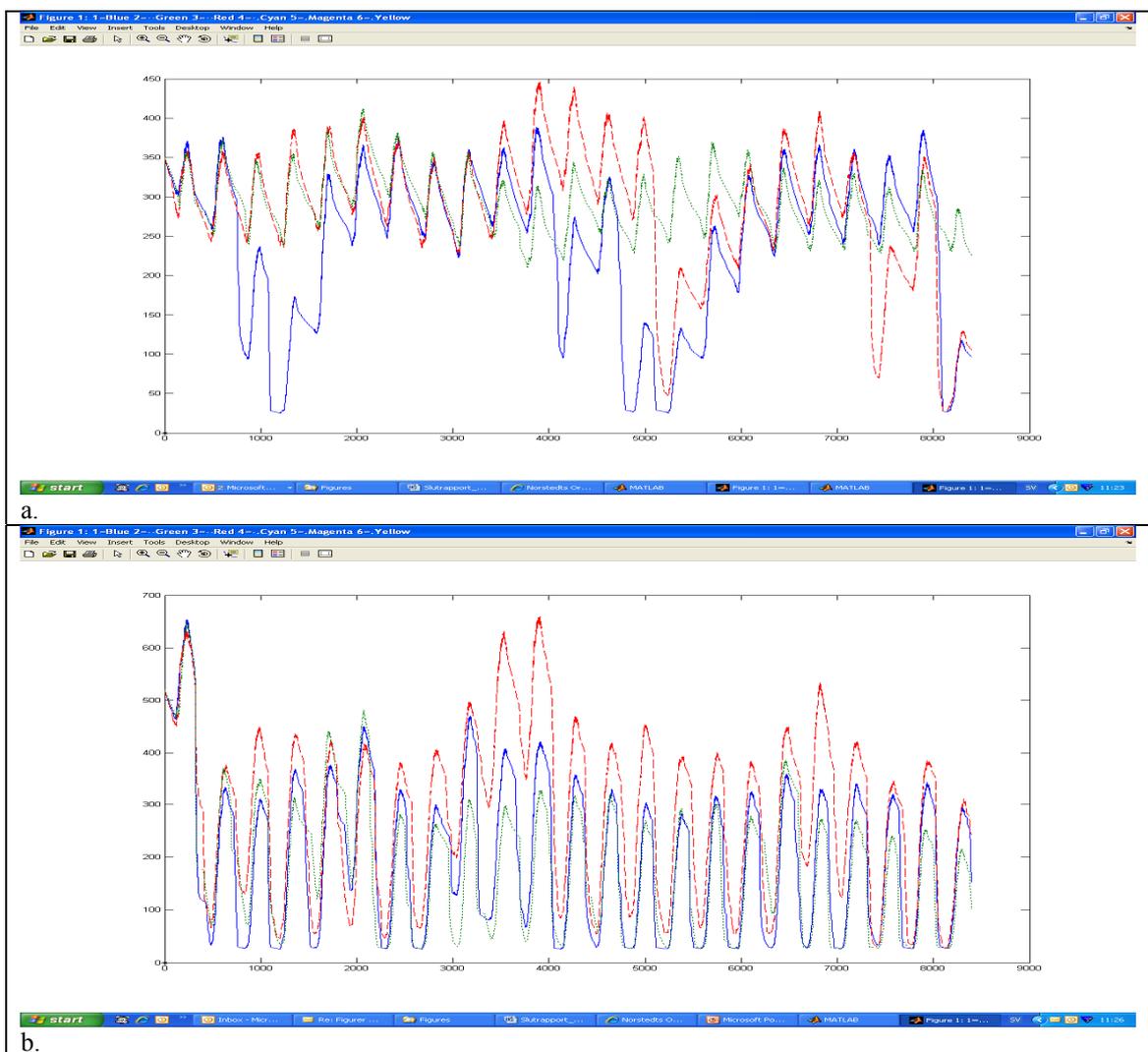


Figure 6: a. Simulated above ground biomass (below clipping height) of *Agrostis stolonifera* turf and b. *Poa annua* turf in Umeå (green), Västerås (blue) and Lund (red) for the period 1965-1987.

Særheim and Västerås are situated at approximately the same latitude and thus interesting to compare. The comparison showed that the daily growth rate fluctuated much more in Særheim (Fig. 7). This was more a function of fluctuation in radiation than in temperature. Especially in 2007, frequent days with low insolation were recorded in Særheim during summer together with frequent precipitation. However, the fluctuation in Västerås could have been underestimated due to the source of radiation data. In Västerås, radiation was reported as interpolated values which levels out the highest and lowest values, whereas from Særheim

measured data were reported. The results should therefore be regarded more as a demonstration of the influence of radiation and temperature on growth than real differences between the places. As expected, the growth period lasted longer due to higher temperatures in the autumn for the coastal climate of Særheim. However in spring the climatic conditions were more similar.

