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Plant Research International, part of Wageningen UR
Business Unit Agrosysteemkunde
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1. Introduction

Our global climate is changing, and so is the Dutch climate. Each of the past five years in the Netherlands has been significantly warmer than the longterm average (Kattenberg, 2008). This climate change receives a lot of attention in society and science. Numerous studies have extrapolated the likely impacts of global change on species distribution (Bakkenes et al., 2002;Midgley et al.) and community assemblages (Guisan &Thuiller, 2005;Guisan &Zimmermann, 2000;Leathwick et al., 1996). In the Netherlands an increase in thermophilic plant species presence has been observed in the final decades of the 20th century that coincided with the marked increase in temperature during that period (Tamis et al., 2005).

Climate change can have many implications for crop cultivation, such as changes in the sort of crops that can be grown and the occurrence of new (invasive) plant diseases, pests and weeds. However, climate change can also have implications for species already present.
In this report we focus on the possible effects of climate change on arable weed species already present in the Netherlands.

We start with an investigation into those processes in plant growth that are strongly related to climate factors (chapter 2). In that review, we will focus on the effect of temperature on spring plant phenology, such as emergence and unfolding of the first leaves, for which the relationship is most profound. Furthermore we explain the importance of the relative timing of weed emergence to the onset of crop-weed competition, which is also dominated by temperature.

In the third chapter we describe the expected changes in the climate of the Netherlands. We start with a description of the available climate scenarios and the uncertainties within these scenarios. Finally, we will focus on the climatic conditions that are important for the phenology of herbaceous species. We will focus on the changes in temperature, the variable most influential for weed emergence.

In the chapters 4 (materials and methods) and 5 (results) we present case studies, in which the effect of the four possible scenarios for temperature change in the Netherlands for 2050 on the emergence of annual and perennial weeds is investigated.

The study described in this report was carried out within the project “Responses of plant pests and weeds to climate change”, part of the research program “KB II Sustainable Agriculture, Climate change and agriculture”, funded by the Dutch ministery of Economics, Agriculture and Innovation.

2. Plant Phenology and weed emergence

In this chapter, we explain why we will zoom into the effect of temperature on the germination and subsequent emergence of weeds. The first reason is that temperature strongly influences phenological processes, and that air temperature is even found to be the main driver for the onset of spring phenological processes (paragraph 2.1). The first phenological event for weeds is its emergence. The second reason is that the relative timing of weed emergence is very important for the onset of crop-weed competition (paragraph 2.2).

2.1 Plant Phenology

Phenology is the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or differing species (Global Phenological Monitoring www.dow.wau.l/msa/gpm). Plant phenology data have been collected in Europe since the 19th century. Observations were mainly performed in botanical gardens on trees and shrubs and involve for instance the timing of the unfolding of leaves and flowering. These observations on plant phenology tell us that spring has started earlier during the past decades with on average 2,5 days per decade. During the past decade there has been an increased interest in this phenomenon and several research groups have investigated the relationship with climate factors (Fitter &Fitter, 2002;Menzel et al., 2008;Menzel &Fabian, 1999;Menzel et al., 2005;Menzel et al., 2006b). As a result, we now know that phenological phases in plants can be related to climate factors such as temperature.
Menzel et al. (2006b) was able to relate the phenological changes in 542 plant species observed in 21 European countries to temperature. For spring and summer phenology in plants the trigger for onset is even nearly exclusively air temperature (Menzel et al., 2008). Figure 1 shows the linear relationship between spring onset dates of first leaf unfolding and changes in temperature. This relationship is an average for all plant species and shows the general impact of temperature on spring plant phenology.

This general relationship is especially strong for species flowering in spring (February, March and April) and the air temperature in the preceding month. These species flower on average 4 days earlier for each degree (°C) increase in the temperature of the previous month. Species flowering in summer (May and June) are more sensitive to changes in the February air temperature, although this influence was still smaller than for the spring flowering species. For all species together the highest correlation can be found with the air temperature in the preceding month (63%), followed by the air temperature in the month of onset (19%) and two months earlier (18%) (MENZEL et al., 2006a). Phenological changes in autumn are not as pronounced as in summer and spring and cannot directly be linked to climate factors (Menzel et al., 2008).
Not only aboveground events such as flowering and the unfolding of the first true leaves can be related to air temperature, but also the first phenological events in spring for germination and emergence of weedy species. Otto et al. (2007) studied the emergence of 12 weed species and related their emergence to air temperature (Otto et al., 2007).

Although the relationship between spring phenology and temperature is valid for all plant species, there are differences between species and species groups. For

instance, annual plants respond more strongly than perennials, insect-pollinated plants stronger than wind-pollinated plants and herbaceous plants stronger than woody plants (Fitter &Fitter, 2002).
The number of phenological studies on herbaceous plants considering climate change is limited, especially for the agricultural relevant species.
A study that included some agricultural relevant herbaceous species was done in Great Britain (Fitter &Fitter, 2002). The mean first flowering date in the period 1990-2000 of a large number of plant species was compared to the mean first flowering date in the period 1954-1990. In general, most herbaceous plants were found to flower earlier in the later decade than in the four previous decades (Table 1) and the change could be correlated to the mean air temperature in the month preceding the month in which the first flowering date occurred.

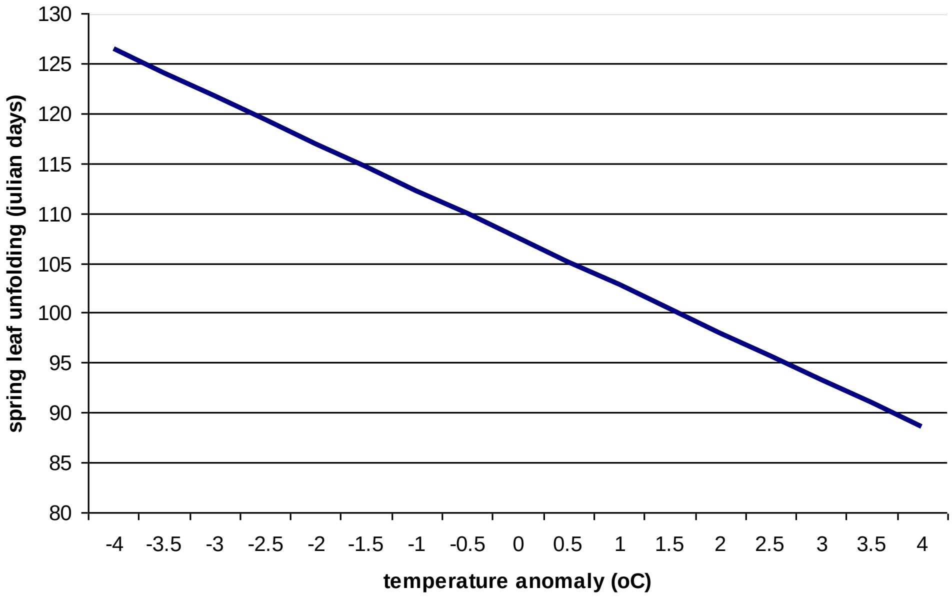


Figure 1 Relationship between the spring onset of leaf unfolding and the temperature anomaly (after Menzel et al 2008).

Table 1. Change in FFD (first flowering day) for arable species during the period 1990-2000 compared to the occurrence of the FFD in the period 1954-1990 in Great Britain. After: Fitter & Fitter (2002).

species	change in FFD (days)
Alopecuris myosuroides	-4
Galium aparine	-7
Myosotis arvensis	-10
Sonchus oleraceus	-12
Sonchus arvensis	-7
Sonchus asper	-11
Veronica arvensis	+5
Veronica chamaedrys	+3
Veronica filiformis	-2

2.2 Weed emergence

Weeds in agriculture cause yield loss through competition for resources such as water and nutrients. The relative timing of weed emergence is very important for the onset of crop-weed competition (Grundy, 2003). The emergence of weeds as observed in a field is the cumulative result of three major processes: dormancy relief, germination and pre-emergence growth (Grundy, 2003).

