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Titel der Dissertation

Description and prediction of the dispersion of
Ambrosia artemisiifolia L. (common ragweed) as
diffusion process

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Mag. DI Robert Richter

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„Vorhersagen sind immer schwierig - vor allem über die Zukunft.“
Niels Bohr

Abstract

Invasive alien species cause a major threat to our ecosystems and health. In the past it was shown that the processes of diffusion can be used to model the spread of plants and animals. In this thesis the spread on behalf of the study species *Ambrosia artemisiifolia* L. (common ragweed) is simulated, parametrized according to 512 documented infested sites in the study region Austria and Bavaria, until the year 2005. This presence absence data show that the dispersion has accelerated in the last years of the investigation until 2005. It can be assumed that due to climate change the spread will even get worse in the next decades as the study species is thermophile.

In this thesis the dispersion is simulated until the year 2050 under current climate as well as under two different climate change assumptions (i.e. temperature increase of 0.025 °C and 0.04 °C per year equivalent to an increase in temperature of 1.5 °C and 2.4 °C from the year 1990 until 2050). As *Ambrosia artemisiifolia* L. causes a lot of pollen allergies the possibilities of curtailing its further spread is discussed. Therefore, management schemes under constrained budget are implemented to illustrate the costs of surveillance and eradication processes. Benefit-cost analyses show that it is wise to manage only a subset of the cells of the study area, determined by the habitat suitability. Further the management success is much higher when selecting the cells to be surveyed every year in order of decreasing habitat suitability rather than by random. For higher available budgets the optimum number of cells to be surveyed increases. The cost for management was first calculated in abstract values and then specified in Euro to be able to carry out benefit-cost calculations. The costs for management are thereby compared with arising health costs due to pollen allergies. Therefore, pollen flight is implemented into the spread model to be able to determine the pollen pressure in the cells of the study region. It proved that the savings in health costs, compared to the business-as-usual scenario (i.e. without management), outreach the costs for management by far resulting in a benefit-cost ratio of 10:1 (i.e. one Euro spent in management results in ten Euro savings for health costs). The savings throughout the management period (2011 until 2050) accumulate to 12 billion Euro for the more extreme temperature increase of 0.04 °C per year.

Zusammenfassung

Invasive Pflanzen stellen eine Gefahr für unser Ökosystem und unsere Gesundheit dar. In der Vergangenheit wurde gezeigt, dass für die Ausbreitung von Pflanzen und Tieren Diffusionsmodelle verwendet werden können. In dieser Dissertation wird die Ausbreitung anhand einer Musterpflanze, der invasiven *Ambrosia artemisiifolia* L. (das Beifußblättrige Traubenkraut oder Ragweed) simuliert, parametrisiert mit Hilfe von 512 dokumentierten Funden aus der Musterregion Österreich und Bayern bis zum Jahr 2005. Diese Funddaten zeigen, dass sich die Ausbreitung in den letzten Jahren der Erhebung bis 2005 beschleunigt hat. Es kann angenommen werden, dass die Ausbreitung in den nächsten Jahrzehnten durch den Klimawandel noch weiter zunimmt, da die Musterpflanze wärmeliebend ist.

In dieser Arbeit wird die Ausbreitung bis zum Jahr 2050 sowohl unter Annahme eines gleichbleibenden Klimas als auch mit zwei Klimawandelalternativen (d.h. Temperaturerhöhung von 0.025 °C und 0.04 °C pro Jahr, äquivalent zu einer Temperaturerhöhung von 1.5 °C und 2.4 °C von 1990 bis 2050) simuliert. Da *Ambrosia artemisiifolia* L. ein Auslöser für starke Pollenallergien ist, werden auch Möglichkeiten die Ausbreitung einzudämmen diskutiert. Daher wurden Managementpläne unter der Annahme von begrenztem Budget eingebaut, um Kosten für Such- und Vernichtungsprozesse darstellen zu können. Nutzen-Kosten Analysen zeigen, dass es ratsam ist, nur einen Teil der Musterregion, festgelegt nach Habitategnung, nach *Ambrosia artemisiifolia* L. abzusuchen. Weiters wird der Managementerfolg höher, wenn die Zellen in absteigender Habitategnung anstatt zufällig abgesucht werden. Wenn mehr Geldmittel zur Verfügung stehen, steigt die optimale Anzahl an abzusuchenden Zellen. Die Kosten für das Management wurden zunächst in abstrakten Werteinheiten berechnet und anschließend in Euro beziffert, um eine Nutzen-Kosten Rechnung durchführen zu können. Diese Managementkosten werden dabei mit den entstehenden Gesundheitskosten aufgrund von Pollenallergien verglichen. Daher wurde auch der Pollenflug in diesem Modell simuliert, um die Pollenbelastung in den einzelnen Zellen der Musterregion herauszufinden. Es hat sich gezeigt, dass die Einsparungen an Gesundheitskosten, verglichen mit einem Szenario ohne Management, die Kosten des Managements bei weitem übertreffen und sich somit ein Nutzen-Kosten Verhältnis von 10:1 ergibt (d.h. pro eingesetztem Euro im Management ergeben sich Einsparungen in den Gesundheitskosten von zehn Euro).

Die Einsparungen über die gesamte Managementperiode (2011 bis 2050) summieren sich zu 12 Milliarden Euro für die stärkere Temperaturerhöhung von 0.04 °C pro Jahr.

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Chapter 1

Introduction

1.1 Interdisciplinarity

This thesis is the result of a joint work of three physicists and two ecologists. Although every group member belongs to the natural sciences, there are some differences that one has to overcome. Physicists are used to having a big number of data when they want to simulate experimental results. It is common to repeat experiments if additional data are necessary. The data collection used for this thesis cannot be repeated as presence absence data of a specific plant over a period of 15 years was used. As one cannot reverse the time, it is not possible to collect more datasets for the past time period.

Due to this interdisciplinary method we had a division of work. The biological background on the study species as well as the presence absence data were mainly provided by the two ecologists Stefan Dullinger and Franz Essl. The physical part was done by the author with the help of Michael Leitner and Gero Vogl.

1.2 Aliens around us

On Friday the 12th October 1492 Christopher Columbus discovered the American continents. Today it is known that he was not the first European explorer to step onto this continent. However, it led the first time to a continuous contact between America and Europe. From the so called New World (i.e. America) goods like gold, silver and other, for european inhabitants, valuable merchandise were brought to the Old World (i.e. Europe).

Together with this trading, intended and unintended, a lot of plants and animals but also diseases were brought from the New World to Europe and vice versa. The plants and animals that captured new territories this way

are called invasive alien species. The dispersion of such alien species and also diseases can be described by diffusion processes [Fisher, 1937, Skellam, 1951, Gilbert et al., 2004, Vogl, 2012, Vogl, 2014]. Similar to different species in Europe common diseases travelled with infected persons to the New World. Unfortunately the native people there had no antibodies against some of the viruses and, hence, a lot of people died.

Invasive alien species represent a threat to the ecological balance of an area and the biodiversity [McNeely et al., 2001, Vila et al., 2010, Vila et al., 2011]. Therefore, it is a problem that the number of alien plants introduced to Europe is steadily growing. The reason of this increase is intensifying global trade. In a recent study 5 789 vascular plants have been identified [Lambdon et al., 2008]. Although the majority of these species will disappear quickly, a minority will become naturalized [Diez et al., 2009]. Of these plants again a small part will become invasive and, therefore, represent a problem to the ecosystems [Hulme, 2003]. Unfortunately, it is not yet understood why some alien species have a higher impact on ecosystems than others. However, this knowledge would help implementing effective management strategies [Kumschick et al., 2014]. The time span from the introduction of alien species until they become invasive was detected to be long. Depending on the species and the environment this lag phase can be between a few decades and up to a few hundred years [Kowarik, 1995]. Hence, the number of invasive alien species will increase in the next decades as a big number of new alien species was detected in the last years [Essl et al., 2011b]. Recently politicians have also become aware of the problem and are doing their best to manage it [Hulme et al., 2009]. This can be seen on an extensive political and legal framework elaborated by the European Commission to diminish the negative impacts of invasive alien species [Shine et al., 2010]. One step to reduce such negative impacts is to prevent further introductions of alien species due to better control mechanisms. A second step is to eradicate or at least curtail already existing populations of alien species. The latter is a big challenge, because arranging and implementing management strategies for invasive alien species that are already common represent a complex task [Epanchin-Niell and Hastings, 2010]. This may even be more complicated, if the distribution of the targeted species is known insufficiently. Different studies came to the result that systematic management schemes could increase management success [Fox et al., 2009, Krug et al., 2010, Panetta et al., 2011, Regan et al., 2011]. One part is the kind of management technique, the other is the strategy on how to select the area to be surveyed. Concentrating surveillance on regions with high habitat suitabilities yielded in promising results [Fox et al., 2009, Hauser and McCarthy, 2009, Giljohann et al., 2011]. It seems obvious to increase management success by concentrating surveillance on cells with high suitabilities

as those are the parts with high population densities of the invasive alien species, especially when only limited budget is available. On the other hand, with such a management scheme, the invasive species can spread without limits within and into cells with lower habitat suitability but high enough that at least a part of arriving seedlings will germinate. Usually, there exists no sophisticated scheme to carry out management, instead ad hoc decisions are made, that are not coordinated between different authorities [Krug et al., 2010].

This thesis is based on a recent study that used discrete annual time steps to simulate the spatial and temporal spread of *Ambrosia artemisiifolia* L. in Austria [Vogl et al., 2008, Smolik et al., 2010] and in Austria and Germany [Leitner et al., 2012] divided into cells of same size. Here, it is evaluated whether suitability-based spatial prioritization schemes are useful for fighting against invasive alien species. A large scale spread model for plants is used for simulating the spread of the study species, *Ambrosia artemisiifolia* L., a highly allergenic annual weed, based on presence absence data in the years 1990 until 2005 in Central Europe. Additionally, a further spread until the year 2050 is predicted. This is done by using elements of species distribution models and interacting particle systems [Thuiller et al., 2008, Vogl et al., 2008, Smolik et al., 2010]. The spread is simulated across a gridded landscape, producing about 5000 cells of same size, in discrete annual steps because the study species used in this thesis is an annual weed. With this model the spread of *Ambrosia artemisiifolia* L. is simulated in Austria and southern Germany (Free state of Bavaria), hence called study area, under three different climatic futures (current climate and climate change due to two different rates of temperature increase). Beside predicting the spread without action taken against the further dispersion of this invasive plant, management schemes are implemented. For the integration of such a curtailing process two different management strategies were analysed, using the habitat suitability of the grid cells. Therefore, the study area was divided into cells to be surveyed and cells not to be surveyed. Under these circumstances the question to be answered is, if there is an optimal threshold p that divides the study area in cells to be managed and cells not to be managed. In other words, if there is an optimal threshold where management success reaches a maximum under a given budget. This necessary investment for management is handled in different ways. There are studies that model management with unconstrained budget [Bogich and Shea, 2008] and others that consider constrained budget [Giljohann et al., 2011] and yet others that use both versions [Hauser and McCarthy, 2009]. For the relatively large study area used here, it was decided to implement a constrained budget as unlimited budget was considered as unfeasible. It was also examined whether

the sequence of order for surveying the cells above the threshold p makes a difference in management success. This is especially important when, due to constrained budget, not the whole set of cells given by the suitability threshold can be surveyed and eradicated within one year. In an area as large as the considered one it is common not to manage the whole region within one year not only because of budget constraints, but also due to lack of manpower. Especially carrying out surveillance in a fixed order according to the cell suitability may be more efficient than selecting cells to be surveyed by random. The reason is that first areas with high suitability for the invasive alien species are surveyed and possible infestations eradicated and, therefore, the spread is curtailed from the beginning onwards. Afterwards less suitable sites are surveyed to eradicate also in those cells unlikely but still possible populations.

The dispersion of species is often triggered by climatic factors such as temperature. With increasing temperature as predicted for future decades [IPCC, 2007, IPCC, 2013] native species as well as introduced ones will spread to yet uninfested regions [Thuiller et al., 2005, Petitpierre et al., 2012]. This is of course also true for Europe, where a lot of alien plants and animals seem only to have a limited area available, because of current climatic conditions [Walther et al., 2009]. This means that climate change due to temperature increase may accelerate the spread of invasive species in yet unpopulated areas or intensify the spread in sparsely populated regions and, hence, strengthen the negative impact on biodiversity and human health [Vila et al., 2010, Vila et al., 2011]. The study species, *Ambrosia artemisiifolia* L., is such an invasive alien plant whose distribution is accelerated with increasing temperature and has a strong impact on human health in Europe [Brandes and Nitzsche, 2007, Essl et al., 2009, Vila et al., 2010, Bullock et al., 2012] as well as in North America [Ziska et al., 2011].

To implement a sound management strategy, including surveillance, eradication and monitoring, complementary fields have to be activated. A start in the right direction is a recent amendment of the European Union on improved seed regulation [EU, 2011] which demands rigorous rules for imports of bird seeds, that is often mentioned as one of the sources for spread of *Ambrosia artemisiifolia* L. [Vitalos and Karrer, 2008]. Another achievement is the mowing of infested embankments of major roads in some regions of Austria to prevent *Ambrosia artemisiifolia* L. from building seeds and pollen [Karrer et al., 2011]. And yet others call for the responsibility of landowners and encourage them to root out this invasive weed [StMUG, 2012]. However, a cross-border coordination for management is currently not carried out, limiting efficiency of management success.

In addition the spread and consequences of management are evaluated

in this thesis not only under the current climate, but also a moderate and more extreme climate change, due to temperature increase is considered. Obviously, the real benefit of management cannot only be seen in a reduced number of infested grid cells, but also and even more in benefit-cost ratios. For the latter it is necessary to know the health costs provoked by *Ambrosia artemisiifolia* L. allergies as this is the main part of costs created by this invasive alien species. Therefore, the pollen dispersion is predicted based on data from pollen traps and wind data and pollen spread is combined with human population density. The savings with regard to the health costs are the difference of the health costs with and without management. On the other hand the arising costs for surveillance, eradication and monitoring are needed. These costs were estimated with few assumptions. All this together yields in an optimal management scheme with best benefit-cost ratio depending on the available budget.

1.3 Aim of this work

Alien species can be a threat to our ecosystems and our health. Often it is not possible to prevent the introduction of such invasive species. Therefore, it is necessary to curtail already introduced ones.

In the first place this thesis wants to show how the spread of invasive alien plants can be predicted. This is done by means of the study species *Ambrosia artemisiifolia* L. The distribution according to the current climate is predicted as well as under two different climate change assumptions. This way the consequences of increasing temperatures are pointed out. Secondly, possible management strategies are discussed and implemented into the model. This shall help decision makers to decide how to survey and eradicate invasive alien species. Thirdly, the pollen load for all cells of the study area is predicted, because of the plant's high capability as allergy trigger. One may argue that the results are sugarcoated because the same distribution model is used to simulate the spread and management. It is true that the infested cells are known as predicted by the model, but this information is not used to take decisions which cells to survey next.