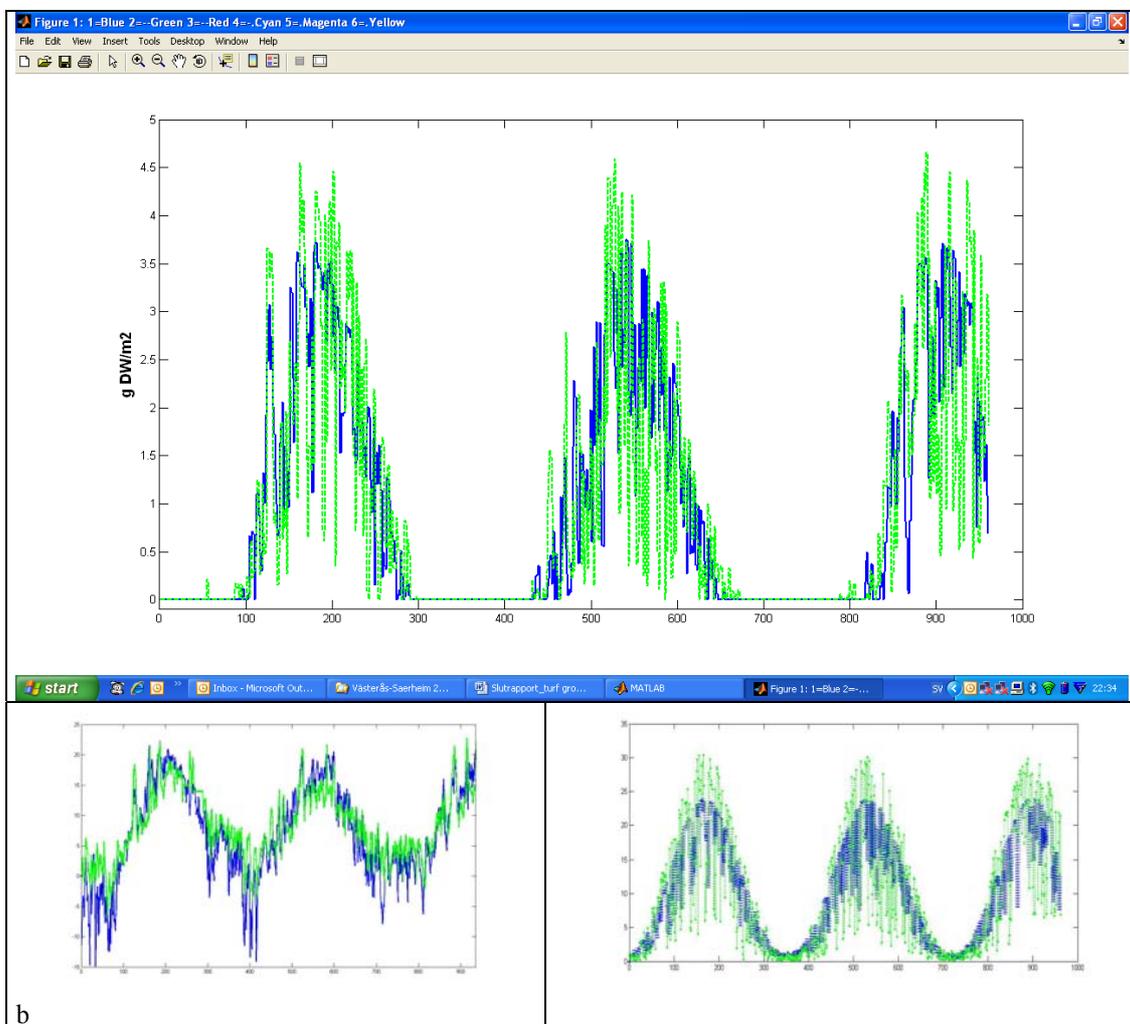


Figure 7. a. Simulated daily biomass production of *Agrostis stolonifera* **b.** temperature and **c.** radiation in Særheim (green) and Västerås (blue) for the period 2006-2008.