Dormancy relief
There is no agreement about the concept of dormancy. In many cases seeds and tubers are called dormant when they are simply not germinating. However, according to Vleeshouwers et al. (1995) dormancy should be regarded as a seed characteristic, as the degree of which defines what conditions should be met to make a seed germinate. So, in other words, dormancy is only related to the requirements for germination, not to the question whether or not these requirements are met in the environment. Germination can be regarded as the response of the seed when both internal germination requirements (state of dormancy) and external requirements (environmental conditions) overlap (Vleeshouwers et al., 1995). This view is in accordance with the concept of Karssen (1982)(Karssen, 1982). He stated that seasonal periodicity in the fieldemergence of annuals is the combined result of seasonal periodicity in the field temperature and seasonal periodicity in the width of the temperature range suited for germination. Germination in the field is restricted to the period when field temperature (environmental factor) and the temperature range over which germination is possible (degree of dormancy) overlap. So, dormancy is related to the width of the temperature range over which germination can proceed and not to the question whether or not the current field temperature is in that range. Dormancy varies on a continous scale, visualized by continous changes in the range of environmental factors under which germination can take place (Vleeshouwers et al., 1995). At this moment, the only known factor that directly influenced that degree is temperature.

Germination
Germination is the result of the dormancy state of the seeds (range of environmental conditions at which germination can occur) and the simultaneous occurrence of these environmental conditions. Environmental factors comprise temperature, nutrients (nitrate), light, moisture and gasses (oxygen) (Bouwmeester &Karssen, 1992;Hilhorst, 1998;Vleeshouwers et al., 1995). The range of environmental conditions at which germination can occur is determined by temperature experienced by the seed or perennial structure.

Emergence
The ability of a germinated weed seed or perennial structure to successfully produce a seedling or emerged stem will depend on the burial depth and the requirement for pre-emergence growth (Grundy, 2003). Detailed pre-emergence models have been developed that enhance our understanding of the processes involved: soil penetration resistance, burial depth, seed weight and temperature (Vleeshouwers, 1997).

For all these three major processes detailed models have been developed that give us usefull information about the mechanisms underlying these processes. These studies show that temperature is the main environmental factor, dominating all major processes involved in the germination and subsequent emergence of weed species.

However, these mechanistic models are very complex and require a lot of detailed input (Grundy, 2003), which is not available for most species.
Empirical models may offer the necessary simplicity and flexibility that is required to predict future weed emergence under changing climate conditions.

In the 1970s and 1980s periodicity tables for weed emergence were developed. These tables provide a general guide to timing of germination flushes fo weed species (Roberts, 1964). They demonstrated that there are potentially predicatable species-specific flushes of emergence (Laswon et al., 1974). Most of these studies are however descriptive. The outcome of these studies were static, in that they could not show how the average weed emergence flush may be significantly modified following changes in weather conditions (Grundy, 2003).
Later studies used thermal time or hydrothermal time (Forcella, 1992;Grundy et al., 2000) to predict the emergence flushes of weeds in the field. The thermal time concept (e.g. GDD) has been described as a sum of efficient temperatures accumulated each day above a base temperature (Washitani &Takenaka, 1984). Later, this concept has been enlarged to hydrothermal time (HTT) to include the base water potential as a threshold under which no germination occurs (GUMMERSON, 1986).

Although many studies have shown that HTT provides us with a better tool to explain weed emergence, we will use GDD in this study. Our goal is to investigate whether we can expect large changes in weed emergence for possible changes in climate variables, and not to investigate the mechanisms behind weed emergence. On top of that, a recent study of barnyard grass (*E. crus-galli*) has indicated that the use of GDD can be as good as the use of HTT for natural seed banks (Bagavathiannan et al., 2010).

In Chapter 4 we will present the heat sum calculations we use in this study in detail.

3. Climate change scenarios

3.1 KNMI ‘06 scenarios

During the last decade, many studies regarding climate change have been performed. Several scenarios have been developed for various regions in the world. Climate change scenarios provide us with plausible pictures of the possible changes in our climate for the future.
The KNMI (Royal Dutch Meteorological Institute) has developed four possible scenarios for the Dutch climate, the KNMI ’06 scenarios (Van den Hurk et al., 2006) These scenarios describe the most likely changes of the climate around 2050 (*i.e*. the period 2036-2065), as compared to around 1990 (*i.e*. the period 1976-2005). The four scenarios give a description of the changes of important climate variables such as temperature, precipitation, wind and sea level for winter and summer periods.

In 2009, KNMI performed an additional study to evaluate the KNMI ’06 scenarios with respect to recent scientific developments regarding the following aspects (Klein Tank &Lenderink, 2009):

- CO_2 emissions
- Global temperature
- Storms
- Observed temperature rise in the Netherlands
- Soil dehydration
- Intensity of summer precipitation
- coastal precipitation in summer and autumn.

The 2009 additional study also provided more details on changes in temperature and precipitation patterns for spring and autumn, as well as for the individual months. Values were obtained by interpolation of the winter and summer data (Klein Tank & Lenderink, 2009). No scientific basis was established triggering the development of new scenarios. The KNMI ’06 scenarios were obtained by combining knowledge of global and regional climate change models and observations to determine which climate models gave the best description for Western Europe (Figure 2).
Also, the observations were used to translate the model output into local weather characteristics.

The IPCC (Intergovernmental Panel on Climate Change) studies (2007) showed that climate models differ considerably in their calculation of global temperature rise. Nevertheless, most global climate models expect a global temperature rise of at least 1 and at most 2°C around 2050 (Van den Hurk et al., 2006). Therefore, the KNMI used a global temperature increase of 1 or 2 °C as input for the regional climate models.

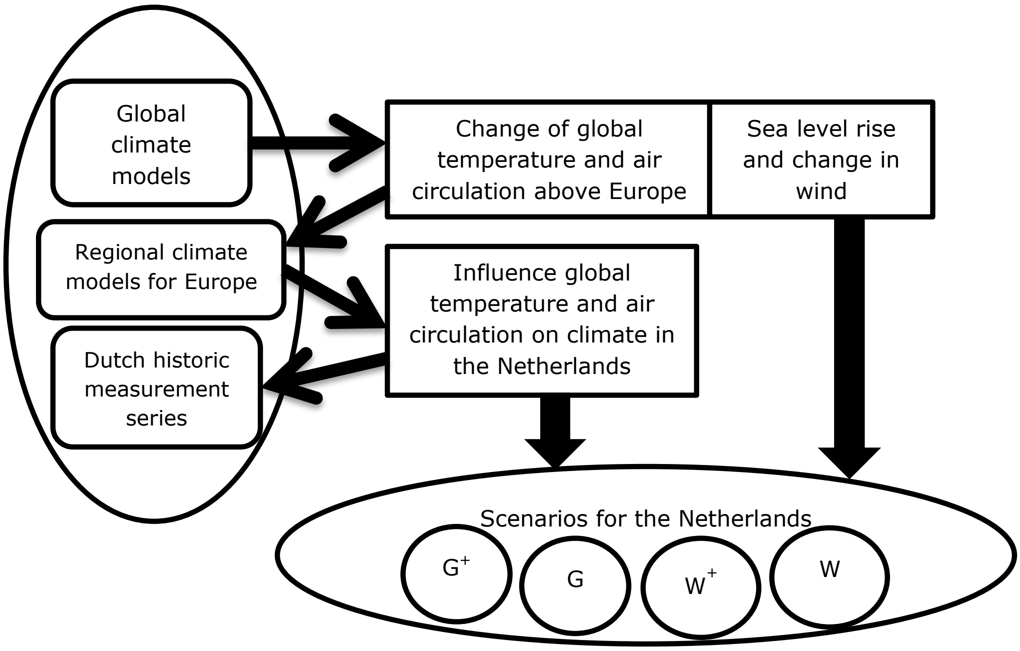


Figure 2. Schematic representations of the methodology used to construct the KNMI '06 climate scenarios (Van den Hurk et al., *2006; Klein Tank & Lenderink, 2009). Global climate models were used to provide a range of possible changes in global temperature and air circulation above Europe. The output of the global models is used as input for Regional climate models for Europe and provide information on the influence of the global temperature and air circulation on the Dutch climate. Together with Dutch historic measurement series and information on sea level rise and change in wind this output was used to construct four scenarios.*