Together with an estimation of the costs for management and expected health costs due to pollen allergies caused by *Ambrosia artemisiifolia* L. the benefit-cost ratio is calculated.

To sum up, the aim of this thesis is to show that the spread of invasive alien species can be predicted and that it pays off to start management immediately to curtail further dispersion. Hence, it is a recommendation for a structured control of invasive alien species.

Chapter 2

Theory

In this chapter, the details of the study species, *Ambrosia artemisiifolia* L. are explained. Further, some insight in the application of diffusion in different fields is given.

2.1 Study species

The study species used in this thesis to describe and predict the spread of invasive plants, is *Ambrosia artemisiifolia* L. (common ragweed) (Fig. 2.1, Fig. 2.2).



Figure 2.1: *Ambrosia artemisiifolia* L. in Lower Austria.



Figure 2.2: *Ambrosia artemisiifolia* L. blooming.

2.1.1 *Ambrosia artemisiifolia* L. facts and figures

Ambrosia artemisiifolia L. is a very old species that has existed for a long time according to pollen that has been found in 60 000 year old interglacial deposits in Canada [Basset and Crompton, 1975]. From then onward it was native to North America until first specimen appeared in Europe in the nineteenth century. Here, it has been an invasive alien plant and a plague for a few decades [Chauvel et al., 2006, Brandes and Nitzsche, 2007, Dullinger et al., 2009, Smolik et al., 2010, Leitner et al., 2012]. The pathways of introduction were various. The introduction was partly intended, by blending crop seeds with seeds from *Ambrosia artemisiifolia* L., to pretend that they are of better quality from North America as the latter usually was contaminated [Peschel, 2000, Kowarik, 2003]. Mainly it was introduced uninten-

tionally in Eastern and Western Europe separately [Gladieux et al., 2011]. *Ambrosia artemisiifolia* L. was not only introduced to the European continent. In the 1930s, it also appeared in China [Zhou et al., 2014] and exists today also in Japan [Yamazaki et al., 2000, Tamura et al., 2004] and in Australia [Reznik, 2000]. *Ambrosia artemisiifolia* L. can be frequently encountered in ruderal areas (disturbed habitats), fields and along roadside [Basset and Crompton, 1975, Brandes and Nitzsche, 2007, Essl et al., 2009, Vitalos and Karrer, 2009]. It reaches a height of 10 cm up to 180 cm [Alberternst et al., 2006] or 200 cm [Basset and Crompton, 1975].

Ambrosia artemisiifolia L. is an annual weed from the genus of *Asteraceae* [Brandes and Nitzsche, 2007]. A single plant can produce up to 50 000 seeds (Fig. 2.3) [Brandes and Nitzsche, 2007] or even 62 000 seeds [Dickerson and Sweet, 1971] although on average the number of seeds is 3 000 to 4 000 [Alberternst et al., 2006]. Germination tests have shown that the seeds



Figure 2.3: Seeds of *Ambrosia artemisiifolia* L. with a length of about 3 to 4 mm.

of *Ambrosia artemisiifolia* L. can sprout after 20 years [Kofol-Seliger, 2001] or even after 39 years [Toole and Brown, 1946] or 40 years [Baskin and Baskin, 1977]. These experiments have shown the longevity of its seed bank. This has to be taken into account when carrying out management with subsequent

monitoring. Therefore, an eradicated site has to be controlled for decades to prevent further spread.

On average about 1 billion pollen grains (Fig. 2.4) originate from one single specimen [Fumanal et al., 2007]. The already high numbers of produced seeds and pollen per plant may even rise in the next decades, because climate change triggered by increasing temperatures, will lead to higher amounts of pollen production and, therefore, higher pollen loads in the air [Ziska et al., 2011].

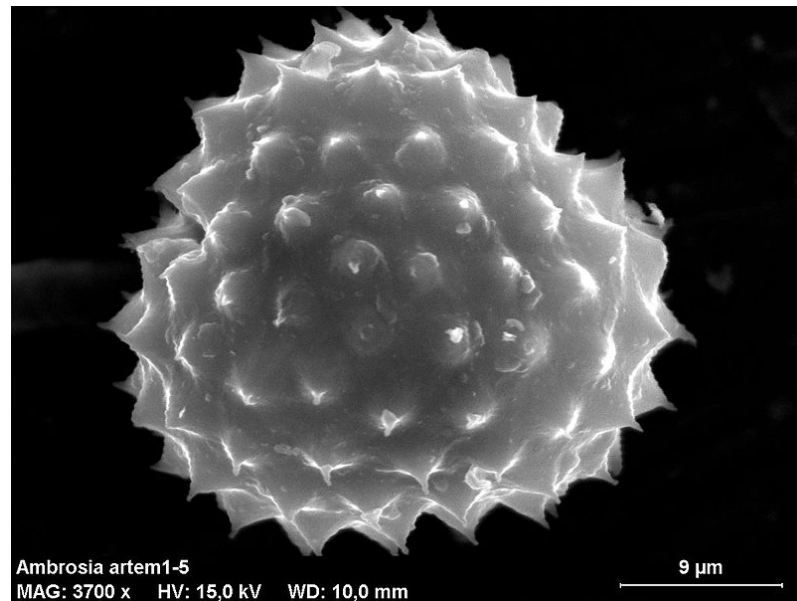


Figure 2.4: Pollen of *Ambrosia artemisiifolia* L. ©Marie Majaura

Due to its high allergenic pollen it causes relevant costs for public health systems [Reinhardt et al., 2003, Tamarcaz et al., 2005, Jäger, 2006, Ngom and Gosselin, 2013].

The seeds are heavy and, therefore, not airborne [Bohren, 2007]. Their dispersion, especially over longer distances, is mainly caused by humans, for example, in contaminated bird seeds and attached to vehicles like cars or mowing machines [Alberternst et al., 2006, Brandes and Nitzsche, 2006, Vitalos and Karrer, 2009].

Today *Ambrosia artemisiifolia* L. is distributed all over Europe [Essl et al., 2015], hence, complete eradication seems unfeasible. However, curtailing its distribution is possible and would entail a benefit for public health and agriculture. This is even more important as the study species is thermophile [Basset and Crompton, 1975, Deen and Hunt, 1998]. Therefore, it can spread

to yet unsuitable regions due to climate change triggered by temperature increase.

Besides all the negative effects of *Ambrosia artemisiifolia* L., decades ago, it is mentioned that the fluid extract can stop bleeding and its bitter tonic is used for dyspepsia [Bausor, 1937]. Although it seems that it was not very successful, because no further information confirms this fact.

2.1.2 *Ambrosia artemisiifolia* L. distribution data

For this thesis available distribution data of *Ambrosia artemisiifolia* L. from Austria and southern Germany (Free state of Bavaria) until the year 2005 were used. These data were extracted from the databases of the project Floristic Mapping of Central Europe (FMCE) in Austria [Niklfeld, 1998] and Bavaria [Schönfelder, 1999]. This project systematically collects distribution data of all vascular plant species since the 1960s. A regular raster of 3 x 5 geographical minutes ($\sim 35 \text{ km}^2$) was used. Additionally, data from public and private herbaria as well as literature [Essl et al., 2009] were used and each of the records was assigned to a grid cell of the FMCE. For the calculations the date (= year) of each record was used from the FMCE database or the original source or the responsible botanist was consulted, respectively. Until the year 2005 the distribution shows highest infestations in the eastern regions of the study area (Fig. 2.5).

Of course this dataset does not represent a complete spatio-temporal invasion process, because the grid cells have not been surveyed each year. Additionally it cannot be argued that cells without observations are completely free of *Ambrosia artemisiifolia* L. as the size of the cells is comparatively large. Thus, cells with extensive *Ambrosia artemisiifolia* L. populations are called infested cells and those with negligible populations are called uninfested cells.

Although the simulations (see section 3.1 ‘Spread model’) are restricted to the area of Austria and Bavaria, propagule pressure from outside the study area is allowed in the simulations. Hence, distribution data from available regions around the study area (these are Hungary, Slovenia, and South Tyrol) are included by assigning them to a grid cell of the FMCE. Those *Ambrosia artemisiifolia* L. populations stayed constant throughout the simulation period, but nevertheless were used to predict the spread within the study area.

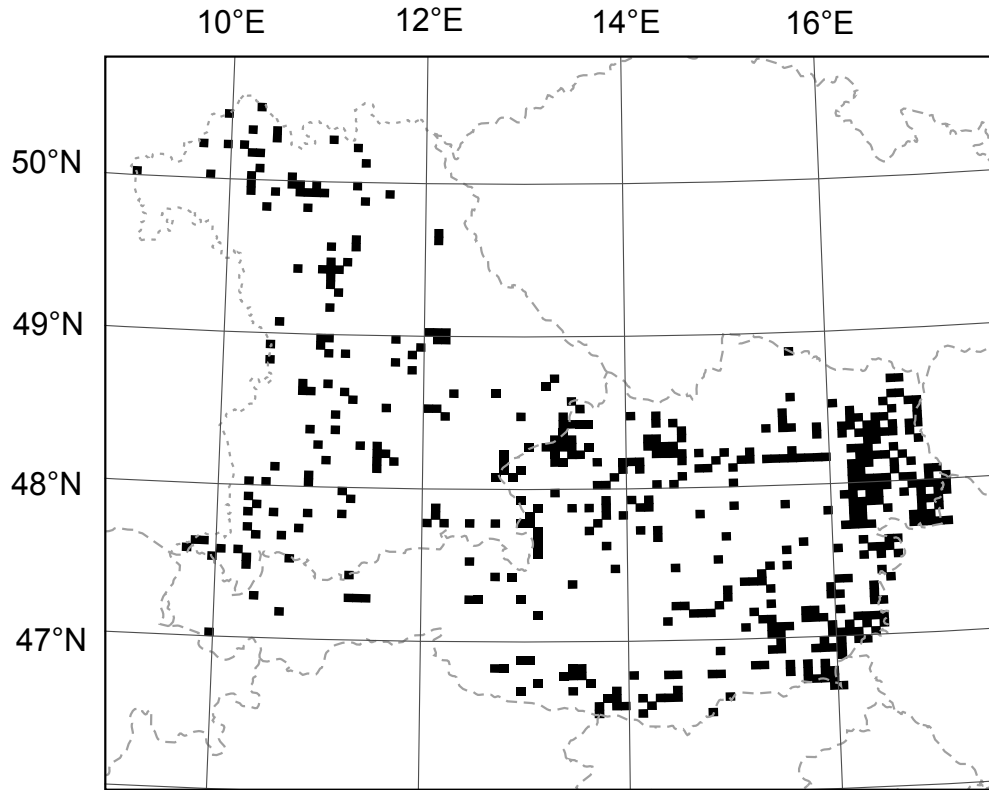


Figure 2.5: Distribution of *Ambrosia artemisiifolia* L. in Austria and Bavaria in the year 2005. Black squares symbolize infested grid cells. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3 x 5 geogr. minutes, $\sim 35 \text{ km}^2$).

2.1.3 Biological control

One of the reasons that the invasive alien species *Ambrosia artemisiifolia* L. can spread unregulated is the absence of enough natural enemies. E.g. in the native range usually an equilibrium between different species has established. In North America *Ambrosia artemisiifolia* L. is depleted by about 450 phytogamous insects [Aistova et al., 2014]. In the introduced range such a balance between species is missing. When *Ambrosia artemisiifolia* L. began to spread in a new territory, no such natural enemies were around, therefore, it was tried to introduce some of those insects to curtail this invasive weed [Igrc et al., 1995, Reznik, 2000, Reznik et al., 2008, Zhou et al., 2014]. One of these phytogamous insects is the leaf beetle *Zygogramma suturalis* F. that was introduced to Russia already in 1978 and in 1985 it seemed to have been successful. By the end of the century, however, it turned out

that this biological control has failed, due to inadaptability of this leaf beetle to crop rotation [Reznik, 2000, Reznik et al., 2008]. The same authors wrote about obviously failed introduction of *Zygogramma suturalis* F. also in Croatia, China and Australia. A different leaf beetle, *Ophraella communis* (Fig. 2.6), was discovered 1996 in Japan [Yamazaki et al., 2000] where it was assumedly accidentally introduced [Tamura et al., 2004, Zhou et al., 2014], 2013 in Italy [Bosio et al., 2014] and also in 2013 in southern Switzerland [Müller-Schärer et al., 2014]. *Ophraella communis* seems nowadays the



Figure 2.6: Imago and larva of the ragweed leaf beetle (*Ophraella communis*). ©Takahashi

most promising insect in curtailing *Ambrosia artemisiifolia* L. [Bosio et al., 2014, Müller-Schärer et al., 2014, Zhou et al., 2014]. This beetle feeds nearly exclusively on *Ambrosia artemisiifolia* L. [Tamura et al., 2004, Zhou et al., 2014]. The larva as well as the adult beetle live on the leaves of *Ambrosia artemisiifolia* L., feed on them and kill it by this action [Tamura et al., 2004, Bosio et al., 2014, Müller-Schärer et al., 2014, Zhou et al., 2014]. However, until the beginning of the year 2015 no specimen of *Ophraella communis* was sighted in the study area of Austria and Bavaria. Furthermore, there are no studies on the introduction of this leaf beetle to curtail *Ambrosia artemisi-*

ifolia L. in any region. Hence, it is unclear if *Ophraella communis* might one day kill also *Ambrosia artemisiifolia* L. populations here. Until this happens - if so - it is necessary to manage this invasive weed as described in this thesis. Additionally it is not yet evident if the ragweed leaf beetle *Ophraella communis* will not become an invasive species itself. When it is introduced, irrespective if by purpose or unintended, it itself is an alien species as this is not its native range. The risk that it causes damage in future as an invasive species should be considered.

2.2 Diffusion in different fields

Diffusion is a term from the field of physics, meaning the net movement of particles from a region with high concentration to regions with low concentration. The basic work was done by Adolf Fick by analysing the concentration gradient of a saturated salt solution [Fick, 1855]. A few decades earlier the botanist Robert Brown observed the movement of pollen in water. In comparison he studied also particles with a diameter of about one micrometer from window glass and even from the Sphinx. To his surprise Brown saw the same movement independent of the origin of the particles. [Brown, 1828]. This phenomenon we call today ‘Brownian motion’. It took nearly a century until Albert Einstein found the source of this movement in 1905. However, he only said that the motion he describes could be the ‘Brownian motion’ as he has not enough information about the latter. Einstein shows that the movement of in water suspended particles, that are visible with a microscope, can be explained with thermodynamic movement. Furthermore, he treats the relation of the Brownian motion with diffusion and results in the differential equation of diffusion, also called Fick’s second law [Einstein, 1905]:

$$\frac{\partial f}{\partial t} = D \cdot \frac{\partial^2 f}{\partial x^2}, \quad (2.1)$$

Some scientists have looked beyond their own noses and have used the principle in a slight different way. In this case the word ‘particles’ stands for genes, animals, men, ideas and others [Heitjans and Kärger, 2005].