Winter hardiness of turfgrass under different climatic conditions

Simulated turf LT_{50} dynamics showed great differences between the three Swedish sites (Fig. 8) with the most obvious differences between Umeå and the two southern sites, Lund and Västerås. Turf in Umeå neither developed nor maintained winter hardiness which resulted in severe mortality almost every year. In the simulations this was mainly due to a relatively high LT_{50c} (minimum potential LT_{50}) for *Poa* turf in Umeå compared to predominately *Agrostis* turf in the southern sites. LT_{50c} limits the maximum potential winter hardiness that is obtainable for a species or genotype given optimum hardening conditions. Differences in winterhardiness between sites with similar turfgrass composition are determined by the local prevailing weather conditions during the vernalization period. Differences in winter hardiness between Västerås and Lund, which had similar parameterizations, were driven by the differences in autumn temperatures between the two sites. Mild autumn temperatures in Lund lead to limited hardening during vernalization and therefore turf in Västerås developed greater

winter hardiness than turf in Lund. Despite greater winter hardiness however, Västerås experienced more years with severe winter mortality primarily because winter temperatures were much milder in Lund. Differences in simulated winter hardiness development and dynamics between years for any of the particular sites were also quite large, and were a result of differences in autumn temperatures during the vernalization period. Cool autumns help the development of winter hardiness and cold winters help maintain the hardiness which protects the plants in case of a cold spell (cf yrs 74, 80 and 81 in Fig. 9). On the other hand, warm autumns hinder the development of winter hardiness (cf. yrs. 78 and 79 in Fig. 9) and warm spells during the winter (cf. yr 76 in Fig. 9) hastens dehardening prematurely and thus leaves the plants susceptible to frost damage during subsequent cold spells when temperatures drop below LT_{50} .

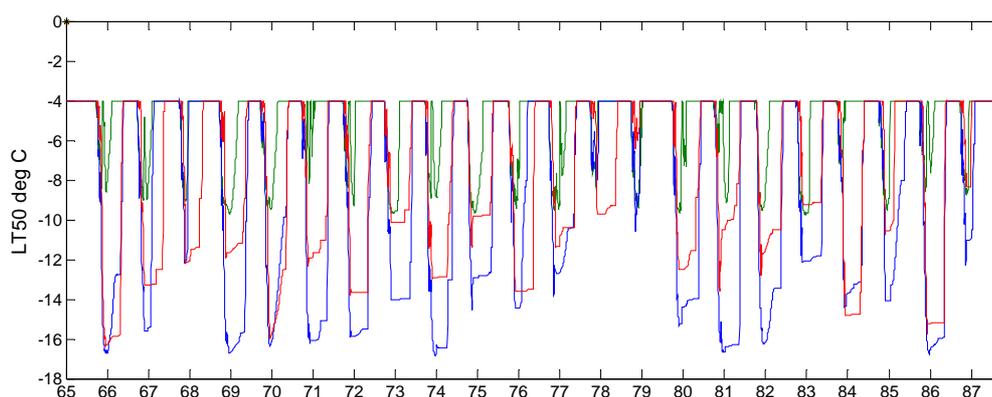


Figure 8. Simulated daily LT_{50} for *Poa pretense* turf in Umeå (green) and *Agrostis stolonifera* turf in Västerås (blue) and Lund (red) for the period 1965-1987.

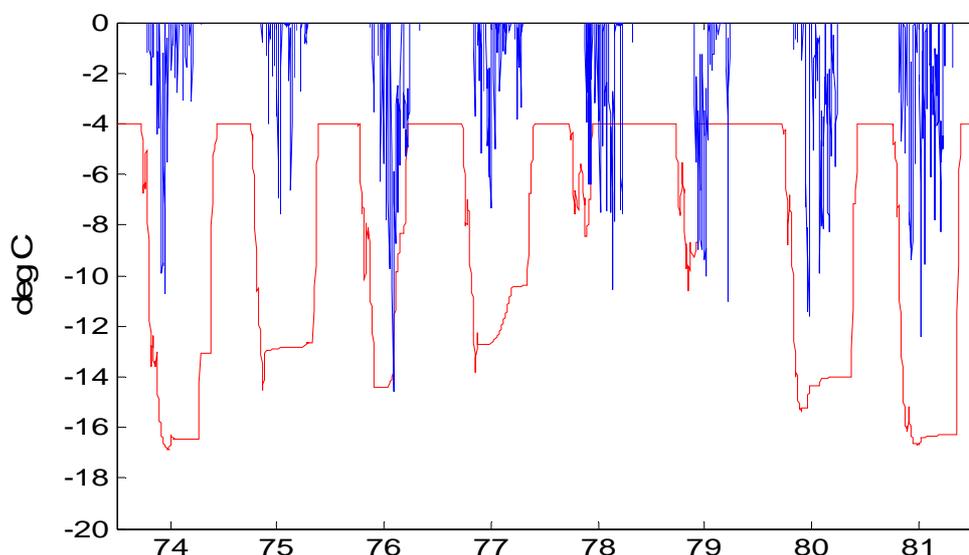


Figure 9. Simulated daily LT_{50} for *Agrostis stolonifera* turf in Västerås (red) and temperature at soil surface (red) for the period 1974-1981. When temperatures drop below LT_{50} , mortality occurs.