Furthermore, climate models showed that air circulation patterns above Europe have a strong influence on the local climate in the Netherlands. Therefore, the Dutch scenarios are based on two possibilities of the worldwide temperature increase and on two possible patterns of air flow for Western Europe (Van den Hurk *et al.*, 2006, Figure 1). The Dutch historic measurement data series used were from the period 1976-2005. These scenarios have an equal likelihood to occur, there is no best estimate. The four possible scenarios are called G, G+, W and W+ (Figure 3). The G scenarios are based on a global temperature increase of 1 °C, the W scenarios are based on a global temperature increase of 2 °C. The scenarios indicated with a + (G+ and W+) are based on a changed air flow pattern in Western Europe.

In this chapter we will focus on temperature, which is the main trigger for spring plant phenology.

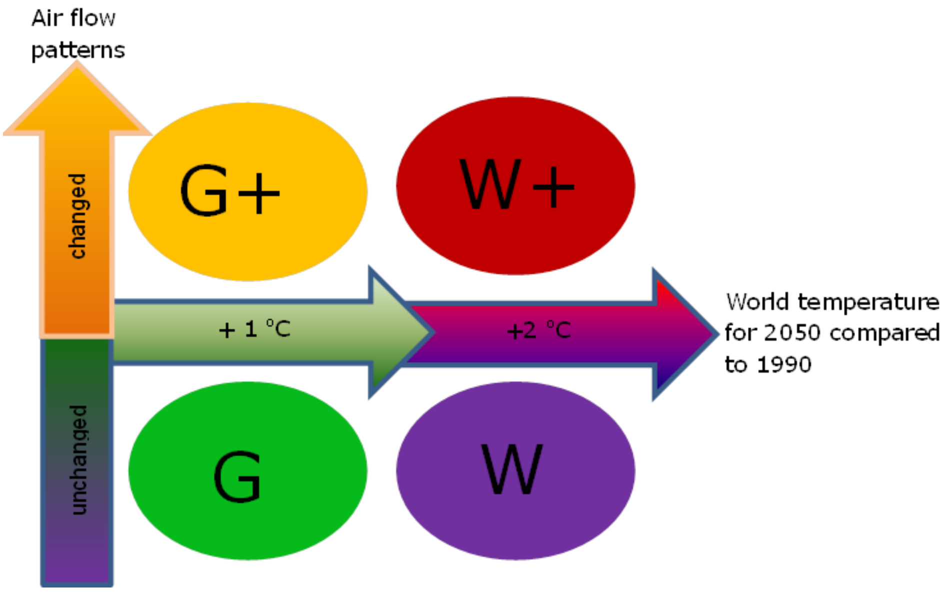


Figure 3 Four possible climate scenarios, G, G+, W and W+. G indicates a scenario with an unchanged air flow pattern and a global temperature increase of 1° C, W+ indicates a scenario with a changed air flow pattern and a global temperature increase of 2°C around 2050. The other two scenarios (G+ and W) describe the other possible combinations of changes. Source: www.KNMI.nl

3.2 Temperature

The KNMI '06 scenarios show that we can expect an average increase in temperature in the Netherlands, compared to around 1990, varying from 0.9 to 2.3°C in winter, from 0.9 to 2.6°C in spring, from 0.9 to 2.8°C in summer and from 0.9 to 2.7°C in autumn (Table 2) (Klein Tank &Lenderink, 2009). Temperature extremes are also expected to change and in some cases, these may be most relevant for weed occurrence, for instance, strong freezing temperatures for tuber survival. In that regard, the coldest winter day shows elevated temperatures to a slightly higher degree than the average temperatures (varying from 0.1 to 0.6°C).

According to Kattenberg (2008) (Kattenberg, 2008), since 1950, the temperature in the Netherlands and surrounding countries has increased twice as much as the global temperature. The increase is especially noticeable in the most recent years (2003-2008). This increase appears to be systematic and not due to natural fluctuations. Various causes are mentioned for this stronger increase in western Europe compared to the global temperature increase. The main cause in the winter is the increase of westerly winds. The main cause in the summer is the increased incoming solar radiation due to a reduction in cloudiness, which is probably a result of the drying above the European continent, combined with a cleaner air (a reduction of the aerosols). The climate models do not take these changes sufficiently into account and as a result the local warming in the Netherlands has been underestimated for the past 50 years (Klein Tank &Lenderink, 2009).

Table 2. Average temperature change in the Netherlands around 2050 per season compared to around 1990 for the four KNMI '06 scenarios (Klein Tank & Lenderink, 2009)

		Scenario			
Season*	**Climate parameter**	**G**	**G+**	**W**	**W+**
Winter	average temperature (°C)	+0.9	+1.1	+1.8	+2.3
	coldest winter day per year (°C)	+1.0	+1.5	+2.1	+2.9
	warmest winter day per year (°C)	+0.8	+0.9	+1.6	+1.7
Spring	average temperature (°C)	+0.9	+1.2	+1.8	+2.6
	coldest spring day per year (°C)	+1.0	+1.4	+2.0	+2.8
	warmest spring day per year (°C)	+1.0	+1.5	+2.0	+2.9
Summer	average temperature (°C)	+0.9	+1.4	+1.7	+2.8
	coldest summer day per year (°C)	+0.9	+1.1	+1.7	+2.3
	warmest summer day per year (°C)	+1.0	+1.9	+2.1	+3.8
Autumn	average temperature (°C)	+0.9	+1.3	+1.8	+2.7
	coldest autumn day per year (°C)	+1.0	+1.3	+2.0	+2.6
	warmest autumn day per year (°C)	+1.0	+1.8	+2.0	+3.6

**) Winter: December, January, February; Spring: March, April, May; Summer: June, July, August, Autumn: September, October, and November.*

The processes causing the increase of westerly winds and the reduction of cloudiness are not fully understood, which makes an extrapolation to the future impossible. Since 2000, no further reduction in the number of aerosol particles has been observed. It is expected that the level of aerosols will remain stable until around 2050. The W and W+ scenarios account best for the strong local temperature increase in Western Europe (Klein Tank &Lenderink, 2009).

3.3 General Limitations and assumptions of the KNMI '06 scenarios

The climate models used by the KNMI to construct the four scenarios for the Netherlands make use of several emission scenarios. However, the emission of greenhouse gasses and particulate matter is strongly determined by socio-economic developments, which are very hard to predict. One of the uncertainties in the scenarios is therefore the socio-economic development. Other important factors that are a source of uncertainty on the global level are the solar activity itself and possible volcanic eruptions (Klein Tank &Lenderink, 2009).

The four KNMI '06 scenarios assume that the Dutch climate is homogeneous between different regions in the Netherlands. However, the Netherlands is characterized by regional climate differences. Furthermore, no differences between rural and urban areas are assumed; changes in the city are assumed to be equal to changes in the countryside (Klein Tank &Lenderink, 2009).