(1) In 1937 Fisher describes the spread of genes by using a diffusion model. He considers as habitat a coast-line, i.e. a one dimensional model, that is uniformly colonised. Fisher argues that a random gene mutation, that is beneficial for survival, will expand from this point of the habitat. After a certain time all individuals have this mutated gene, first in the neighborhood of the random mutation and later also farther away. Fisher introduced the term ‘wave of advance’, behind this wave 100 % of the genes are mutated.

The velocity of this wave of advance is given with:

$$v = 2 \cdot \sqrt{k \cdot m}, \quad (2.2)$$

where k is the coefficient of diffusion and m is the growth factor, i.e. the intensity that the mutated gene will prevail over the not mutated one. Fisher was also aware of the fact that in reality the population density will not be homogenous and, therefore, he expected irregularities [Fisher, 1937].

(2) In his famous work Skellam described the spread of muskrat (*Ondatra zibethica* L.) based on the detailed date given by Ulbrich (1930). 1905 prince Colloredo-Mannsfeld came back from a hunting journey in Alaska accompanied by three pairs of muskrat, although one male died before arriving in Europe. The other five individuals were released in a lake 40 km south-western of Prague. From this point the animals started to spread all over Europe in the next decades [Ulbrich, 1930]. Skellam showed that there exists a direct proportionality between the time of spread and the square root of the area covered by muskrat [Skellam, 1951].

(3) From 1985 onward the horse chestnut leafminer (*Cameraria ohridella*) spread, beginning in Macedonia, all over Central and Western Europe with the effect that chestnut trees get brown leaves already in summer. With questionnaires and visual surveys the spread in Germany was documented. Gilbert et al. (2004) assumed a short and long distance distribution and combined it with the population density. The latter was necessary to model the phenomenon that subpopulations were located far from the border of the main population. Those subpopulations coincided with regions with high population density [Gilbert et al., 2004].

(4) 1984 the geneticist Cavalli-Sforza together with the archaeologist Ammermann applied the principle demonstrated by Fisher (1937) to simulate the spread of agriculture in the Neolithic. Beginning in the south-east the hunters and gatherers were displaced by farmers throughout Europe over a period of about 4 000 years [Ammermann and Cavalli-Sforza, 1984].

(5) At the end of the last glacial epoch (about 13 000 to 12 000 years ago) early Americans immigrated from Siberia via Alaska to South America. This was possible because the Bering Strait and a corridor along the North American West Coast was ice-free. Gero Vogl estimates the wave of advance by using data from pygmies, the last hunters and gatherers. His calculations showed that it was not possible to cover a distance of 12 000 km within 2 000 years by random walk. Vogl concludes that either the immigration started earlier or the movement was rather a directed one than a random walk [Vogl, 2012, Vogl, 2014].

Chapter 3

Methods

The methods of this chapter are based on the publications [Richter et al., 2012, Richter et al., 2013].

In this chapter it is explained how the spread of the alien species *Ambrosia artemisiifolia* L. is simulated by means of a diffusion model as well as how the curtailing process (i.e. management) is implemented. Further the prediction of pollen spread and the calculation of health costs are explained.

3.1 Spread model

The area used to simulate the spread of *Ambrosia artemisiifolia* L. is Austria and Bavaria, hence called study area. This region was selected for carrying out the simulations, because this was a connected area with detailed presence absence data available. The study area is divided into 4722 grid cells, corresponding to the raster of 3 x 5 geographical minutes ($\sim 35 \text{ km}^2$) from the databases of the project Floristic Mapping of Central Europe (see section 2.1.2 ‘*Ambrosia artemisiifolia* L. distribution data’). This resolution is used, because the presence absence data of the study species have the same resolution. Therefore, a finer resolution is not possible as there is no information where within a cell *Ambrosia artemisiifolia* L. has been sighted. A coarser resolution makes no sense when trying to predict the dispersion on the species as accurately as possible. As the data of the actual findings of the study species are only presence absence data and contain no information about the size of the populations, each single cell can be in one of two possible states, either infested or uninfested. Infested means extensive *Ambrosia artemisiifolia* L. populations, because small populations and single specimen easily can be overlooked. Therefore, uninfested stays for negligible populations meaning not to claim that every single specimen has to be detected as

this is unfeasible. The state (i.e. infested or uninfested) can change annually. Here it has to be distinguished between the dispersal of *Ambrosia artemisiifolia* L. and its management (see section 3.4 ‘Management’). The former allows only the change of state from uninfested to infested as self-extinction is not permitted in this model. The reason is that there are no data indicating that once infested cells become uninfested without human action. One reason for it could be the longevity of the seed bank as mentioned in the subsection 2.1.1 ‘*Ambrosia artemisiifolia* L. facts and figures’. When applying management the status of grid cells can also change from infested to uninfested, due to eradication of the study species. According to the definition of uninfested this means that in the managed cell there are only negligible populations left.

In the following the simulation of the spread process is described. The spread model presented in this thesis is based on the work by Smolik et al. (2010), who combined elements of species distribution models and interacting particle systems, i.e. a ‘hybrid’ model [Thuiller et al., 2008, Vogl et al., 2008, Smolik et al., 2010, Leitner et al., 2012]. First, the probability that an uninfested cell becomes infested is calculated. Therefore, the habitat suitability of the cell and the seed influx from all other cells are needed. The habitat suitability indicates how good a cell matches with the needs of the invasive alien species, here *Ambrosia artemisiifolia* L., with a number reaching from 0 (meaning a seedling will never germinate in this cell) to 1 (meaning each seedling that can germinate will do so). For the habitat suitability $H(x)$, therefore, only variables are used that describe the cell appropriate to the conditions needed by the study species [Kühn et al., 2009]. Here the habitat suitability is calculated by using the four environmental variables that proved significant correlates of *Ambrosia artemisiifolia* L. distribution in Austria [Smolik et al., 2010]. These variables are the mean annual temperature (ν_T) (Fig. 3.1), annual precipitation sums (ν_P) (Fig. 3.2), summed length of major streets per grid cell (ν_S) (Fig. 3.3) and the land use (ν_L) (i.e. the proportion of urban areas and agricultural fields) (Fig. 3.4). These variables fit to the places where *Ambrosia artemisiifolia* L. can be found, namely ruderal areas, along roadsides and in agricultural fields (see 2.1.1 ‘*Ambrosia artemisiifolia* L. facts and figures’). It was checked again if omitting one or more of these variables in the model will result in better agreement with actual findings, but it proved necessary to use all four environmental variables.

The habitat suitability $H(x)$ (Fig. 3.5) is represented as a logistic regression function,

$$H(x) = \frac{1}{1 + e^{-h(x)}} \quad (3.1)$$

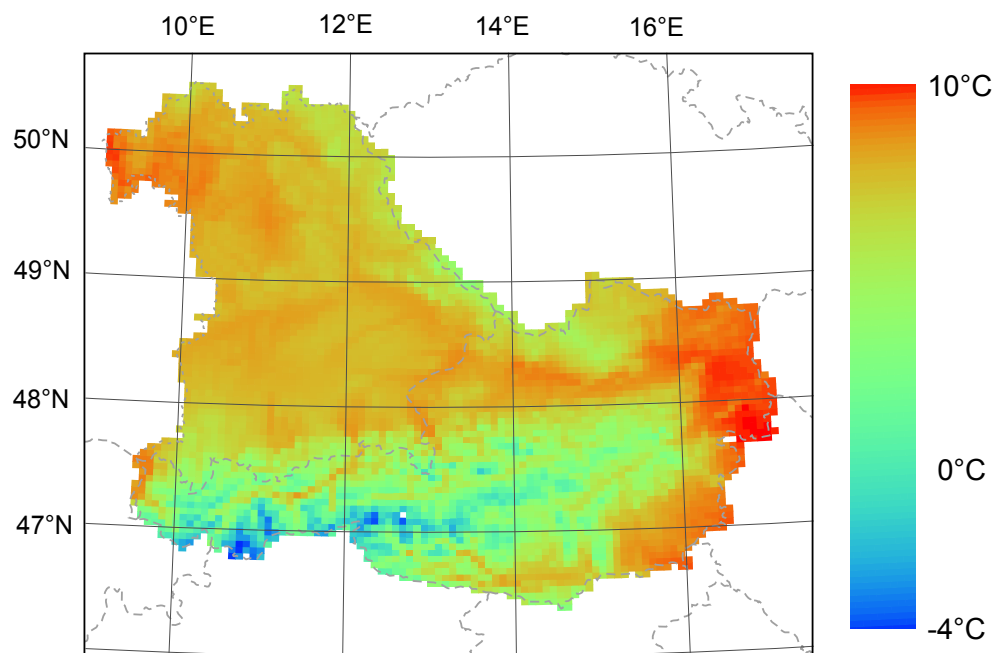


Figure 3.1: Mean annual temperature of Austria and Bavaria from the average of the years ~ 1950 until 2000. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3×5 geogr. minutes, $\sim 35 \text{ km}^2$). Colours indicate the height of the mean annual temperature ν_T .

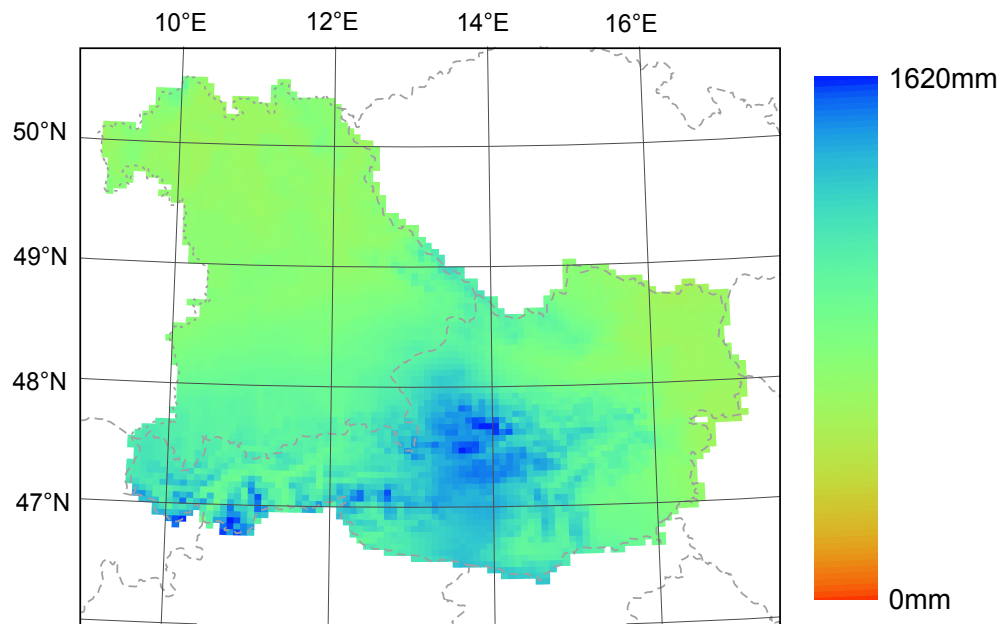


Figure 3.2: Sum of precipitation in Austria and Bavaria from the average of the years ~ 1950 until 2000. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3 x 5 geogr. minutes, $\sim 35 \text{ km}^2$). Colours indicate the amount of precipitation ν_P .

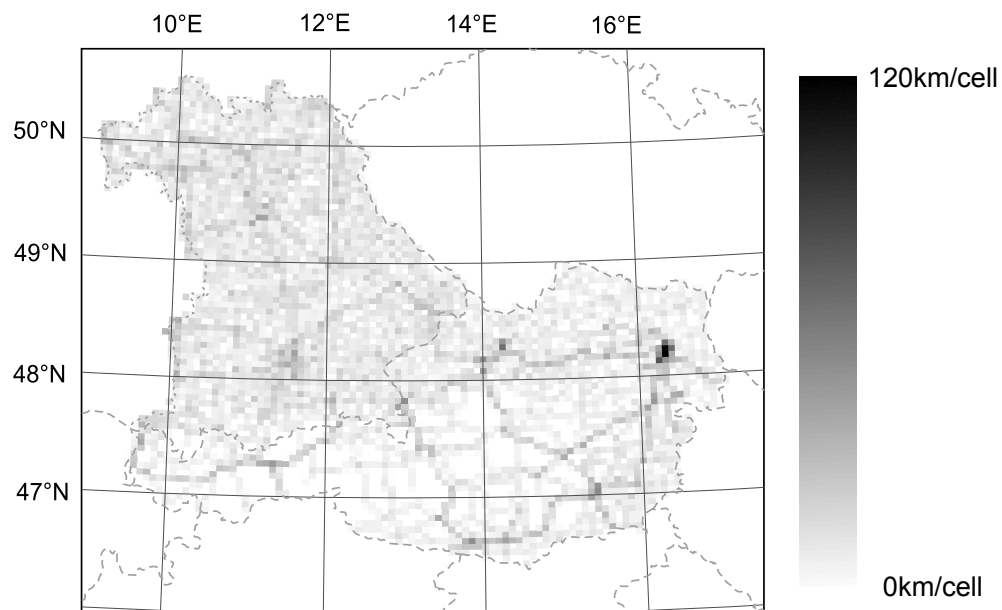


Figure 3.3: Summed length of major streets per grid cell in Austria and Bavaria. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3 x 5 geogr. minutes, $\sim 35 \text{ km}^2$). Shades of grey indicate the summed length of major streets ν_S

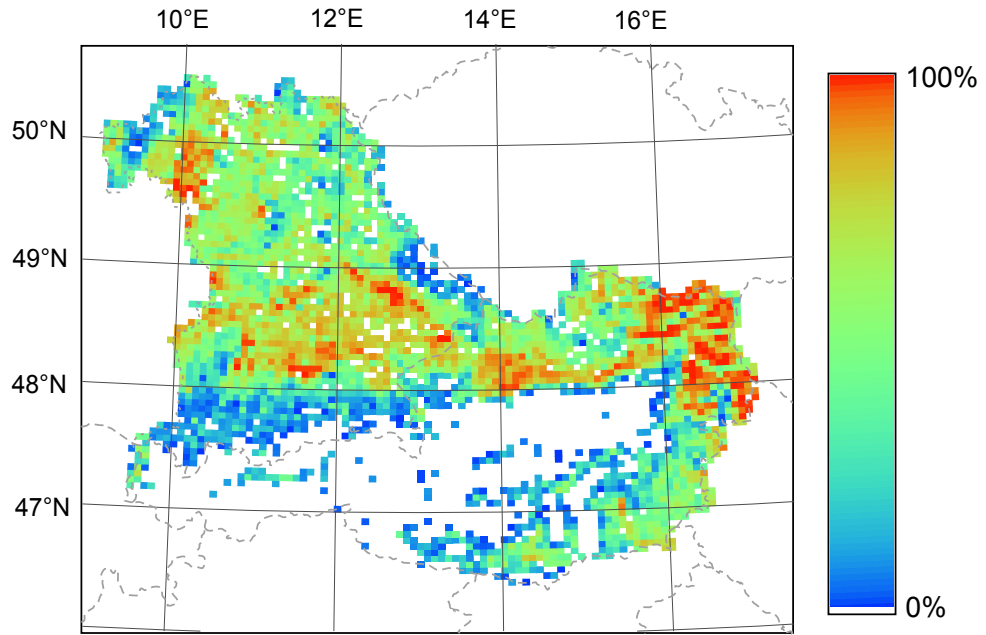


Figure 3.4: Proportion of urban areas and agricultural fields in Austria and Bavaria. White regions indicate 0% of urban areas and agricultural fields in the appropriate cell. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3 x 5 geogr. minutes, $\sim 35 \text{ km}^2$). Colours indicate the proportion of urban areas and agricultural fields ν_L

with

$$h(x) = \alpha_0 - \sum_{i=T,P,S,L} \alpha_i \cdot \nu_i(x) \quad (3.2)$$

where α_0 is the inflexion point of the logistic regression function and α_i (with $i = T, P, S, L$) are the weighting coefficients of the location dependent environmental variables $\nu_i(x)$ in cell x .