The effect of a warmer climate on turf growth and winter survival

Using the climate change scenarios based on the IPCC emission scenario A2 for ~2085 the accumulated harvest (clippings) increased between 16 and 23% for Lund, Västerås and Umeå when compared to the mean values for the period 1965 to 1987 (Table 3). The winter

mortality increased in Umeå due to a less effective hardening during autumn and shorter periods with snow cover during winters. In Västerås and Lund did the winter mortality decrease.

For the shorter period, 2006-2008, climate change caused a slight increase of harvest in Västerås, but an increase of about 20% in Saerheim. This was due to the winter mortality increasing in Västerås and decreasing in Saerheim (Table 4).

Table 3. Shoot biomass, harvest (tonnes ha⁻¹ y⁻¹) and winter mortality (m_{ow} , given as the mean value for the period) at different locations under climate change ~2085 (A2). Values in brackets [] are % change in relation to reference period (current climate). For Umeå the *Poa* cultivar was used and for all other sites the *Agrostis* cultivar.

Location	Mean	Shoot biomass		Harvest Mean	Winter mortality Mean ($10^{-3} d^{-1}$)	Temperature Mean (°C)
		Minimum	Maximum			
Reference period 1965-87						
Umeå	1.06 [+2]	0.15 [-12]	2.64 [-8]	1.30 [+23]	9.01 [+43]	7.2
Västerås*	1.34 [+1]	0.18 [+6]	2.10 [-3]	1.53 [+20]	1.33 [-33]	9.7
Lund	1.51 [-1]	0.23 [+21]	2.32 [-5]	1.85 [+16]	0.04 [-94]	12.0
Reference period 20060101-20080819						
Västerås	1.57 [-10]	0.65 [-50]	2.29 [0]	1.64 [+6]	0.84 [+1300]	11.3
Saerheim	1.67 [+6]	1.24 [+12]	2.29 [+3]	1.87 [+18]	0.01 [-87]	11.9

* Climate change scenario for Uppsala was projected on Västerås weather data.

Projection of the potential climate change scenario on the development of cold tolerance decreased maximum obtained winter hardiness in turfgrass at both Lund and Västerås sites (Figure 10). The warmer winter temperatures under potential climate change also drastically hastened dehardening after the vernalization period was complete. However, the effects of decreased winter hardiness on turf grass mortality were different for the two sites. Increased mean monthly temperatures during autumn and winter months decreased the risk for frost damage and mortality of turf grass in Lund despite the decrease in winter hardiness. For example, projecting the climate change scenario for turf grass in Lund for the period 1965 – 1987 decreased the number of years were temperature dropped below LT_{50} from 3 to 1 during the 22 year period. On the other hand, the warm weather effect of decreasing winter hardiness led to increased problems with frost damage when cold spells were still severe enough. For example the climate change scenario projected on turf grass in Västerås increased the number of years were temperature dropped below LT_{50} from 6 to 8 during the same period of 1965-1987, and therefore indicates an increased risk for winter mortality. The climate change scenario in Umeå did not cause drastic changes in winter hardiness however it did affect the dynamics of hardening and dehardening differently between years. Regardless, these changes did not lead to major changes in winter mortality primarily due to the already poor winter hardiness of *Poa*, regardless of slightly warmer or colder winters. However, there is the possibility that the predicted climate change in Umeå will create conditions where other species may become viable alternatives to use for turfgrass and thus change the situation for winter survival.