The four scenarios were constructed using regional climate models and historic measurement data (Figure 2) from the period 1975-2005. The effect of using a time scale of 30 years is that the inter-annual variability is levelled out. The inter-annual variability in the 20th century is however for some climate variables, such as precipitation and wind, larger than the seasonal mean changes foreseen by the model calculations. A quantitative estimate of the future inter-annual variability of seasonal means is not yet possible due to a lack of thorough understanding of all relevant processes (Klein Tank &Lenderink, 2009).

3.4 Comparison of the KNMI ’06 scenarios with the current climate in other European regions

In order to obtain further insights in what possible climate change for the Netherlands might mean for herbaceous species, we made an attempt to find regions in Europe where present climate conditions look most similar to that possible climate change for the Netherlands. Behaviour and occurrence of herbaceous, weedy species, in those purportedly similar climatic regions then may provide clues to future weed occurrence and behaviour in the Netherlands. We investigate the question to what extent a comparison of the current climate in (southern) European regions with the KNMI ’06 scenarios for the Dutch climate around 2050 can be made. We discuss three studies with relevance for this question.

As a first approximation, Figure 4 shows the average annual temperatures in the Netherlands in 2006 and 2007 in comparison to temperature zonation recorded in France in the period 1961-1990 (Kattenberg, 2008). The measured temperatures in the period 2003-2008 in the Netherlands (De Bilt) were significantly higher than the long term averages for the Netherlands (De Bilt). Dutch temperatures were comparable to the annual temperatures in central France of the period 1961-1990.

As this is only a rough comparison of annual temperature averages, its predictive power is questionable. Unfortunately, the possibilities to make more complete comparisons of the current climate in certain regions with the climate scenarios for around 2050 are very limited. Climate is not just the average temperature or precipitation. Certain areas in Europe can have a current average temperature that is similar to an average temperature of one of the KNMI ’06 scenarios, but a completely different precipitation pattern or extreme temperatures. In general, a comparison of one or two climate variables between regions can be made, but a comparison of climates between regions not (pers. comm. KNMI helpdesk).

In the next paragraphs we will refer to two studies in which temperature and precipitation in the Netherlands in 2050 according to one or more of the KNMI ’06 scenarios, have been compared to the current averages of the same climate variables in other European regions.

In the first study, which only addressed the summer season, the average climate variables in the Netherlands at present and in 2050 according to the four KNMI ’06 scenarios were compared with the current climate in Paris (www.knmi.nl/klimaatscenarios/faq/index.php#Inhoud4).
This comparison shows that the average daily temperature, the maximum temperature and the number of summer days in scenarios W and W+ are comparable to the average long term values for Paris (Table 3). The percentage of days without precipitation in Paris in summer at present is close to the percentage in the W+ scenario. The total current precipitation in Paris is however lower than the precipitation in one of the scenarios.

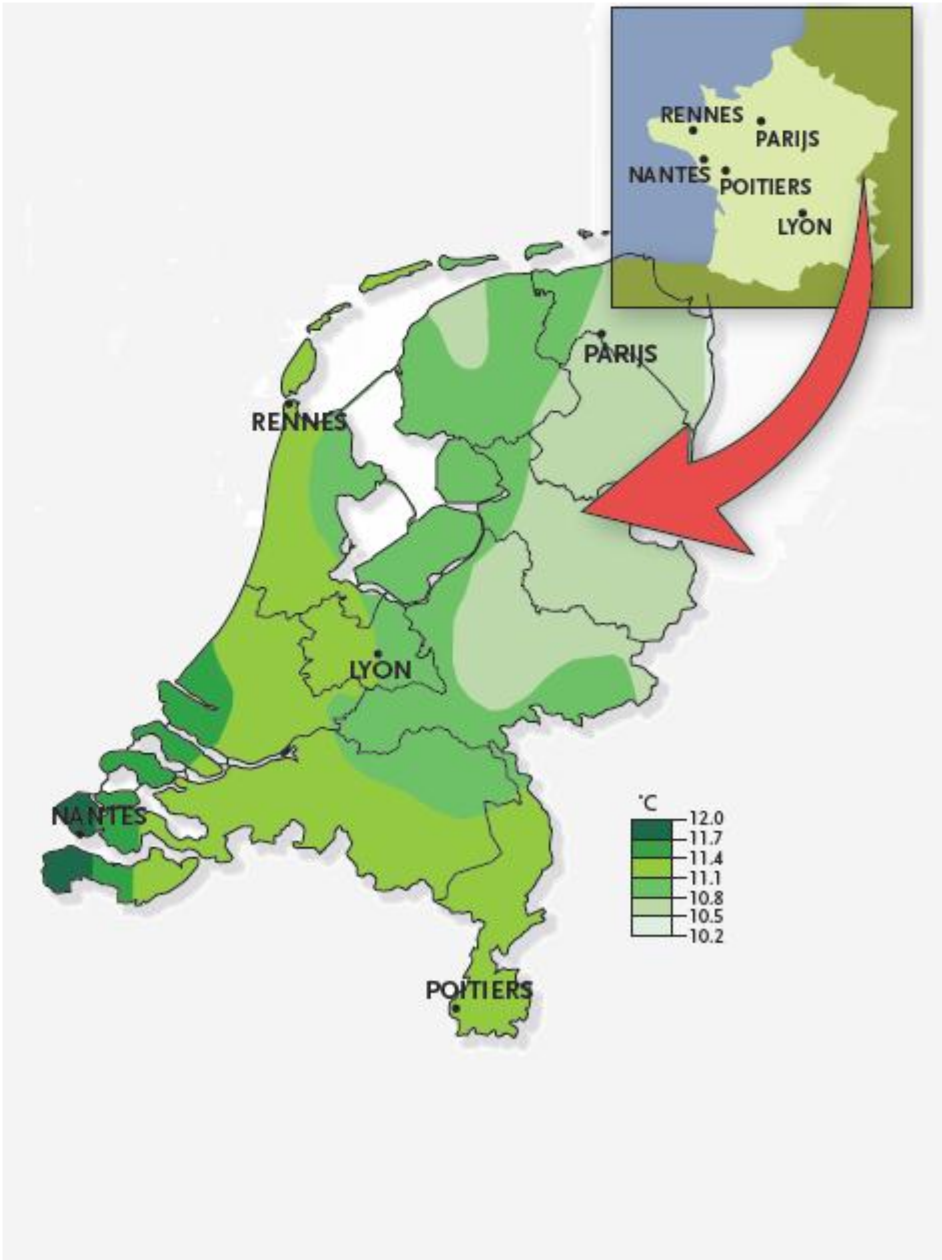


Figure 4. The average yearly temperature measured in 2006 and 2007 in the Netherlands was equal to the long term average (1961-1990) in central France (from: Kattenberg, 2008).

Table 3 Description of an average summer (June to August) in the Netherlands (De Bilt), at present and around 2050 and the current summer climate in Paris. The minimum and maximum values per variable for the period 1976-2005 are presented between brackets (www.knmi.nl/klimaatscenarios/faq/index.php#Inhoud4)

Variable	De Bilt (1976-2005)	G 2050	G+ 2050	W 2050	W+ 2050	Paris (1976-2005)
Daily temperature (ºC)	16,8 (15,3-18,7)	17,7	17,6	17,9	19,6	19,3
Max. temperature (ºC)	21,7 (19,8-24,6)	22,6	23,1	23,4	24,5	23,9
Summer days (max. temperature ≥ 25 ºC)	24 (4-48)	30	34	39	47	45
Tropical days (max. temperature ≥ 30 ºC)	4 (0-13)	7	9	10	14	9

The second study investigated the resemblance of the KNMI '06 scenario with the largest changes, the W+ scenario, with the 20th century climate measured at weather stations across Europe (Böing, 2007). Monthly means of two climate variables (temperature and precipitation) were used to calculate a similarity index for each weather station in Europe between 20W and 28E and 30N and 65N. The similarity index is a measure for the (scaled) deviation of the mean monthly temperature and precipitation measured at a European weather station from the mean monthly temperature and precipitation calculated for De Bilt for the W+ scenario in the period 2086-2115. The result is shown in Figure 5. Red areas are those that show a high degree of correlation to de Bilt. The central Italian climate seems to come quite close to the W+ scenario. However, the climate has been defined in terms of monthly means of temperature and precipitation. The probability distribution of precipitation and temperature over the months is not taken into account and is important as an indicator for drought risk (Böing, 2007). However, also note that the W+ scenario for the period 2086-2115 was used, reaching beyond the year 2050, which takes us beyond the period that is the focus of this report.