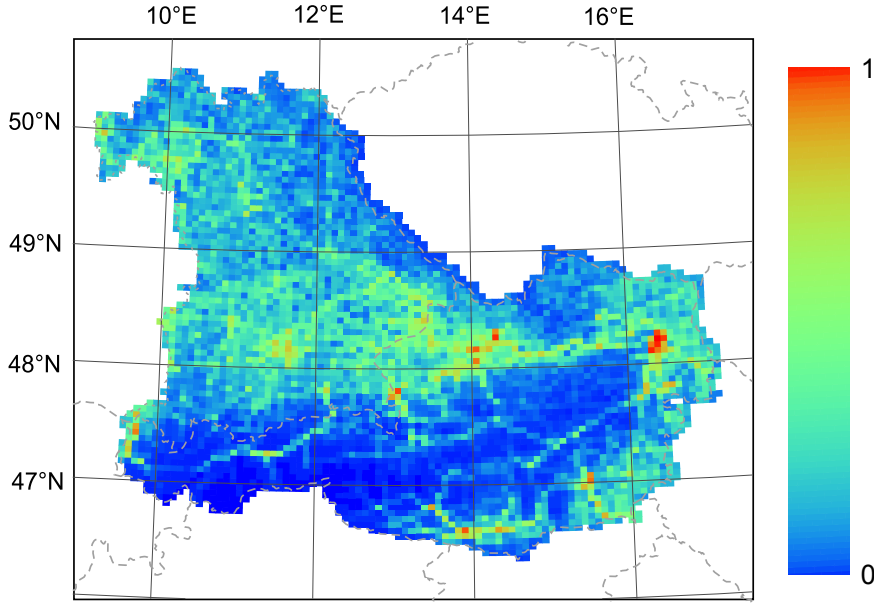


Figure 3.5: Distribution of habitats suitable to *Ambrosia artemisiifolia* L. in Austria and Bavaria in the year 2005 under current climate. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3 x 5 geogr. minutes, $\sim 35 \text{ km}^2$). Colours indicate the degree of suitability, $H(x)$, according to Eq. 3.1

Beside the habitat suitability $H(x)$ the seed influx $I(x, t)$ of all other cells has to be known. To compute this influx an isotropic dispersal kernel $S(d)$ is used that maps the probability that seeds produced in cell x may arrive in cell y as a function of the distance of the cell centres $d = |x - y|$. Therefore, the incoming seed flux into cell x from all other occupied cells of the study area at time t is

$$I(x, t) = \sum_y S(|x - y|) \cdot \sigma(y, t) \quad (3.3)$$

with $\sigma(y, t) = 1$ if the cell y is occupied at time t and $\sigma(y, t) = 0$ if the cell y is not occupied at time t . An important factor is the dispersal kernel $S(d)$ that describes the behaviour of the spread. Different kind of kernels were tested, that is a Gaussian function

$$S(d) = b \cdot e^{\frac{-d^2}{2a^2}} \quad (3.4)$$

with the height b and the width a and a power law function

$$S(d) = \left(\frac{d}{d_0} \right)^{-\gamma} \quad (3.5)$$

with the dispersal distance d_0 and the exponent γ . The second kernel shows the typically leptokurtic dispersal curves of invading organisms that describe the long distance distribution better [Kot et al., 1996]. It is also called a fat tailed curve, because of its shape in comparison to the Gaussian function (Fig. 3.6). The leptokurtic dispersal kernel is more pronounced at the

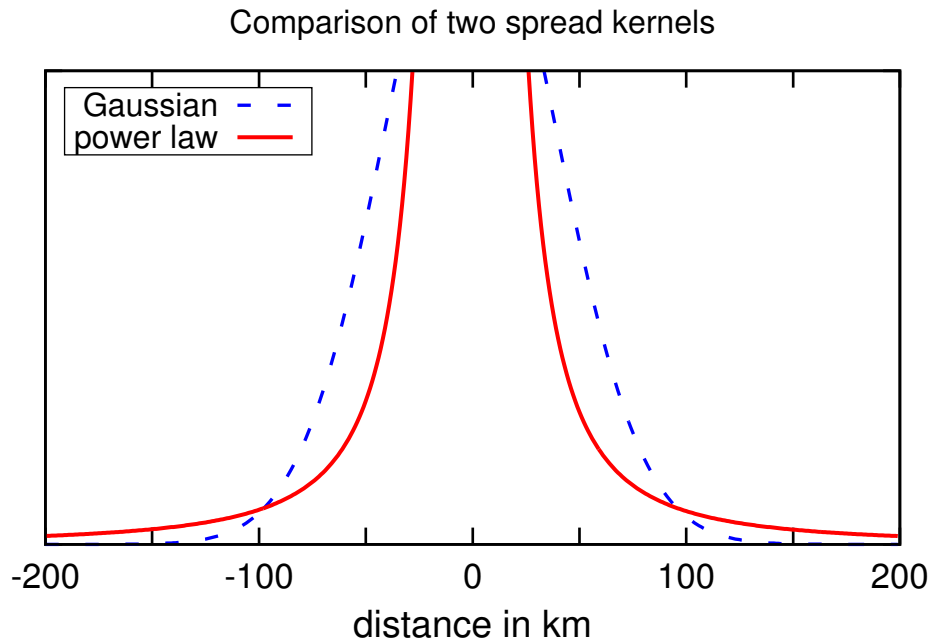


Figure 3.6: Comparison of the two kernels, Gaussian function and power law function. The former is less pronounced at the boundary. The power law function is, hence, also called fat tailed.

boundary and, therefore, can better describe the spread of invasive species to

longer distances. Both kernels were used to simulate the spread of *Ambrosia artemisiifolia* L. from 1990 until 2005. As expected the parametrization (see. section 3.2 ‘Optimization’) demonstrated a better agreement of the prediction made by the power law function with actual presence absence data than made by the Gaussian function. Therefore, all results given in this thesis are based on using the leptokurtic power law function.

The total probability P that an until year t uninfested cell becomes colonised in the following year $t + 1$ is dependent on the product of the seed influx and the habitat suitability. In other words the likelihood that an incoming seedling germinates and produces a new population is considered to be proportional to the cell’s habitat quality. Thus the overall probability is presented as:

$$P(\sigma(x, t + 1) = 1 | \sigma(x, t) = 0) = 1 - e^{-H(x) \cdot I(x, t)}, \quad (3.6)$$

where $\sigma(x, t + 1) = 1 | \sigma(x, t) = 0$ means that the cell x becomes infested in the following year ($\sigma(x, t + 1) = 1$) provided that this cell is not infested in the current year t ($\sigma(x, t) = 0$). The expression $1 - e^{-H(x) \cdot I(x, t)}$ guarantees that the probability P is scaled to the interval $[0, 1]$.

3.2 Optimization

In equation 3.6, representing the probability that an uninfested cell becomes infested, a few parameters are included, that have to be defined. These are α_0 and α_i (with $i = T, P, S, L$) of the habitat suitability $H(x)$ (see Eq. 3.1 and Eq. 3.2) and d_0 and γ of the kernel $S(d)$ (see Eq. 3.5) included in the seed influx $I(x, t)$. The values of these parameters are gained by optimization as described in the following.

In the beginning all 4722 cells of the study area (i.e. Austria and Bavaria) got the infestation status 0. This means that all cells were treated as being uninfested from beginning. Then, step by step, the status of specific cells was changed to infested because of populations sighted (Fig. 3.7). For the year 1990 the infestation status of cell x was set to 1 (infested) for all cells where *A. artemisiifolia* L. was mentioned in the year 1990 or before. From 1991 onward the infestation status of cell x was changed from 0 to 1 in the year $A. artemisiifolia L. was first mentioned in the collected records (Fig. 3.8). Once the status of a cell is 1 it is not changed back to 0, because self-extinction is neglected for reasons explained in section 3.1 ‘Spread model’.$

Then the maximum likelihood estimates of the parameters α_0 , α_i (with $i = T, P, S, L$), d_0 and γ were calculated by maximizing the product of the probabilities of all observed transitions (either $0 \rightarrow 0$ or $0 \rightarrow 1$) across all cells

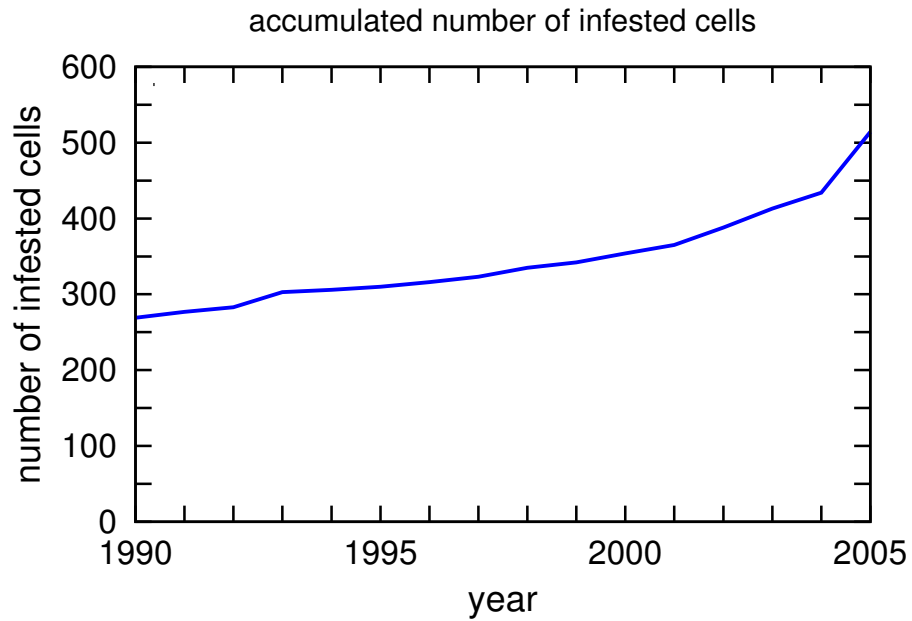


Figure 3.7: Accumulated number of infested grid cells as function of the first occurrence. All data before 1990 are plotted as being first sighted in the year 1990.

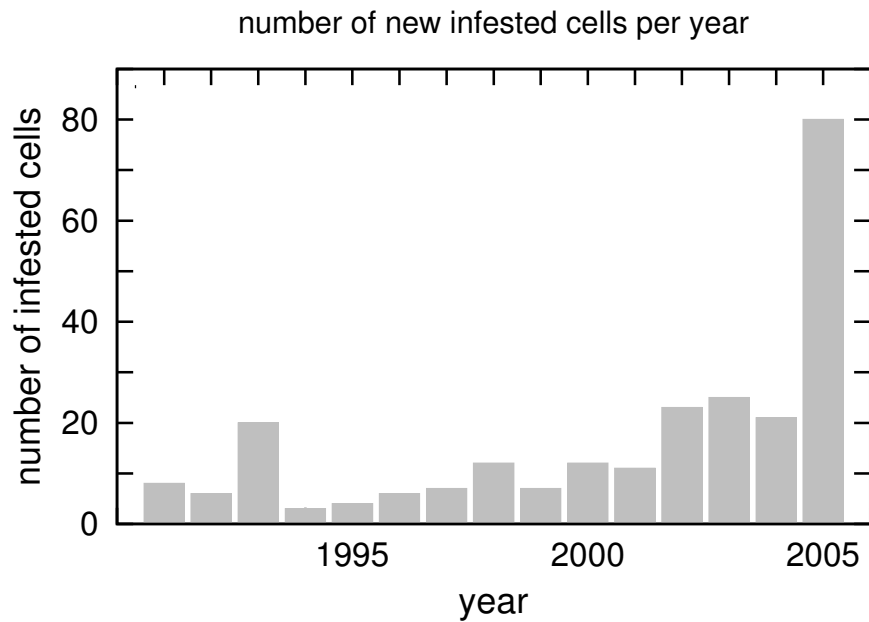


Figure 3.8: Number of new infested grid cells as function of the occurrence beginning with 1991.

and years. This was done by multiplying the probabilities of the transitions over all 15 years (from 1991 until 2005), with a set of starting parameters. For cells getting infested the first time the calculated probability of getting infested was used and for cells staying uninfested the calculated probability of staying uninfested. In equation 3.7 $\Lambda_1(t)$ is the subset of all cells infested in year t for the first time (transition $0 \rightarrow 1$) and $\Lambda_0(t)$ is the subset of all cells remaining uninfested in year t (transition $0 \rightarrow 0$). The likelihood function to maximize, $F(\alpha_0, \alpha_i, d_0, \gamma)$, is defined by:

$$F(\alpha_0, \alpha_i, d_0, \gamma) = \prod_t \prod_{x \in \Lambda_1(t)} (1 - e^{-H(x) \cdot I(x,t)}) \prod_{x \in \Lambda_0(t)} (e^{-H(x) \cdot I(x,t)}) \quad (3.7)$$

This is a product of 15 years and 4 722 cells ($\Lambda_0(t) + \Lambda_1(t)$), i.e. a product of 70 830 values. As probabilities are values in the interval $[0,1]$, $F(\alpha_0, \alpha_i, d_0, \gamma)$ reaches very small values. To omit this, the logarithm $\ln(F(\alpha_0, \alpha_i, d_0, \gamma))$ was used. This is possible as the logarithm function is strictly monotonically increasing. In the interval $[0,1]$, therefore, negative values occurred, that is why the result additionally was multiplied with minus one. Hence, the maximizing problem of $F(\alpha_0, \alpha_i, d_0, \gamma)$ is converted into a minimizing one of $F_{con}(\alpha_0, \alpha_i, d_0, \gamma)$.

$$F_{con}(\alpha_0, \alpha_i, d_0, \gamma) = -\ln(F(\alpha_0, \alpha_i, d_0, \gamma)) \quad (3.8)$$

The optimization was done by the Nelder-Mead simplex method [Nelder and Mead, 1965] using GNU Octave 3.2.4. The aim of this method is to reach the minimum by using starting parameters, that are changed by the Nelder-Mead algorithm to converge to the minimum. The resulting numerical parameter estimates are given in table 3.1.

parameter	numerical values and standard deviation
$d_0(km)$	0.63 ± 0.14
γ	2.02 ± 0.10
α_0	-10.3 ± 1.27
α_T (1/°C)	0.57 ± 0.10
α_P (1/mm)	0.00338 ± 0.00074
α_S (1/km)	0.074 ± 0.014
α_L	1.56 ± 0.43

Table 3.1: Parameters of the *Ambrosia artemisiifolia* L. spread model, using the power law function for the dispersal kernel, based on the observed distribution in Austria and Bavaria beginning in 1990 and ending in 2005. d_0 and γ are the characteristic dispersal distance and the exponent of the dispersal kernel, respectively, (see Eq. 3.5). α_0 is the inflexion point of the logistic regression function (see Eq. 3.1 and Eq. 3.2). The α_i (with $i = T, P, S, L$) are the weights of the environmental variables used to characterize habitat suitability. α_T is the parameter corresponding to the mean annual temperature, α_P the parameter corresponding to the annual precipitation sums, α_S the parameter corresponding to the summed length of major streets and α_L the parameter corresponding to the land use.