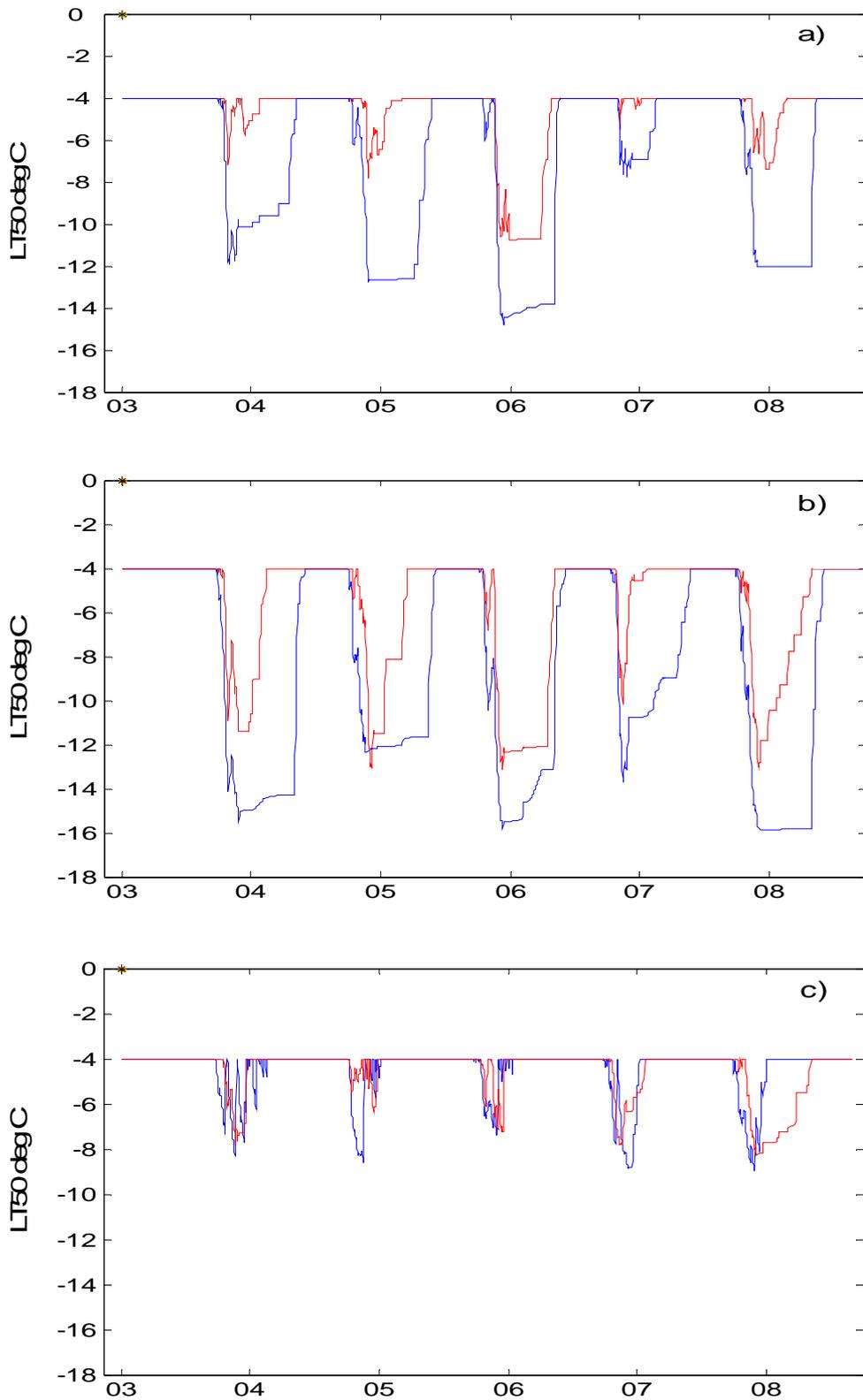


Figure 10. Simulated daily LT_{50} for *Agrostis stolonifera* turf in **a)** Lund **b)** Västerås and **c)** *Poa annuas* turf in Umeå during the period 2003-2008 based on actual weather data (blue line) and weather data adjusted according to the SMHI potential climate change scenario for ~2085 (red line).

Discussion

The model used in this study was developed from a general crop growth model and a winter mortality model, which were aggregated into one turf grass model. The established model could reproduce growth pattern of turfgrass (*Agrostis stolonifera*) within the range of measurements several years when compared to independent data of grass clippings. A further tested model could be used to establish growth curves for different normalized weather scenarios, that for example could be used as a guideline for fertilization. However, there are still many uncertainties in the parameterization of the model, and especially with the winter mortality part, because the lack of physiological knowledge of the grass species studied and a lack of observations to test the model against. For further development of the model better information on the temperature sensitivity during the hardening and de-hardening processes is needed, as well as specific data concerning winter mortality. To get more observation data to test the model, data from the different ongoing field experiments in the Nordic countries where biomass production is measured could be utilized.