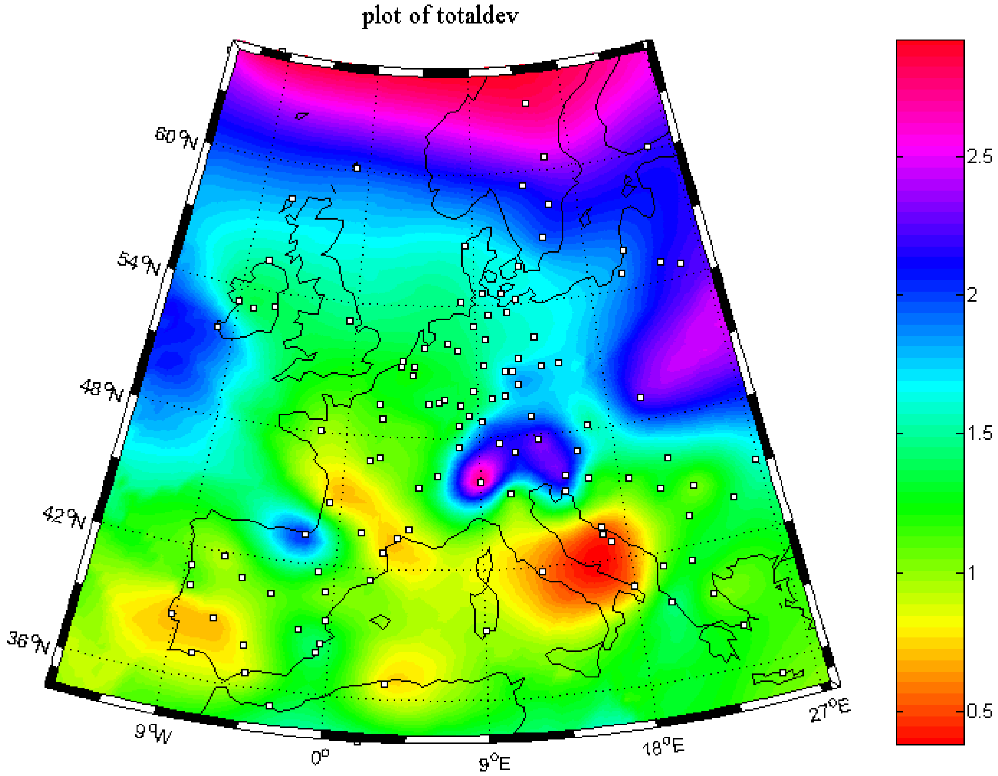


Figure 5. Similarity index based on standard deviations of the monthly mean precipitation and temperature of European weather stations in the 20th century to that of de Bilt in the W+ scenario in the period (2086-2115). White dots indicate measurement points. Red areas indicate a high correlation with De Bilt. From: Böing, 2007.

- Four climate change scenarios for the Netherlands have been developed.
- According to these scenarios temperature in the Netherlands will continue to rise. Mild winters and hot summers will become more common.
- The measured temperatures in the period 2003-2008 in the Netherlands (De Bilt) were significantly higher than the long term averages for the Netherlands (De Bilt), and are higher than the highest temperatures measured in the scenarios.
- The average winter temperature will increase and the temperature on the coldest winter day will increase more than the average winter temperature.
- The average summer temperature will increase and the warmest summer day will increase stronger than the average summer temperature.

4. Case studies

In this chapter we will study the effect of possible changes in (air) temperature to the emergence of one annual and two perennial arable weed species: *Galinsoga parviflora, Cirsium arvense* and *Sonchus arvensis*.
Perennial weeds cause large problems in agriculture worldwide. *Sonchus arvensis* and *Cirsium arvense* are two of the most problematic species in Northern Europe. Control is difficult, especially in organic farming systems. The rapidly growing horizontal and vertical root systems enable these species to spread vegetatively in the infested field. In addition, adventituous buds develop along the length of the root systems. This ensures that new shoots emerge even after intensive soil cultivations. The commonly used mechanical measures to control perennial weeds include cutting of aboveground biomass and stubble cultivation, that is, fragmentation of roots. These strategies aim at preventing photosynthetic assimilates being allocated to roots, where nutrients are stored and used for horizontal dispersal of the weed. Disturbances stimulate emergence of new shoots, which, if the cutting or fragmentation is repeated, result in a depletion of nutrient reserves.The timing of these methods is essential.

Galinsoga parviflora is an annual plant. It is present in agricultural areas in North and South America, Europe, Asia, Africa and Australia (Canne 1977; Warwick and Sweet 1983). *Galinsoga parviflora* originates from the Anders in Peru (Stoffert 1994), Central America (Anonimous 2007). In the eighties the species has become a problem in low-growing vegetable crops such as beans, cabbage, peppers and tomatoes in northeastern North America (Ivany and Sweet 1973). In Europe, *G. parviflora* is a major weed in cultivated crops (Warwick and Sweet 1983). The spread in Germany took place between 1800 (when it was introduced from France in a botanical garden in Berlin) and 1910. In that year it was found in Niedersachsen and Hamburg (Stoffert 1994).Until the 1990s the species has been regarded a problem in the south of the Netherlands, mainly on sandy soils. However, during the last decade, it has been reported to infest fields in the whole country, on almost all soil types. The main problem with *G. parviflora* control is that seeds are non dormant and germination can take place during the whole year.

We will describe the materials and methods in paragraph 4.1: the heat sum calculation as a measure for temperature, and the emergence data we used for each of the species. Data on the emergence of *C. arvense* and *S. arvensis* was collected through field experiments, and data on the emergence of *Galinsoga parviflora* was obtained from literature (Otto et al., 2007). Second, we will present the relationship between the emergence of these species and the GDD. Finally, the effect of possible future temperature changes according to the climate change scenarios (chapter 2) on the emergence of these species will be investigated and discussed.

4.1 Materials and Methods

4.1.1 Heat sum

To relate the emergence of the four species of interest to temperature, we make use of the heat sum. The heat sum, expressed in growing degree days (GDD), is frequently used to describe the timing of biological processes, especially in the area of crop phenology and development (McMaster &Wilhelm, 1997). GDD can be calculated as:

$$\sum GDD = \frac{(T_{\max} + T_{\min})}{2} - T_b$$,where $$\frac{(T_{\max} + T_{\min})}{2} = T_b$$ if $$\frac{(T_{\max} + T_{\min})}{2} \leq T_b$$ then $$\frac{(T_{\max} + T_{\min})}{2} = T_b$$.

Where T_{max} is the daily maximum air temperature, T_{min} is the daily minimum air temperature, T_b is the temperature below which the process of interest does not progress (McMaster &Wilhelm, 1997). T_b varies among species, see Table 4 for the T_b used in this study.

Table 4. Base temperatures used in heat sum calculations for emergence for each species.