3.3 Simulation of spread

With the parameters given by section 3.2 ‘Optimization’ the further spread of *Ambrosia artemisiifolia* L. was simulated in Austria and Bavaria until the year 2050. The spread of plants cannot be predicted in an exact way as it depends on many factors. To implement this stochastic element the method of interacting particle systems was used. They can be seen as generalised cellular automata [Smolik et al., 2010]. To be able to predict which cells are infested in the following year the calculated probability $P(\sigma(x, t + 1) = 1)$ of yet uninfested cells was compared to uniform random numbers in the interval $[0, 1]$ [Smolik et al., 2010]. If $P(x)$ is larger than the random number, the cell x changes its status from uninfested to infested, otherwise it stays unoccupied (Fig. 3.9).

This procedure is repeated until the end of the simulation period. The infestation density of the study area (i.e. Austria and Bavaria) with *Ambrosia artemisiifolia* L. was evaluated (a) in terms of mean annual infestations (i.e. the mean number of infested cells over the entire management period from 2011 until 2050) and (b) by the number of occupied grid cells at the end of the simulation period (2050). The former can be used to calculate the accumulated health costs because of allergies caused by *Ambrosia artemisiifolia*

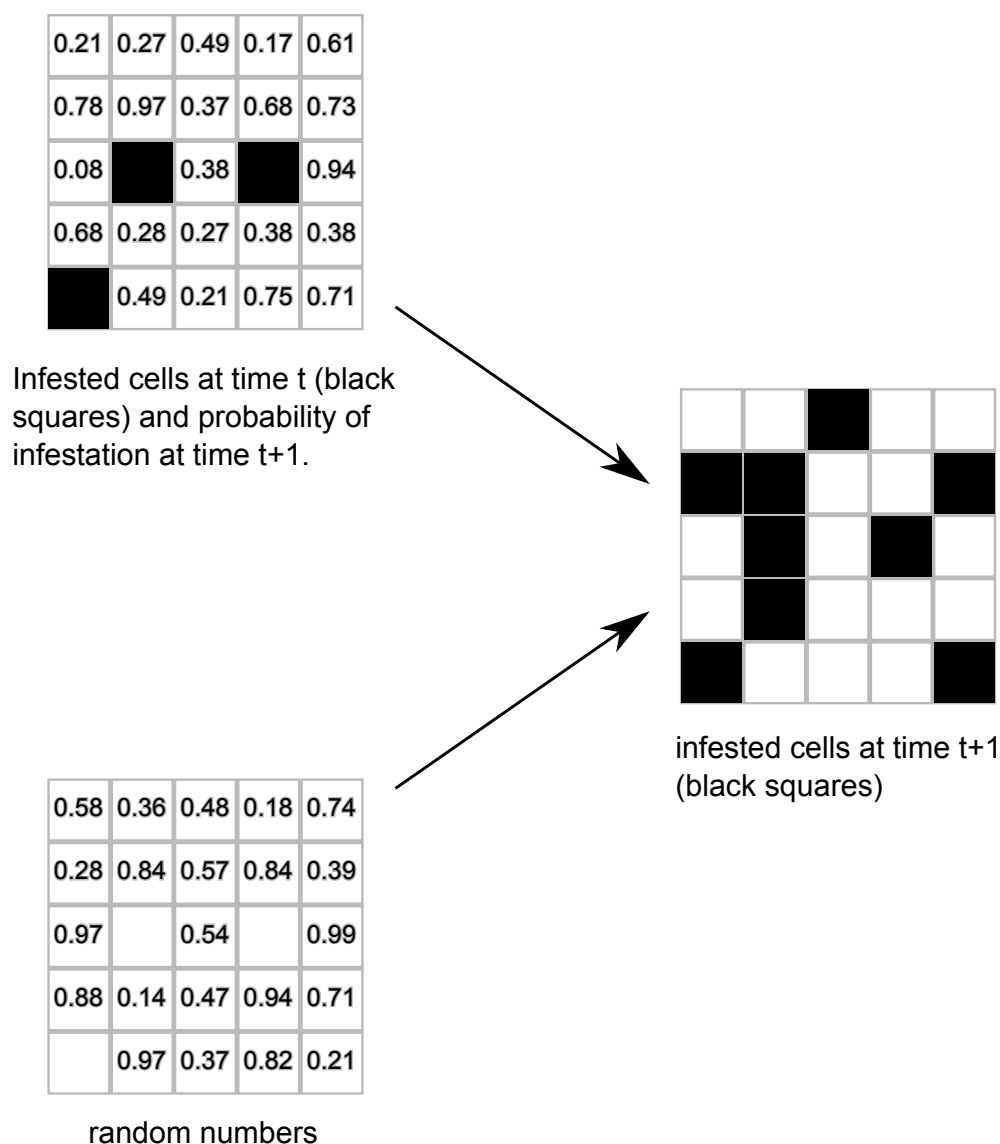


Figure 3.9: Example of the transformation of cell status from 0 to 1. The upper left square shows the cells already infested with *Ambrosia artemisiifolia* L. (small black squares) and the calculated infestation probability $P(x)$ for yet uninfested cells. The lower left square shows the computed random numbers for cells not infested at time t . Corresponding cells are compared - if $P(x)$ is larger than the random number, the cell becomes infested at time $t + 1$, otherwise it stays uninfested. The right square shows the infestation status calculated by this algorithm at time $t + 1$.

L. pollen. The latter is useful for conclusions of the spread potential after the end of the simulation period (i.e. from 2050 onward). Each simulation was repeated 1000 times, to account for stochastic elements in the spread model. The results are the mean values of these repeated simulations.

3.4 Management

Up to now the simulations were only treated without human influence (i.e. without management) also called a business-as-usual scenario. In this section it is explained how the transition of the cell status from 1 to 0 (i.e. from infested to uninfested) is implemented. There is no information of self-extinction of *Ambrosia artemisiifolia* L. and so the transition from infested to uninfested can only be explained by eradication through man.

One aim of this thesis is to find out the best way of curtailing the spread of *Ambrosia artemisiifolia* L. This management includes surveying the study cells with a size of 3 x 5 geographical minutes ($\sim 35 \text{ km}^2$) in order to localize populations. In a second step all specimen, that were found during this process, are eradicated and hence reset the occupancy state $\sigma(x, t) = 1 \rightarrow \sigma(x, t) = 0$.

This thesis does not specify the way of eradication. For invasive alien species there are several methods of doing so as e.g. root out, chemical treatment, fire clearing or biological control. The latter can be carried out by introducing the ragweed leaf beetle (see subsection 2.1.3 ‘Biological control’), although this would not be a controlled management as discussed here. There is no documentation so far, that this beetle was introduced by man successfully, hence, management schemes as described here have to be taken. In this model always perfect eradication is assumed, i.e. it is not accounted for incomplete eradication (probabilities < 1). This is not inconsistent with the assumption not to catch every single specimen, as cells with negligible populations are defined as uninfested (see subsection 2.1.2 ‘*Ambrosia artemisiifolia* L. distribution data’ and section 3.1 ‘Spread model’). The reason to do so is that the presence absence data do not contain partly populated cells, but only the binary state infested or uninfested. Included in the management is also the monitoring of infested cells in subsequent years due to the long-lasting seed bank. Monitoring means to control if in the following years new specimens have germinated from seeds still in the ground. This does not mean to survey the whole cell in the following years, but the exact position of the located specimens, e.g. by using GPS data. Therefore, eradicated cells can become infested again at other locations within the same cell by influx from other infested cells.

It was decided to start with the management in 2011 and carry it out until the year 2050. The time span of those 40 years is, hence, called management period. This time period seems not to be too short and, with a time span of about two generations, not too long either.

Management is always combined with costs. These costs can differ from country to country and so it was decided, first, to quantify management costs in abstract values (management effort units). In a second step it was tried to estimate the actual costs in Euro (see section 3.7 ‘Estimation of management costs’). The estimation of the costs is a very problematic and challenging task as there is very little to no information available. Hence, the ratio between surveying and eradication cannot be carried out in an exact way and can only be guessed. There exist different studies where cost-ratios of eradication programmes are reported [Veitch and Clout, 2002, Myers and Bazely, 2003]. It was decided that it takes 1 management effort unit to eradicate one study cell and execute subsequent monitoring and 0.1 management effort units to survey one cell. This ratio lies within the range of the studies mentioned above. Beside this 1:10 surveillance:eradication cost ratio also with other ratios (e.g. 1:3) simulations were run, which delivered qualitatively identical results.

One of the main tasks for decision makers is prioritizing cells to be managed. The first question to be answered is if the whole area should be managed or only a part of it. For the latter case it has to be decided how to split regions to be surveyed from regions not to be surveyed. When this point is clarified, the second question is how to select the order of managing the cells of the study area. There are several possibilities in doing so: Simply to start on one end of the study area, e.g. in the west, and work through (line by line in north-south orientation) to the east end of the area. Another possibility is to first survey regions with a high population density and then go on to areas with less density. A third one is to select the regions to be managed by random. And a fourth variation is to begin surveying in areas with the highest habitat suitability for the study species. In this thesis it was decided to compare the last two possibilities as described in the following.

Generally, it was decided not to manage the whole area as it seems a priori not useful to survey cells with very low habitat suitabilities as e.g. on top of mountains. Hence, the cells to be surveyed were divided from the others depending on their suitability for *Ambrosia artemisiifolia* L. For management all cells of the study area were ordered according to their habitat suitability $H(x)$. Then this row of cells was divided into 100 sets of equal numbers. As mentioned above, it was decided to neglect cells below a critical lower suitability value, called threshold p . The success of management was studied as a function of the choice of p . When selecting the lowest limit, i.e. $p = 0$, all

cells are managed independently of their habitat suitability. With increasing the threshold, management is focussed on cells with better conditions for *Ambrosia artemisiifolia* L., e.g. $p = 0.75$ means that the best suited 25% of the cells were chosen for management.

When the suitability threshold was reached and there was still money remaining from the available budget, the threshold was automatically reduced until all money was spent. This procedure was chosen as in real life it is common to use all available budget. As a result, the number of infested cells levels out above a certain chosen threshold, because it is automatically reduced.

For selecting the cells above the threshold p two different management strategies were considered (1) random sampling and (2) fixed order sampling. Random sampling means that the cells selected for management were drawn at random. Within one year one cell could only be surveyed once. However, in different years the selection process was independent, meaning that one specific cell could also be surveyed in consecutive years even before all other cells were visited at least once. Therefore, it is possible to survey the same cell in consecutive years and other cells never during the whole management period. For fixed order sampling the ordered set of cells (regarding decreasing habitat suitability) was used and management executed by starting on the best suited cell (i.e. the cell with the highest value for $H(x)$, equation 3.1). Then the cells were surveyed in decreasing order of their habitat suitability. In the following year management continued where it had stopped the year before. When reaching the cell equivalent to the selected threshold p (i.e. the cell with the lowest habitat suitability of the selected subset of cells), management continued by starting again on the best suited cell. For each year a fixed budget of 50 management effort units was assumed for management (i.e. surveying and eradicating with monitoring). This budget is equivalent to surveying 500 cells (i.e. about 10% of the study area) or eradicating the invasive alien plant population of 50 cells. Each year the cells were managed until the available budget had been consumed. To be able to evaluate the influence on available budget, it was simulated also with lower and higher annual budgets.

3.5 Climate change

That the climate will change in future due to higher temperatures is a widely accepted opinion. To account for such a climate change the habitat suitability $H(x)$ was allowed to change throughout the simulations. It was implied that the habitat suitability changes only because of temperature rise, while

all other site conditions are supposed to remain constant. Of course it can be assumed that the other three environmental variables $((\nu_P), (\nu_S)$ and (ν_L) i.e. annual sums of precipitation, length of major streets and land use, respectively) are correlated to the temperature. For example, precipitation is usually connected to temperature, in regions with lower temperatures precipitation is higher and vice versa, as can be seen in figure 3.2 compared to figure 3.1. The same is true for land use that is more intense in regions with lower latitudes and, therefore, higher temperatures (see Fig. 3.4 vs. 3.1). A correlation between temperature and all the other three environmental variables was discovered. When calculating temperature increase it is, therefore, necessary to correct this hidden dependence on the other variables so that there is no influence of temperature any more. This is achieved with a corrected proportionality factor for temperature increase

$$\alpha_T^* = \sum_{i=T,P,S,L} \frac{\alpha_i \cdot \text{cov}(\nu_i, \nu_T)}{\text{var}(\nu_T)} \quad (3.9)$$

with cov the covariance and var the variance of the environmental factors. The covariance measures how the two variables (here the environmental factor ν_i and the factor for temperature ν_T) change together. From a statistic point of view the covariance is positive when generally in cells with higher temperature also higher values of ν_i occur. In the other case where ν_i has lower values for higher temperatures, the covariance is negative. The magnitude of the covariance cannot be interpreted as stronger or weaker correlation between the two variables as it is not normalised. The variance (or square of the standard deviation) is the covariance with itself ($\text{var}(\nu_T) = \text{cov}(\nu_T, \nu_T)$) and measures the deviation from the mean. The division by the variance in equation 3.9 is used for the purpose of normalisation. Hence, the factor $\text{cov}(\nu_i, \nu_T)/\text{var}(\nu_T)$ quantifies the linear variation of ν_i per variation in temperature. When this is multiplied by the weight of the environmental variable α_i , we get the variation in $h(x)$ per variation in temperature that is hidden in the temperature dependence on ν_i (with $i = T, P, S, L$). When there is a difference in $h(x)$ (equation 3.2), it refers to the difference in temperature

$$\Delta h(x) = \alpha_T^* \cdot \Delta \nu_T(x). \quad (3.10)$$

This way the effect of change in one parameter (in this thesis in temperature) can be calculated and the other environmental factors remain constant. With the resulting parameters α_i and α_T^* (see table 3.2) it can be calculated with climate warming starting in 1990. Due to the annually change in temperature, the parameters d_0 and γ of the dispersal kernel get slightly different

values compared with the current climate scenario (see table 3.1 vs. table 3.2).