The results on winter mortality showed very interesting results and identified the complexity between the two opposite processes of hardening and dehardening and the interaction with the climatic conditions during winter to determine the effects on plant mortality. The model showed that although a milder climate reduced the risk for temperatures below the minimum temperatures for grass tolerance at maximum hardening, mild autumns can lead to a less effective hardening so that maximum hardening never is reached. The weaker hardening made the grass more sensitive to low temperatures. A milder climate also decreased the number of days during winter with snow cover. The number of days with snow cover and the depth of snow are very important parameters for the soil surface temperature and thus for the survival of the turf.

With the calibration of model it was shown that the utilisation efficiency of solar radiation (ϵ) was low for all turf species in comparison with young grass leys and agricultural crops (Blombäck & Eckersten 1997, Blombäck, 1998). The low ϵ could be an indicator for the stress and damage of leaf blades caused by mowing and other wear. The higher value of ϵ for *Poa* compared to the *Agrostis* and *Festuca* species was analogous to the known higher growth efficiency by *Poa* in practice.

References

- Bergjord, A.K., Bonesmo H., Skjelvåg A.O., 2008. Modelling the course of the tolerance in winter wheat. I Model development. *European Journal of Agronomy* 28:321-330.
- Biscoe, P.V., Gallagher, J.N., Littleton, E.J., Monteith, J.L. & Scott, R.K. 1975. Barley and its environment. IV. Sources of assimilate for the grain. *Journal of Applied Ecology*, 12, 295-318.
- Blombäck, K., 1998. Carbon and Nitrogen in Catch Crop Systems. Modelling of seasonal and longterm dynamics in plant and soil. Doctoral thesis. Swedish University of Agricultural Sciences. Agraria 134. Uppsala.
- Blombäck, K. & Eckersten, H., 1997. Simulated growth and nitrogen dynamics of perennial rye grass. *Agricultural and Forest meteorology*, 88:37-45.
- Blombäck, K., Strandberg, M. & Lundström, L., 2003. Emergo 2003:9. Det organiska materialets betydelse för markens biologiska aktivitet och gräsets etablering och tillväxt i en golfgreen (The influence of soil organic matter on soil microbial activity and grass establishment and growth in a putting green). ISSN: 1651-7210
- Blombäck, K., Ericsson, T & Aamlid, T., 2007. Fertilizer strategies for golf turf: Implications for physiological driven fertilization. First year report.
http://sterf.golf.se/dynamaster/file_archive/090203/cdc229d1e693be5b2591d4001dc6c67c/Sterfrappport_2008-12-12_kortversion.pdf
- Dalmansdottir, S., Helgadóttir, A. & Gudleifsson, B. E., 2001. Fatty acid and sugar content in white clover in relation to frost tolerance and ice-encasement tolerance. *Annals of Botany* 88, 753-759.
- Eckersten, H. & Jansson, P. E. 1991. Modelling water flow, nitrogen uptake and production of wheat. *Fert. Res.* 27, 313-329.
- Eckersten, H., Kornher A., Bergkvist G., Torssell B., Sindhøj E., Nyman P. manuscript. Climate indices for prediction of cereal yields in long-term experiments.
- Eckersten H., Torssell B., Kornher A., Nyman P., Olsson U. 2004. Modelling radiation use and regrowth in grass and red clover swards – method of calibration. *Acta agriculturae Scandinavica. Section B, Soil and plant science*, vol 5
- Eckersten H., Torssell B., Kornher A., Boström U. 2007. Modelling biomass, water and nitrogen in grass ley: Estimation of N uptake parameters. *European journal of agronomy*, vol 27, nr 1, 89-101
- Fowler, D.B., Limin A.E., Ritchie J.T. 1999. Low-temperature tolerance in cereals: model and genetic interpretation. *Crop Science* 39: 626- 633.
- Gusta, L.V.; Butler, J.D.; Rajashekar, C.; Burke, M.J. 1980. Freezing resistance of perennial turfgrasses. *HortScience* 15: 4, 494-496.
- Hetherington, P.R., McKersie, B. D. & Keeler, L. C., 1990. The influence of mineral nutrition on the expression of traits associated with the winter hardiness of two winter wheat (*Triticum aestivum* L.) cultivars. *Canadian Journal of plant science* 70, 443-454.
- Junttila, O., Svenning, M. M. & Solheim, B., 1990. Effects of temperature and photoperiod on frost resistance of white clover (*Trifolium repens* L.) ecotypes. *Physiologia Plantarum* 79, 435-438.
- Pontis, H. G., 1989. Fructans and cold stress. *Journal of Plant physiology* 134, 148-150.
- SMHI, 2006a. Faktablad nr 29. Klimat i förändring. En jämförelse av temperatur och nederbörd 1991-2005 med 1961-1990. SMHI, Norrköping. Oktober 2006. (*Climate in change. A comparison of temperature and precipitation between the periods 1991-2005 and 1961-1990*)
- SMHI, 2006b. Observationer. Avvikelsekartor. (*Observations. Maps on deviations*)
www.smhi.se
- Tompkins, D.K., Ross, J.B. & Moroz, D.L., 2000. Dehardening of annual bluegrass and creeping bentgrass during late winter and early spring. *Agronomy Journal* 92, 5-9.
- Torssell, B., Eckersten H., Kornher A., Nyman P., Boström U. 2007. Modelling carbon dynamics in mixed grass–red clover swards. *Agricultural systems*, vol 94, nr 2, 273-280