Species	T_b (°C)	source
Cirsium arvense	0	(Donald, 2000)
Sonchus arvensis	0	(TØRresen et al., 2010)
G. parviflora	5	(Otto et al., 2007)

Daily minimum and maximum air temperatures were obtained from a nearby weather station (Source: Meteorological Station, Wageningen University, http://www.met.wau.nl) and used to calculate the heat sum.

4.1.2 Emergence of *Cirsium arvense* and *Sonchus arvensis*

Roots were collected in autumn from a sandy field near Wageningen and stored in sand in wooden containers placed outside. On March 23rd 2009 roots were washed and cut into root pieces (see Table 5 for average weight and length of root pieces) and pieces were placed in ridges of approximately 5-7 cm deep on a field in Wageningen, the Netherlands (51°59'N, 5°35'E) with a Eutric Fluvisol (texture loamy fine sand) soil. The preceding crop was potato. The field was fertilized with 90 kg N per ha.
The design was a complete randomized block, with four blocks of each 38 m long. In each block, root pieces were placed in a row of the same length as the block, 33 cm apart. The field remained untouched for a year to allow the species to grow and establish in order to observe emergence from an established population. In the following spring, every two days stem emergence was noted until no main stems were emerging from the buried root pieces. Stems emerging in between observation dates were assumed to have emerged on the observation day. Every newly emerged stem was marked with a coloured stick, each colour representing a new day of emergence.

Table 5. Length and weight of buried root pieces of C. arvense and S. arvensis.

Latin name	length (cm)	stdev	weight (g)	stdev
Cirsium arvense	6.400	1.06	0.637	0.20
Sonchus arvensis	8.030	2.54	1.099	0.54

Emergence was calculated as the percentage of the total number of plants that emerged per row. The minimum and maximum daily air temperature were obtained from a local weather station (Meteorological Station, Wageningen University, http://www.met.wau.nl) and used to calculate the number of growing degree days (GDD) with the method described in paragraph 4.2.1. Base temperature (T_b) used was 0 °C (Table). A non-linear logistic four parametric regression model was used to fit emergence vs. GDD:

$$E = c + \frac{(d-c)}{\left(1+\exp^{\left(\frac{e-GDD}{b}\right)}\right)}$$

, with emergence *E,* growing degree days GDD, maximum cumulative emergence d, minimum cumulative emergence c slope b and e representing the number of GDD at which 50% of the plants have emerged. Parameter d was set at 100 and parameter c at 0.

4.1.3 Emergence of *Galinsoga parviflora*

We used the relationship between *G. parviflora* emergence and GDD as described in literature (Otto et al., 2007). Otto *et al.* (2007) studied the emergence of this (and other) species from 2003 to 2004 in three sites in Northern Italy between Lake Garda and the River Adige. Seed beds were prepared in late winter on fields naturally infested with *G. parviflora*. Emergence was counted once or twice a week during the following spring and seedlings were removed after counting. It was assumed that the base temperature of *G. parviflora* is 5 °C. For more detailed information on the experimental set up we refer to Otto *et al.* (2007).
The emergence was modelled with a Gompertz model:

$$E = 100 \times \exp(-ae^{-bGDD}),$$

with emergence *E,* growing degree days GDD, a the GDD lag before emergence starts and b is the rate of increase of emergence once it has begun (Otto et al., 2007). Parameter a was estimated to be 20.98 ± 3.190, and parameter b 0.013 ± 0.001.

4.1.4 Growing degree days according to scenarios and Julian day

Historical weather data available from the weatherstation in Lelystad (Longitude: 5 38 E, latitude: 52 34 N) from the period 1980-1996 were transformed for the four different KNMI '06 scenarios using the tool provided by the KNMI: http://climexp.knmi.nl/Scenarios_monthly/. The resulting daily minimum and maximum temperatures for the period 2040-2056 were used to calculate the growing degree days with a base temperature of 0°C (both perennials) and of 5 °C (*G. parviflora*).
In addition, historic measurements (1985-1990) and (2006-2011) were used to calculate growing degree days for the same base temperatures.

The calculated growing degree days for each base temperature were plotted against the Julian day (Figures 7 and 8).

5. Results

5.1 Emergence patterns of *G. parviflora, S. arvensis* and *C. arvense*

Otto *et al*. (2007) found that the Gompertz model gave the best fit to relate *G. parviflora* cumulative emergence to GDD, whereas a log logistic model fitted the emergence pattern of *C. arvense* and *S. arvensis* in our field experiments best (Figure 6, Table 6).

Table 6. Parameter estimates and their standard errors (s.e.) for the logistic regression model:

$$E = c + \frac{(d-c)}{\left(1+\exp^{\left(\frac{e-GDD}{b}\right)}\right)}$$

where E is the emergence as a fraction of total emergence and GDD is the number of growing day-degrees. For all fitted curves: p>0.001.

	Parameter estimate and s.e.			
Species	e	se	b	se
Cirsium arvense	212.12	8.239	-2.82	0.252
Sonchus arvensis	324.69	5.022	-6.41	0.647

Although a slightly different model was used for *G. parviflora*, the cumulative emergence pattern was a typical S-shaped curve for all of the species when plotted against GDD (Figure 6).
Some marked differences between species behaviour can be observed from this data. The cumulative emergence of *G. parviflora* starts around 21 GDD (paragraph 3.2.3, Otto et al. (2007)) and it will take more than 600 GDD to be completed. Half of the plants can be expected to be emerged around 373 GDD. *S. arvensis* cumulative emergence from root buds in spring is also expected to be halfway around that time, it takes this species 324 GDD to reach 50% stem emergence (Figure 6). *C. arvense* only requires 212 GDD before 50% of all stems have emerged. Both perennials require a relatively short period for the stem emergence in spring: *C. arvense* has completely emerged before 250 GDD and *S. arvense* before 375 GDD. The emergence of *G. parviflora* takes place more gradually: emergence starts around 21 GDD and takes more than 600 GDD to finish (Figure 6).