	$\Delta T = 0.025^\circ\text{C}$ per year	$\Delta T = 0.04^\circ\text{C}$ per year
$d_0(km)$	0.65 ± 0.15	0.67 ± 0.25
γ	1.98 ± 0.11	1.96 ± 0.11
α_0	-10.8 ± 1.2	-11.1 ± 1.1
α_T (1/km)	0.61 ± 0.08	0.63 ± 0.07
α_P (1/ $^\circ\text{C}$)	0.00313 ± 0.00066	0.00307 ± 0.00056
α_S (1/mm)	0.068 ± 0.016	0.065 ± 0.014
α_L	1.35 ± 0.40	1.23 ± 0.38
α_T^*	0.59 ± 0.09	0.60 ± 0.08

Table 3.2: Parameters of the *Ambrosia artemisiifolia* L. spread model with climate change based on the observed distribution in Austria and Bavaria beginning in 1990 and ending in 2005. d_0 and γ are the characteristic dispersal distance and the exponent of the dispersal kernel, respectively, (see Eq. 3.5). α_0 is the inflexion point of the logistic regression function (see Eq. 3.1 and Eq. 3.2). The α_i (with $i = T, P, S, L$) are the weights of the environmental variables used to characterize habitat suitability. α_T is the parameter corresponding to the mean annual temperature, α_P the parameter corresponding to the annual precipitation sums, α_S the parameter corresponding to the summed length of major streets and α_L the parameter corresponding to the land use. α_T^* is the proportionality factor for temperature increase (see Eq. 3.9). For all parameters the numerical values and standard deviation are given.

Various climatic futures based on different assumptions [IPCC, 2007, IPCC, 2013] exist. The challenge in predicting such futures is the big uncertainty what countries will really do to prevent the forecasted temperature increase. For the simulations with climate change two different assumptions were chosen, beside no temperature increase, a moderate increase (temperature increase of 1.5°C from 1990 to 2050) and a more extreme increase (temperature increase of 2.4°C for the same time period). Those two climate change assumptions were chosen as they correspond approximately to the lower and higher range of temperature increase in Europe predicted by the IPCC A1B scenario [IPCC, 2007] and the IPCC RCP8.5 scenario [IPCC, 2013], respectively. Of course it is a simplification to implement the same temperature increase for each single cell. In reality, the increase will not be the same throughout the whole study area, but for the fine spatial scale used, different temperature increases are not predictable with sufficient precision.

Furthermore, a linear temperature increase over the whole simulated period is assumed. This is in accordance with the IPCC prediction up to the middle of the 21st century [IPCC, 2007, IPCC, 2013], the end of the simulation period. Therefore, in the simulations it is calculated with a constant annual temperature increment of 0.025 °C (i.e. 1.5 °C from 1990 to 2050) and 0.04 °C (i.e. 2.4 °C from 1990 to 2050) for the two climate change assumptions, respectively. Additionally, as already mentioned above, it is implied that the other three environmental variables stay constant. With these assumptions the habitat suitability for *Ambrosia artemisiifolia* L. increases until 2050 due to the temperature increase. For the more extreme future (i.e. 0.04 °C) it increases mainly in the range of 0.1-0.15 and in specific cells even up to 0.25 (Fig. 3.10). In regions with already high habitat suitabilities (like in Vienna,

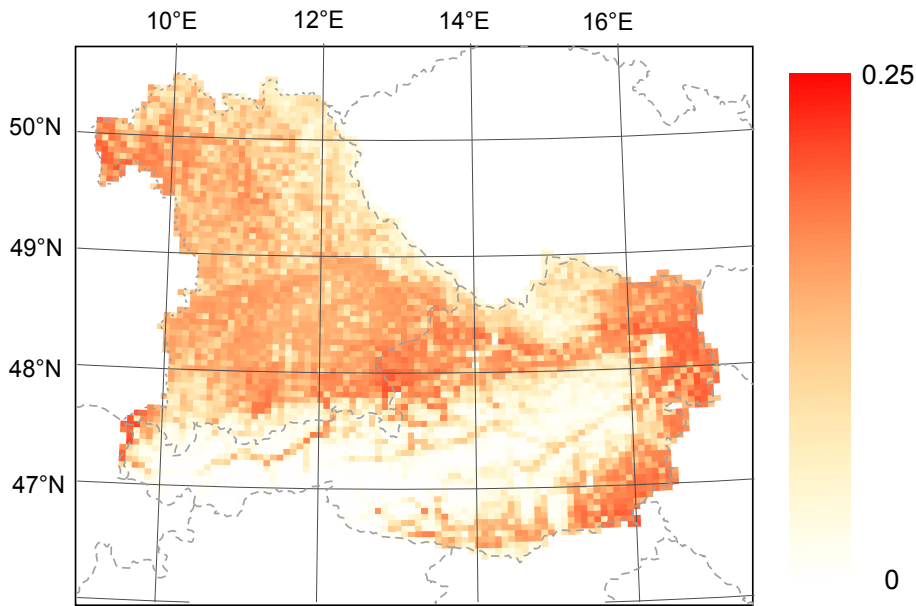


Figure 3.10: Increase of the habitat suitability $H(x)$ for *Ambrosia artemisiifolia* L. under the assumption of a temperature increase of 2.4 °C from 1990 until 2050. Shades of red indicate the increase (a dark red square indicates an increase in habitat suitability by 0.25)

the capital of Austria) the suitability can only increase marginally. In areas with very low temperatures, like the Alps, even the temperature increase

due to climate change is not enough to provide good conditions for *Ambrosia artemisiifolia* L. and, therefore, also here the habitat suitability increases only marginally.

3.6 Pollen dispersion and health costs

Beside crop loss on fields with sunflower, maize or sugar beet [Bosak and Mod, 2000, Varga et al., 2002, Varga et al., 2006, Kazinczi et al., 2007, Bullock et al., 2012] the main problem of *Ambrosia artemisiifolia* L. is the pollen that causes severe allergies [White and Bernstein, 2003, Smith et al., 2013].

The modelling of pollen dispersion is a challenging task, because there are no detailed investigations how pollen travels. There are studies that only 1 % of pollen reaches a distance of more than 1 km [Raynor et al., 1970] and most pollen stays within a distance of 100 m [Gregory, 1978]. Additionally there are studies that in pollen traps mainly pollen of plants within a radius of 30 km are found [Skjøth et al., 2010]. On the other hand, there are also studies showing that pollen is transported over several hundreds of kilometers [Cecchi et al., 2007, Smith et al., 2008], although there is no indication which part of the pollen is affected by such long distances. However, studies indicate that pollen grains might lose their allergenic potential during long-distance journeys through the upper atmosphere with extreme conditions such as humidity, temperature and solar radiation [Cecchi et al., 2010]. Hence, it cannot be said if pollen that has travelled over such long distances really affects allergic people. To be able to detect the current situation of pollen load and predict the near future, special boxes are installed to capture pollen. The pollen found in such traps is counted to clarify the current pollen pressure and try to predict the pollen load of the near future (see e.g. www.polleninfo.org), but is not tested for its allergenic potential. For traps in the study area with a lot of *Ambrosia artemisiifolia* L. populations in the neighborhood, it does not make a big difference if to already trapped pollen also sporadic ones of long distance travel are joined. This can be argued, as only 5 to 10 pollen grains per cubic meter of air are sufficient to trigger allergic reactions in sensitive patients [Taramarcaz et al., 2005].

Based on these facts it cannot be said how far the pollen, captured in pollen traps, has travelled. Until now there has been no success in determining the origin of pollen found in pollen traps. In flat regions with a highly *Ambrosia artemisiifolia* L. populated neighborhood like Eastern Austria with the close-by region of Hungary it can be supposed that a good portion of *Ambrosia artemisiifolia* L. pollen in the traps originates from those densely populated regions (i.e. Hungary in our case). Whereas in other regions, which

are separated from densely populated regions by mountain ranges and distance (like Western Austria and Bavaria), one may assume that the *Ambrosia artemisiifolia* L. pollen load is mainly of local origin. This does not exclude the fact that single pollen grains from long distance travel over hundreds of kilometers are trapped as well, but remain a minority.

Pollen is very small (18 to 22 μm) and light and, therefore, travels with the air mass together [Cecchi et al., 2007]. Hence, theoretically, when weather conditions are known, it could be calculated how far pollen travels before reaching the mucous membrane of allergic people. However, the exact position and time of pollen release is unknown and due to local fluctuations the path of single grains in air can never be predicted over long distances. With the HYSPLIT model (short for Hybrid Single Particle Lagrangian Integrated Trajectory Model) such calculations are possible [Draxler and Rolph, 2014, Rolph, 2014]. Simulations are possible in both directions forward and backward, meaning the HYSPLIT model can, based on meteorologic data, predict where pollen has flown when released at a certain point as well as predict from where the air masses that have reached a specific location came (e.g. where does pollen come from, that reached a specific pollen trap.). The exact position and the time of pollen release and arrival, respectively, has to be put into the model.

Some authors show with such backward trajectories that pollen can travel over very long distances [Stach et al., 2006, Cecchi et al., 2007, Smith et al., 2008, Sikoparija et al., 2009, Kasprzyk et al., 2010]. The argumentation is that air masses with trajectories above regions with no sizeable *Ambrosia artemisiifolia* L. populations cannot be the source for its pollen and, hence, infested sites farther away, at the end of the trajectories, have to be responsible for the pollen load. Although seeming to be a practical tool for the purposes in this thesis (i.e. to predict the pollen load for single grid cells) it proved not to be suitable. The day with the highest *Ambrosia artemisiifolia* L. pollen count in Vienna in 2011 was the 27th of August. With the HYSPLIT model over a time span of 24 hours it was calculated from where the air masses came, arriving at the position of the pollen trap during the 27th of August (Fig. 3.11). The result was quite surprising as the air masses on that specific day came within a few hours from opposite directions. Furthermore, some trajectories have their origin in the southeast of Vienna, meaning air masses travelled over heavy infested cells in Austria and Hungary. Although the pollen traps in use can distinguish pollen with a resolution of two hours, it can be doubted that it can be said for sure if the pollen found in the traps came from sites near Vienna or from infested cells farther away or both. Additionally, the investigation proved that it is not possible to predict from which direction pollen arrives at a specific location. Based on these facts it

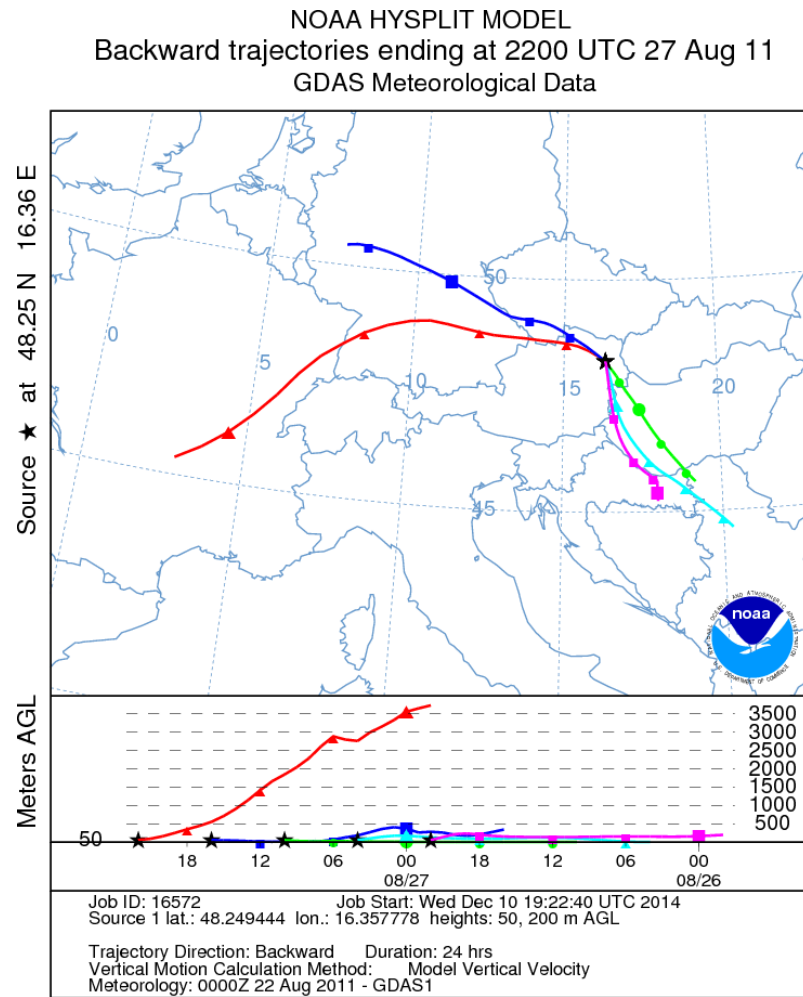


Figure 3.11: Wind trajectories arriving in Vienna at the coordinates of pollen trap 8 (number according to table 3.3) during the day of August 27th 2011. This was the day with the highest *Ambrosia artemisiifolia* L. pollen count in this trap in the year 2011. Depending on the time, the origin of the pollen varies dramatically.

was decided not to use the HYSPLIT model for simulating the pollen travel of *Ambrosia artemisiifolia* L. Instead, the pollen dispersal was calculated with an exponential distribution with the parameter τ assuming a wind with constant velocity and direction for each individual trajectory. Wind data, with a resolution of 10 minutes, from the two weather stations Wien Hohe Warte (48°14'55" North, 16°21'23" East) and Ried im Innkreis (48°13'02" North, 13°28'30" East) of August and September from 2000 to 2008 were used. The wind velocity and direction used in this model was the average over the entire data.