Appendix 1 - Model equations

Growth: The input to the total plant biomass (W_{plant}) is determined by the daily growth that is proportional to the intercepted radiation (R_{sInt}) in accordance to the radiation use efficiency (ϵ , but limited by a temperature factor (f_T) (see Eq A1 in Appendix). The intercepted radiation is calculated from the global radiation (R_s), the leaf area (LAI) and the light extinction coefficient (k) in Beer's law (Eq. A2). The leaf area is proportional to the leaf biomass in accordance with the specific leaf area (c_{SLA}) (Eq. A3). The temperature functions range between zero and one. The temperature response is linear between daily average air temperature (T) of 2 °C and 15 °C (Eq. A4).

Regrowth: In addition to photosynthesis, also biomass already stored in roots (W_{Root}) and stems (W_{Stem}) is to a certain fraction (b_{RG}) available for plant growth. This fraction is, however, limited to zero at $\text{LAI} > 2.5$ and temperatures below 2°C (cf. Herrero *et al.*, 2000) (Eqs. A5-6).

Allocation of biomass: The daily growth is allocated between above-ground biomass and root biomass in accordance with an empirical allocation function (b_r). In addition, a fraction of the shoot growth is allocated to leaf (b_l) and the rest is allocated to stems (Eqs. A7-9). The fraction allocated to leaves decreases with increasing above-ground biomass and is at minimum (0.1) for a biomass above a certain value ($g \text{ d.w. m}^{-2}$) (Eq. A10), whereas b_r is constant.

Losses of biomass: Plant loss of biomass is a fraction (m) of the standing leaf (W_{Leaf}), stem (W_{Stem}) and root biomass (W_{Root}). The amount lost by root turnover is assumed to be proportional (m_r) to the root growth (Eqs A13-15). The loss is basically assumed to be due to respiration that increases exponentially with temperature (Eq. A16).

During winter biomass might be lost due to plants being killed by unfavourable temperature or snow conditions. The winter module predicts a temperature below which 50% of the plants die (LT_{50} ; Sindhoj *et al.*, manuscript). It is assumed that at 5 °C below LT_{50} all plants will die (i.e., LT_{100}) and that at 5 °C above LT_{50} , no plants die (LT_0). The daily rate of mortality is then reduced to 10% of these mortality rates, i.e. when the winter mortality module predicts 50% mortality rate, we set it to be 5% per day (Eqs. A17-19).

Harvest does occur regularly every fourth day. A constant fraction (h) of the standing biomass is harvested. Harvest does not occur if the growth rate is below a certain limit ($\square W_{\text{LSMin}}$) (Eqs. A11-12).

The daily growth.

$$W_{\text{Atm} \rightarrow \text{Grow}} = \epsilon R_{\text{sInt}} f_T \quad (\text{A1})$$

The intercepted radiation:

$$R_{\text{sInt}} = R_s (1 - e^{-k \text{LAI}}) \quad (\text{A2})$$

The leaf area index:

$$\text{LAI} = W_l / c_{\text{SLA}} \quad (\text{A3})$$

The temperature function.

$$f_T = (T - T_{\text{Min}})/(T_{\text{Max}} - T_{\text{Min}}) \quad 0 \leq f_T \leq 1 \quad (\text{A4})$$

The regrowth from roots and stems:

$$W_{\text{Root} \rightarrow \text{Grow}} = b_{\text{RG}} W_{\text{Root}} f_T (1 - \text{LAI}/2.5) \quad \geq 0 \quad (\text{A5})$$

$$W_{\text{Stem} \rightarrow \text{Grow}} = b_{\text{RG}} W_{\text{Stem}} f_T (1 - \text{LAI}/2.5) \quad \geq 0 \quad (\text{A6})$$