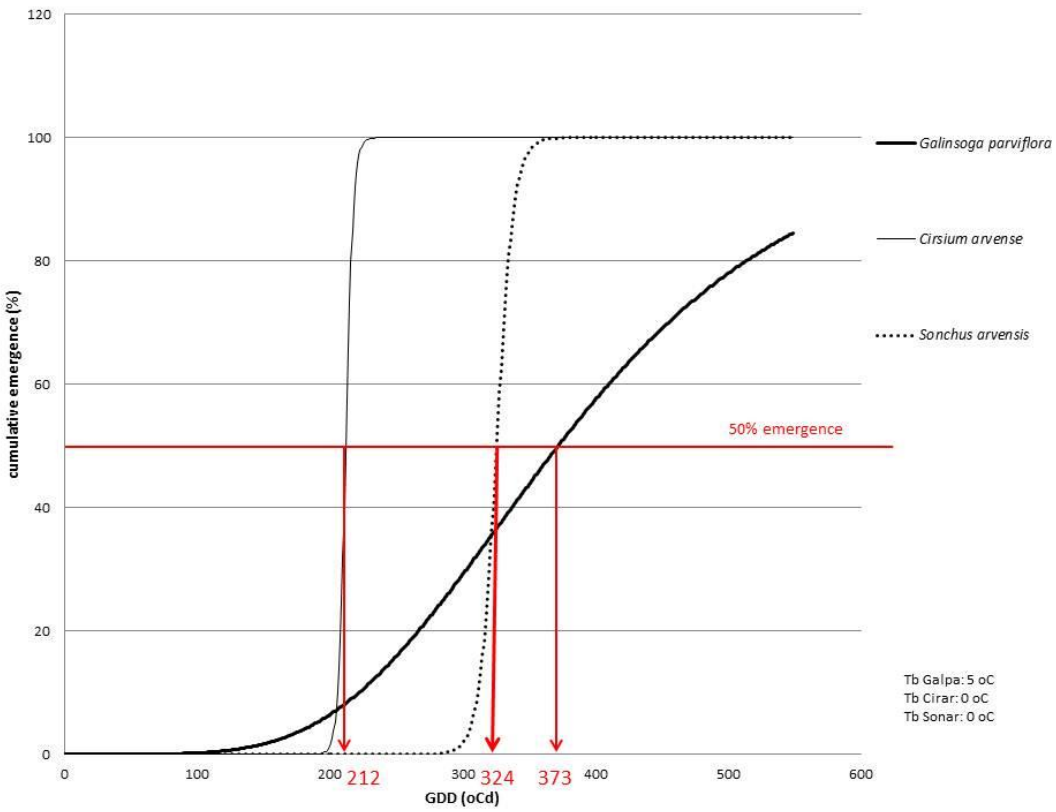
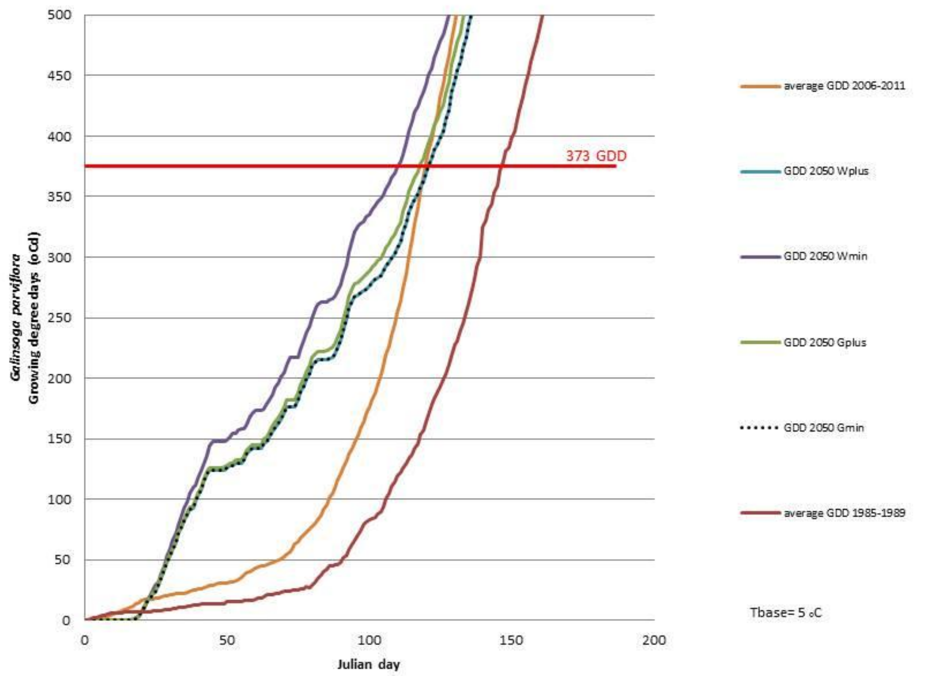


Figure 6. Relationship between the cumulative emergence of Galinsoga parviflora, Cirsium arvense and Sonchus arvensis and the number of growing degree days (GDD). The number of GDD required to obtain 50% cumulative emergence is marked red.

5.2 Effect of temperature changes on emergence patterns

The different relationships between cumulative emergence and growing degree days cause the species to respond differently to possible temperature changes. In Figures 7 and 8 we plotted the growing degree days (Tb= 5 °C and Tb= 0°C respectively) vs. the julian day for the different KNMI '06 scenarios and for two historical data sets.
Figure 6 showed that *G. parviflora* requires 373 GDD for a cumulative emergence of 50%. In the period 1985-1989 this corresponded with julianday 146 (Figure 7). In the period 2006-2011 373 GDD corresponded to julian day 119. This means that *G. parviflora* was able to reach 50% emergence significantly earlier than in the period 15 years earlier. The biggest change for species with a T_b of 5 °C, such as *G. parviflora*, can be expected with scenario W^-. When temperature changes will occur as described by that scenario, the 50% cumulative emergence level can be reached 27 days earlier than in the period 2006-2011.
Figure 6 showed that *C. arvense* and *S. arvensis* require 212 and 324 GDD, respectively, for a cumulative emergence of 50%. Figure 8 shows that in the period 1985-1989 this corresponded with julian days 83 and 98. In the period 2006-2011 these numbers of GDD were already reached at julian days 59 and 79. The biggest change for species with a T_b of 0 °C, such as *C.arvense* and *S. arvensis*, can be expected with scenario W^+. When temperature changes will occur as described by that scenario, the 50% cumulative emergence level of these species can be reached 27 and 35 days earlier than in the period 2006-2011.



This means that all three species were able to reach 50% emergence significantly earlier than in the period 15 years earlier and that this level of emergence will be reached earlier in season in 2050 according to the scenarios.

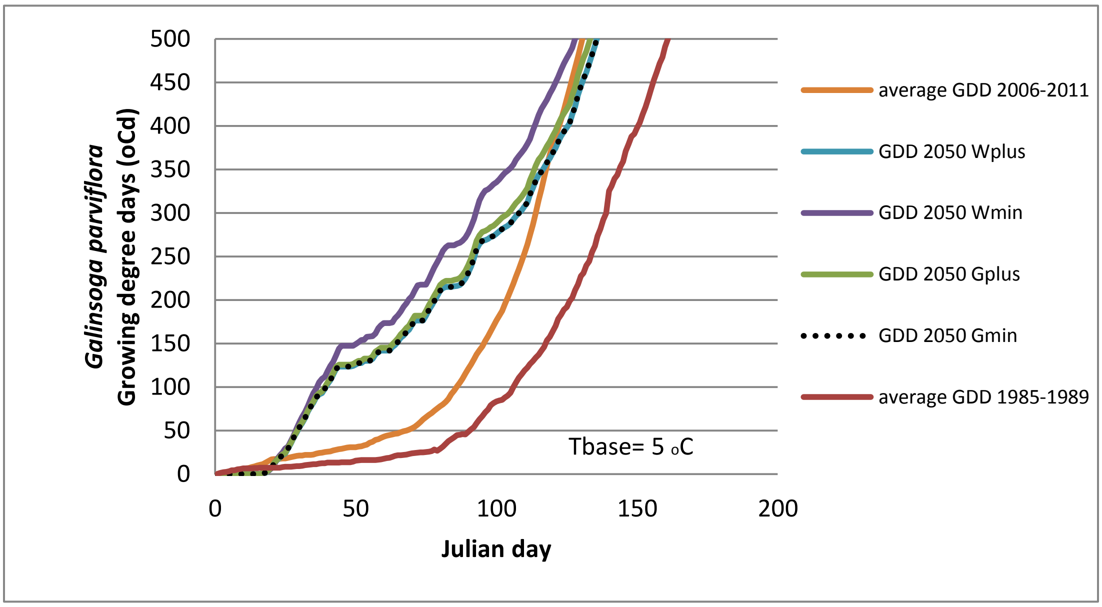


Figure 7. Relationship between the number of growing degree days (GDD) with Tb= 5 °C for the possible climate change scenarios and historic measurement data from two periods (1985-1989) and (2006-2011) and Julian day . The number of GDD required to obtain 50% cumulative emergence of G. parviflora is marked red.