With these data, for each infested cell, the impact of the pollen load to all other cells were calculated. All infested cells from the study area (i.e. Austria and Bavaria) and the close-by regions, for which *Ambrosia artemisiifolia* L. distribution data were available (i.e. Hungary, Slovenia and South Tyrol), were considered. To determine the parameter τ , the simulated pollen dispersion were compared with the corresponding annual pollen counts recorded for the years 2008 to 2011 at eight Austrian pollen-monitoring stations that operated volumetric spore traps of the Hirst design [Hirst, 1952]. The pollen distribution with best agreement to the recorded pollen counts (see table 3.3) is given for $\tau = 1.72$ h (Fig. 3.12). Multiplied by the mean wind speed

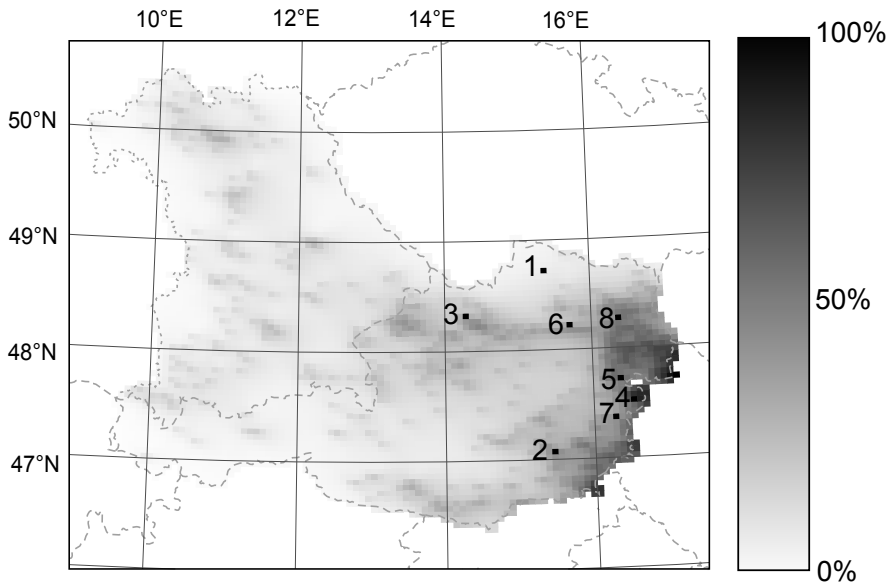


Figure 3.12: Simulated pollen dispersion (darkest shade indicates maximum pollen load) and location of the eight Austrian pollen traps (black squares) with numbering according to table 3.3.

of the two weather stations in August and September from 2000 to 2008 of

Trap	2008	2009	2010	2011
Trap 1	62	n.d.	69	367
Trap 2	n.d.	670	246	246
Trap 3	7	7	2	8
Trap 4	472	442	256	784
Trap 5	790	1310	n.d.	n.d.
Trap 6	32	179	117	74
Trap 7	328	229	362	101
Trap 8	862	1178	711	1329

Table 3.3: Annual sums of *Ambrosia artemisiifolia* L. pollen for eight pollen traps in Austria for the years 2008 to 2011. Traps that were temporarily out of function are indicated with n.d. The position of the traps within the study area can be seen in figure 3.12.

~ 21 km/h, this results in ~ 36 km wide pollen transport on average. This is in good agreement with studies that pollen in traps has its origin within an area with a radius of 30 km [Skjøth et al., 2010].

Obviously there is no information on how many pollen grains are produced in a single cell. In addition also the number of persons who suffer from *Ambrosia artemisiifolia* L. allergies and to which degree is not available. Therefore, it was decided not to calculate the number of affected persons, but the total allergy costs per grid cell. The basis for the scaling is one of the rare calculations of *Ambrosia artemisiifolia* L. allergy costs - 90 million € annual allergy costs in Austria for the year 2005 [Jäger, 2006]. As the allergy costs in each single cell depends on the number of persons living there, also the population density of Austria and Bavaria (see Fig. 3.13) was used for each grid cell [CIESIN and CIAT, 2005]. With the dispersal kernel for pollen spread as described above, the pollen impact of all other cells was calculated for every single cell. The obtained number was multiplied by the corresponding population density of the grid cell. This calculated value is proportional to the annual allergy costs of the appropriate cell. Then the values from all cells of Austria were summed up and scaled the sum to 90 million € (see above) to get the proportionality factor. Using this factor the total annual allergy costs for Austria together with Bavaria result in 133 million €. Depending on the pollen intensity the annual costs per person vary from about 35 € (e.g. in Eastern Austria) to negligible costs in higher mountainous regions. The average costs per person are about 10 € per inhabitant. Of course this would imply that all persons suffer from *Ambrosia artemisiifolia* L. allergies. In reality this is not true, but lacking more detailed data it has to be assumed that the percentage of allergic persons is equally distributed all

over the study area. Supposing 4–5% of the population to be allergic (with regard to *Ambrosia artemisiifolia* L.) [Jäger, 2006, Burbach et al., 2009] the costs per allergic person result in 200–250 €. This amount includes the costs for medical treatment as well as indirect costs such as loss of work days. A recent study estimates costs of 303 € for European persons that suffer from *Ambrosia artemisiifolia* L. allergies [Bullock et al., 2012]. This is very close to the calculation in this thesis. One has to consider that these are average amounts of money that can vary from person to person and, therefore, can also be much higher for persons that react extremely sensitively with allergic asthma [Bullock et al., 2012]. The same procedure was used to calculate the annual allergy costs for all simulations up to 2050.

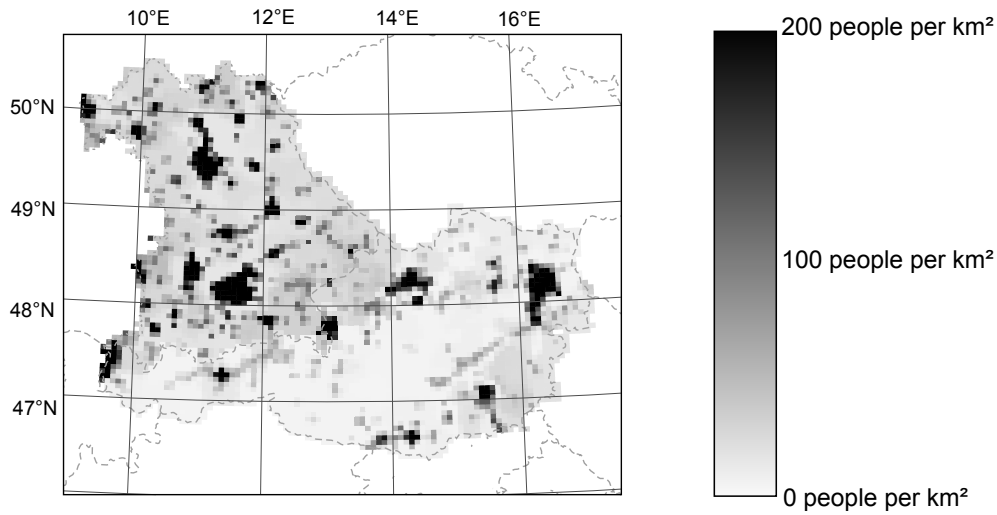


Figure 3.13: Population density in Austria and Bavaria. Shades indicate population density (a black square indicates a population density >200 people per km^2)

3.7 Estimation of management costs

In the previous section the calculation of health costs arising due to pollen allergies was explained. To be able to compare them with management costs it is necessary to determine them as well. Therefore, this section provides a rough estimation of management costs. For decision makers this is relevant information when considering whether management is reasonable. If the available budget is too low, the possible success may not be high enough to justify management. The influence of available budget on management

success can be seen in figure 4.5 in section 4.1.1 ‘Management with random sampling’. This thesis calculates the management costs first in abstract values, i.e. management effort units, and converts them later into euro. The benefit of this approach is that the calculations can be done independently of the actual costs, and different costs can be included afterwards, respectively. The available budget is administered in different ways by different authors. Some use the possibility of unconstrained budget [Bogich and Shea, 2008], some use constrained budget [Giljohann et al., 2011] and others use both [Hauser and McCarthy, 2009]. Here it is opted for the more realistic possibility of constrained budget as no government will provide unlimited resources. To be able to adapt the results to different actual management costs in various currencies, management effort units are used as abstract values. To survey one grid cell the value of 0.1 management effort unit was estimated and for eradication 1 management effort unit (see section 3.4 ‘Management’).

In order to be able to calculate real savings the costs of one management effort unit is estimated. Assuming that one person is capable of surveying a strip of 10 m width when walking at a speed of about 4 km/h it takes 25 hours to survey 1 km². Therefore, it takes about 100 man days (with one man day equal to 8 hours working) to survey one grid cell (~ 35 km²). With an average cross wage of 25 € per hour the 100 man days cost 20 000 €. When including material costs in the amount of 10 000 €, 0.1 management effort units add up to 30 000 €. For eradicating the population in one grid cell (equal to 1 management effort unit) the costs are, therefore, 300 000 €.

Chapter 4

Results

The results presented here are also published in Richter et al. (2012 and 2013), however, this thesis gives a more detailed description.

At the beginning of the simulation period (2005) already 514 grid cells of the study area (Fig. 2.5) were populated by *Ambrosia artemisiifolia* L. This means that from the beginning of the spread in the mid-twentieth century until the beginning of the twenty-first century about 11 % of the grid cells of Austria and Bavaria were invaded by *Ambrosia artemisiifolia* L. However, according to the habitat suitability (Fig. 3.5) the distribution is far from equilibrium. Although *Ambrosia artemisiifolia* L. spread fast during the years before 2005 [Dullinger et al., 2009, Smolik et al., 2010], a lot of cells with high suitability are still not populated.

This chapter gives the results by different perceptions, that is: (1) Infested cells and health costs each as mean annual value and value in 2050, respectively. (2) The kind of management scheme (i.e. random sampling or fixed order sampling). And (3) with or without climate change with two variations in the former. It was tried to establish a logical order of these various perspectives.

4.1 Without climate change

Within this section it is discussed (1) the number of cells infested in the year 2050 (i.e. at the end of the simulation period) and (2) the mean annual infestations from 2011 until 2050. The former can be used as comparison to the current distribution to see if it is further distributed or curtailed without asking what has happened over the intervening years. The latter states something about the whole period and can be used e.g. to calculate costs over the whole management period. As surveillance and eradication (i.e.

management) was calculated to start in the year 2011 and not immediately in the first year of simulation 2006, the mean annual infestations are defined to be an average number over those 40 years (from 2011 until 2050). For a better comparison the same procedure was carried out for the business-as-usual scenario where no management took place.

Beginning with the known distribution of *Ambrosia artemisiifolia* L. in 2005 the simulation predicts the number of infested cells in 2050 to be 1 682 (Fig. 4.1). In other words, without control more than one third of the grid cells of Austria and Bavaria will be invaded by this invasive weed. On the other hand this business-as-usual scenario (i.e. without management) results in 1 147 mean annual infestations from 2011 until 2050. Therefore, the aim was to give a guideline how management has to be carried out to curtail the further spread of the invasive alien species *Ambrosia artemisiifolia* L.

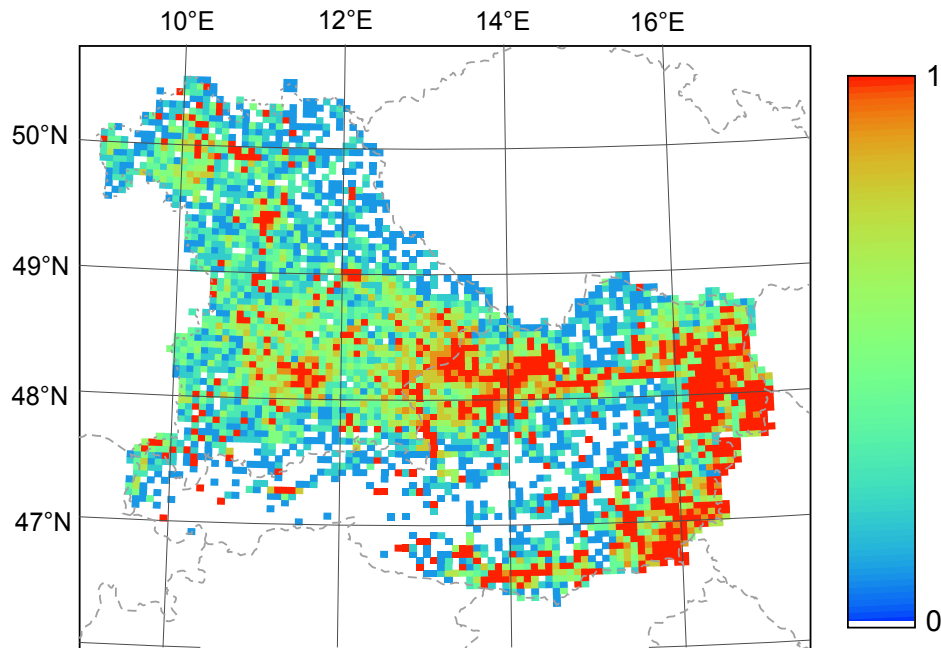


Figure 4.1: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 according to the simulation without management. Grid cells correspond to the raster used in the Floristic Mapping of Central Europe (3 x 5 geogr. minutes, $\sim 35 \text{ km}^2$). Different colours indicate the probability of infestation.

4.1.1 Management with random sampling

Management consists of the two parts surveying and eradication together with monitoring (see section 3.4 ‘Management’). In the random sampling scheme the cells to be surveyed are chosen randomly from the pool defined by the threshold p . The spread of *Ambrosia artemisiifolia* L. can be drastically curtailed both in terms of the mean annual infestations and of the cells infested in 2050. Here it is distinguished between managing all cells ($p = 0$) and those above a certain habitat suitability ($p > 0$). When managing all cells ($p = 0$) with an available annual budget of 50 management effort units, the number of infested cells stays roughly the same as in the starting year 2005: number of infested cells 2050 equals 486 and the mean annual infestations equals 535 in comparison to 514 detected infested cells in 2005.

When increasing the threshold p , meaning that cells with low suitabilities are not managed, the management success is increased up to a certain value of p and then decreases again (see Fig. 4.2).

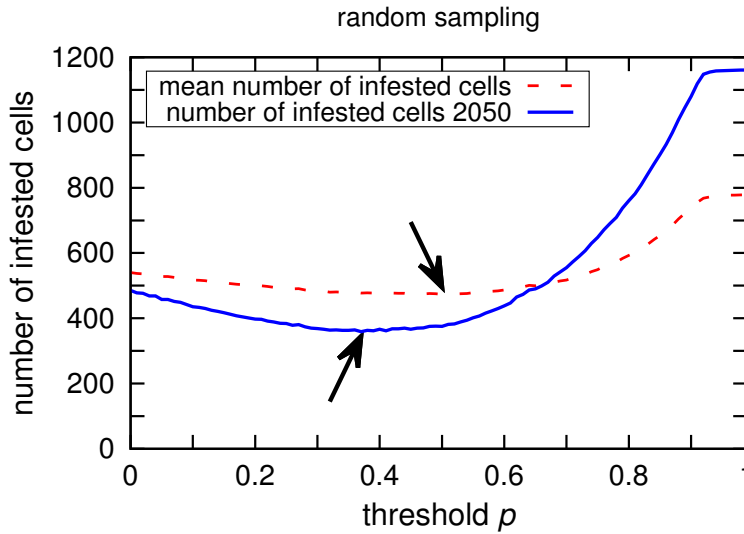


Figure 4.2: Number of infested cells (3×5 geographical minutes, $\sim 35 \text{ km}^2$) by *Ambrosia artemisiifolia* L. for random sampling. The cells to be surveyed and eradicated are defined by the threshold p (e.g. $p = 0.4$ means that the best suited 60% of the cells were chosen for management). The solid line indicates the number of infested cells at the end of the management and simulation period 2050. The dotted line shows the number of mean annual infestations during the management period from 2011 until 2050. The arrows indicate the minima of the curves and hence the threshold p . The position of the arrows is given by looking at the calculated data.

Under the given settings the best result (i.e. lowest number of infested cells), regarding infestations at the end of the management period, is achieved for the threshold $p = 0.37$: number of infested cells 2050 equals 359 and the mean annual infestations equals 465. However, the lowest number of mean annual infested cells is reached for the threshold $p = 0.47$ with 456. The appropriate number of infested cells in 2050 is 365.