Allocation of daily growth to roots, leaves, and stems:

$$W_{\text{Grow} \rightarrow \text{Root}} = b_r (W_{\text{Atm} \rightarrow \text{Grow}} + W_{\text{Plant} \rightarrow \text{Grow}}) \quad (\text{A7})$$

$$W_{\text{Grow} \rightarrow \text{Leaf}} = b_l (1 - b_r) (W_{\text{Atm} \rightarrow \text{Grow}} + W_{\text{Plant} \rightarrow \text{Grow}}) \quad (\text{A8})$$

$$W_{\text{Grow} \rightarrow \text{Stem}} = (1 - b_l) (1 - b_r) (W_{\text{Atm} \rightarrow \text{Grow}} + W_{\text{Plant} \rightarrow \text{Grow}}) \quad (\text{A9})$$

where the leaf allometric function is:

$$b_l = b_{l0} (1 - (W_{\text{Leaf}} + W_{\text{Stem}})/500) \quad \geq 0.1 \quad (\text{A10})$$

Harvested biomass:

$$W_{\text{Leaf} \rightarrow \text{Harvest}} = h_l W_{\text{Leaf}} \quad h_l > 0 \text{ at harvest; else } = 0 \quad (\text{A11})$$

$$W_{\text{Stem} \rightarrow \text{Harvest}} = h_s W_{\text{Stem}} \quad h_s > 0 \text{ at harvest; else } = 0 \quad (\text{A12})$$

$$h_l, h_s = 0 \quad \text{if} \quad dW_{\text{Leaf} + \text{Stem}}/dt < dW_{\text{LSMin}} \quad (\text{A12b})$$

Plant loss of biomass:

$$W_{\text{Leaf} \rightarrow \text{Loss}} = f_{Q10} m W_{\text{Leaf}} \quad (\text{A13})$$

$$W_{\text{Stem} \rightarrow \text{Loss}} = f_{Q10} m W_{\text{Stem}} \quad (\text{A14})$$

$$W_{\text{Root} \rightarrow \text{Loss}} = m_r W_{\text{Grow} \rightarrow \text{Root}} + f_{Q10} m W_{\text{Root}} \quad (\text{A15})$$

where the temperature function is:

$$f_{Q10} = Q_{10}^{((T - T_{\text{Ref}})/10)} \quad (\text{A16})$$

Frost tolerance hardening and dehardening:

$$\text{RATEH} = H_{\text{param}} (10 - T)(\text{LT50}_{t-1} - \text{LT50}_c) \quad T < 10^\circ\text{C} \quad (\text{A17})$$

$$\text{RATED} = D_{\text{param}} (\text{LT50}_i - \text{LT50}_{t-1})(T + 4)^3 \quad T \geq 10^\circ\text{C} \text{ or} \quad T \geq -4^\circ\text{C} \quad (\text{A18})$$

$$\text{RATER} = R_{\text{param}} * \text{RE} * f(\text{snow depth}) \quad (\text{A19})$$

$$\text{RATES} = (\text{LT50}_{t-1} - T) / \exp(-S_{\text{param}}(\text{LT50}_{t-1} - T) - 3.74) \quad (\text{A20})$$

Appendix 2 - Model inputs

Table A1. Parameters of the plant module set from independent data sources

Parameter	Symbol	Range of values	Unit	Source
Fraction of total DM allocated for growth	b_{RG}	0.05		Eckersten et al (2004)
Light extinction coeff. related to leaf area	k	0.5	-	Eckersten and Jansson (1991)
Lower temp. limit of growth	T_{Min}	2	$^{\circ}C$	Eckersten and Jansson (1991)
Specific leaf area	c_{SLA}	0.0265	g/m	Eckersten et al (2004)
Root/Total plant ratio at start of growth	b_r	0.5	-	Eckersten et al (2004)
Leaf/Shoot ratio at start of growth	b_{l0}	0.7	-	Eckersten et al (2004)
Fraction of root growth lost as litter	m_r	0.5	-	Eckersten et al (2004)
Coefficient in respiration temperature response	Q_{10}	2	-	Blombäck & Eckersten (1997)
Coefficient in respiration temperature response	T_{Ref}	20	$^{\circ}C$	Blombäck & Eckersten (1997)
Fraction of leaves lost at harvest	h_l	0.02	-	Estimated from experiment
Fraction of stem lost at harvest	h_s	0.02	-	Estimated from experiment