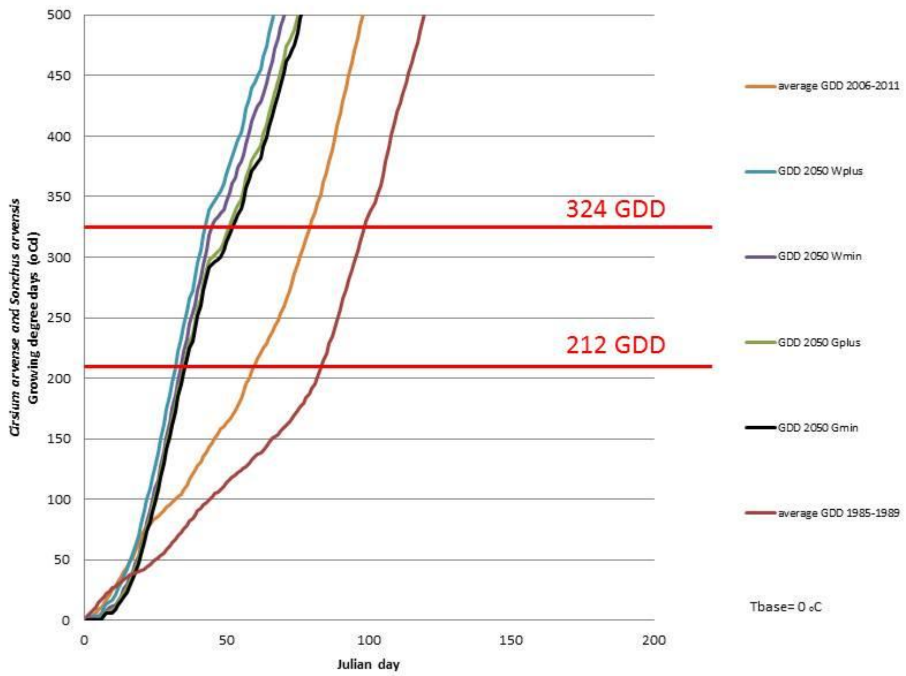


Figure 8. Relationship between the number of growing degree days (GDD) with Tb= 0 °C for the possible climate change scenarios and historic measurement data from two periods (1985-1989) and 20062011 and Julian day . The number of GDD required to obtain 50% cumulative emergence of C. arvense (212) and S. arvensis (324) are marked red.

- All 3 species in this study were able to reach 50% emergence significantly earlier in the period 2006-2011 than in the period 15 years earlier.
- This level of 50% cumulative emergence will be reached earlier in season in 2050 according to the scenarios for all species.

6. Conclusions

In this study we used KNMI climate change scenarios for 2050 to estimate possible effects on three weed species currently present in the Netherlands. In chapter 3 we indicate the assumptions that were made during the construction of these scenarios. We will not discuss these in this chapter, but refer to van den Hurk et al., 2006 for extensive information on these climate change scenarios.

In this study, we used changes in air temperature to estimate possible changes in the emergence of the species. Other climate factors such as precipitation were not taken into account. Although temperature is the main climate factor determining dormancy and thereby emergence, and is known to be the main driver of phenological processes in spring, other climate factors such as precipitation are relevant as well. Weed germination and emergence and bud sprouting are complicated, not yet completely understood processes, in which several environmental factors play a role. Furthermore, climate change will not only affect the weeds themselves, but the whole system in which the weeds grow. Our results indicate that the weeds investigated will emerge earlier and that time until complete emergence will be shortened under the climate changes scenarios.

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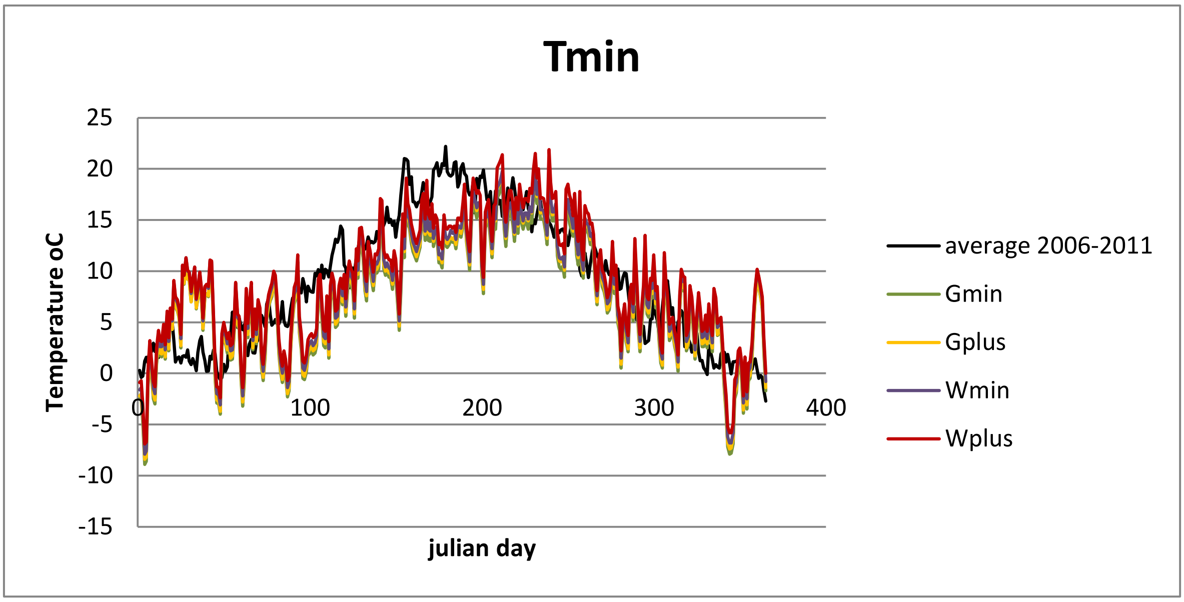
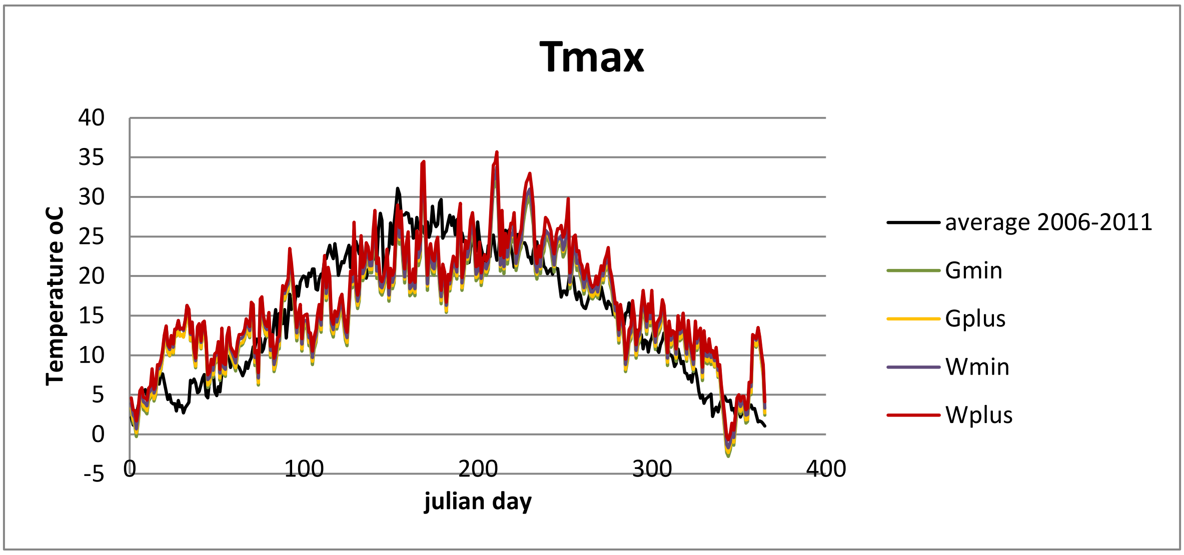
Appendix I.
Minimum and maximum daily temperatures





Appendix II.

GDD vs Julian day for T_b=0 and T_b=5 °C