By choosing higher values of p the number of cells that are managed decreases and, therefore, those cells are surveyed more often. This means that cells with better suitability for *Ambrosia artemisiifolia* L. are treated more often and, therefore, existing populations can be eradicated successfully very quickly. Contrariwise, cells below the chosen suitability threshold are never surveyed. Although those cells do not provide best conditions for the study species, they probably are good enough that populations can spread without limits and hence colonize quite big areas (Fig. 4.3).

To put the results in a nutshell: when choosing a too low threshold p the management success decreases only slightly, when setting it too high, it increases sharply (Fig. 4.2). This seems to suggest that there is no exact threshold, but rather a range of thresholds to gain optimal management. Where this optimum range of threshold p is located, also depends on the length of the management period. The longer the period is, the lower the suitability threshold has to be set (Fig. 4.4). The reason is that when more cells can be surveyed (independent of budget available or length of management period) more invasive species populations can be eradicated and, hence, they are no source for further spread any longer. This means that more budget available will be used for surveillance and less for eradication. When the suitability threshold is set lower, more infested cells can be found and cleared from *Ambrosia artemisiifolia* L. and, hence, management success will increase. Figure 4.3 shows the percentage of infested cells as a function of the threshold p for three different years. It can clearly be seen how the percentage of infested cells decreases in the set of cells to be managed and how it increases in the non managed cells.

It was decided to use the amount of 50 management effort units, because this corresponds to the costs of surveying 500 grid cells - this seemed to be a adequate amount of money. To see the effect of diverse sizes of available budget, the simulation was run with various management effort units - precisely with 25, 50 and 100 management effort units. Figure 4.5 shows the result for (a) the number of infested cells in 2050 and (b) the mean number of infested cells over the management period. The threshold p decreases with increasing management effort (see table 4.1). This can be explained with the fact that more available money leads to the possibility of surveying and eradicating more cells per year. This way the spread can be curtailed more quickly.

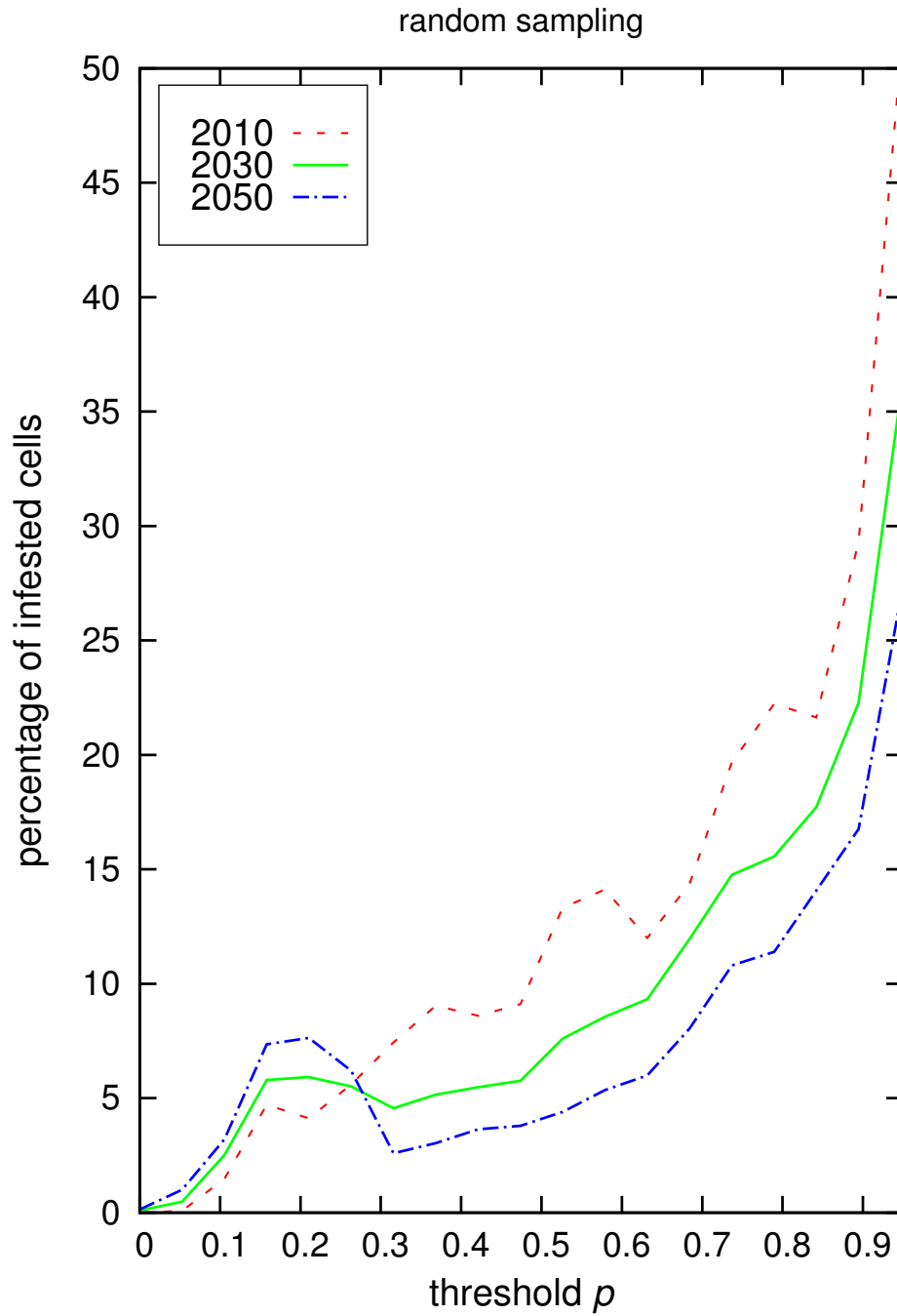


Figure 4.3: Percentage of cells infested by *Ambrosia artemisiifolia* L. as a function of the threshold p for three different years. The dotted line for the year 2010 indicated the percentage of infested cells before the management period begins. The simulations for this figure were run with a threshold of $p = 0.3$ (i.e. 70 % of the study area with the highest habitat suitability was surveyed). It can be seen that the percentage of infested cells decreases above the threshold, whereas below it increases.

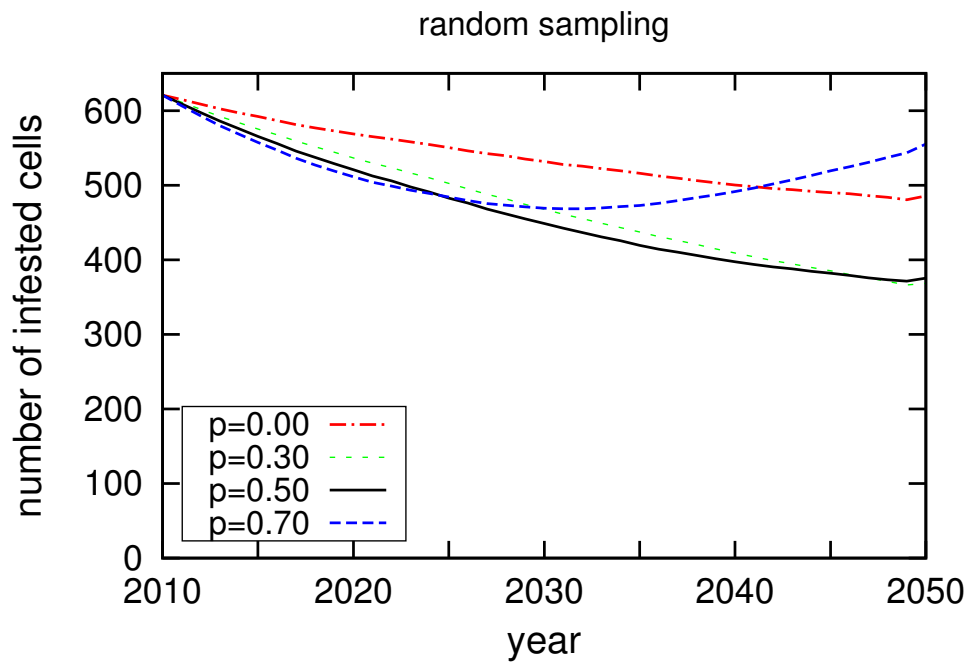


Figure 4.4: Number of infested cells (3×5 geographical minutes, $\sim 35 \text{ km}^2$) by *Ambrosia artemisiifolia* L. for the years 2010 until 2050 for random sampling. Different curves indicate different thresholds p with management only in cells above this value.

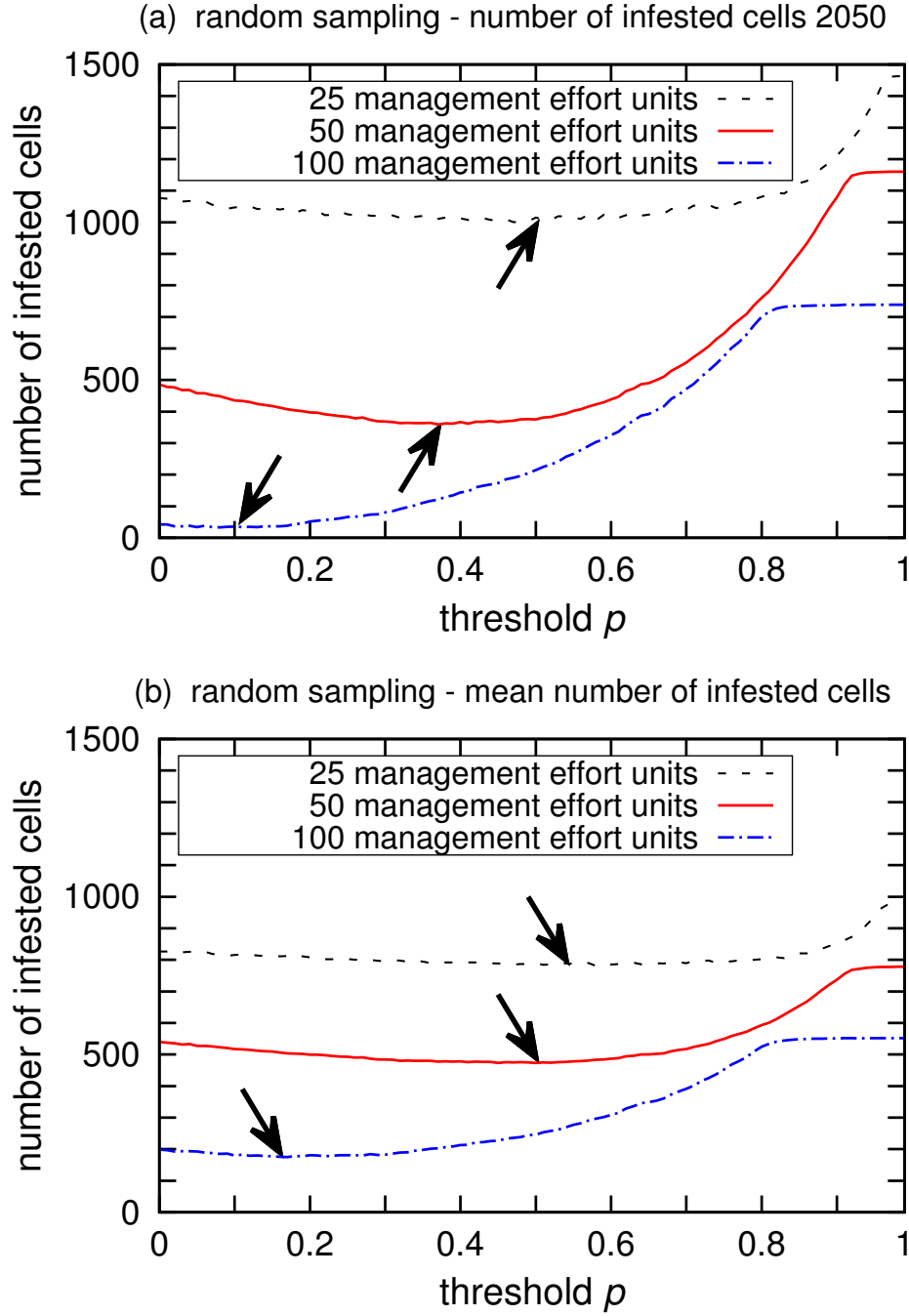


Figure 4.5: (a) Number of infested grid cells at the end of the simulation period in the year 2050 and (b) mean number of infested grid cells during the management period from 2011 until 2050 for three different available budgets for management as a function of the threshold p . The arrows indicate the minima of the curves. The position of the arrows is given by looking at the calculated data.

management effort units	25	50	100
optimal value of p (mean annual infestation)	0.54	0.47	0.16
optimal value of p (cells infested in 2050)	0.50	0.37	0.11

Table 4.1: Threshold p for achieving lowest numbers of infested grid cells for three different available budgets for management with random sampling.

4.1.2 Management with fixed order sampling

Here the surveillance of all cells is simulated in order of their habitat suitability starting at the cell with the highest suitability for *Ambrosia artemisiifolia* L. It proved to increase the management success compared to management by random sampling: the number of cells infested by 2050 decreases to 122 (Fig. 4.6) and the mean annual infestations to 338 (Fig. 4.7 at $p = 0$) when using a budget of 50 management effort units per year.

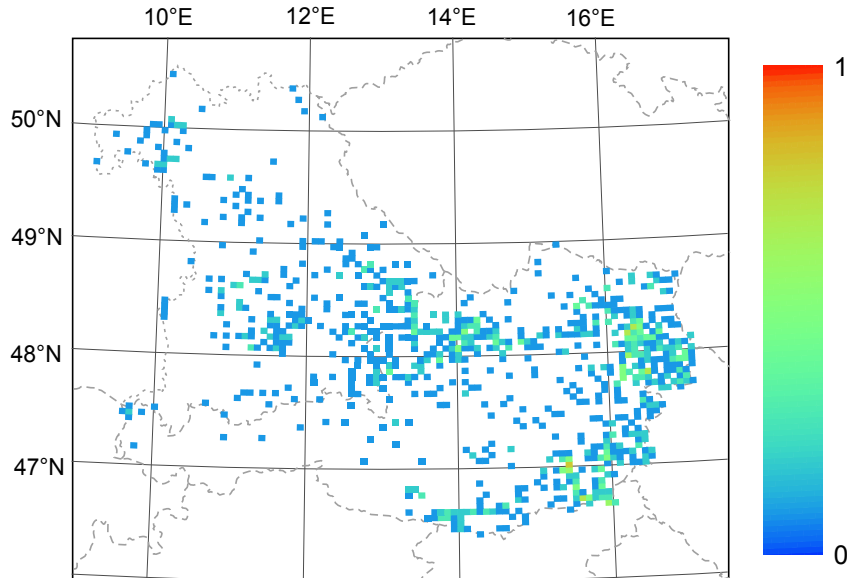


Figure 4.6: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 under current climate. Management was carried out throughout the whole study area with fixed order sampling using a budget of 50 management effort units. Different colours indicate the probability of infestation.

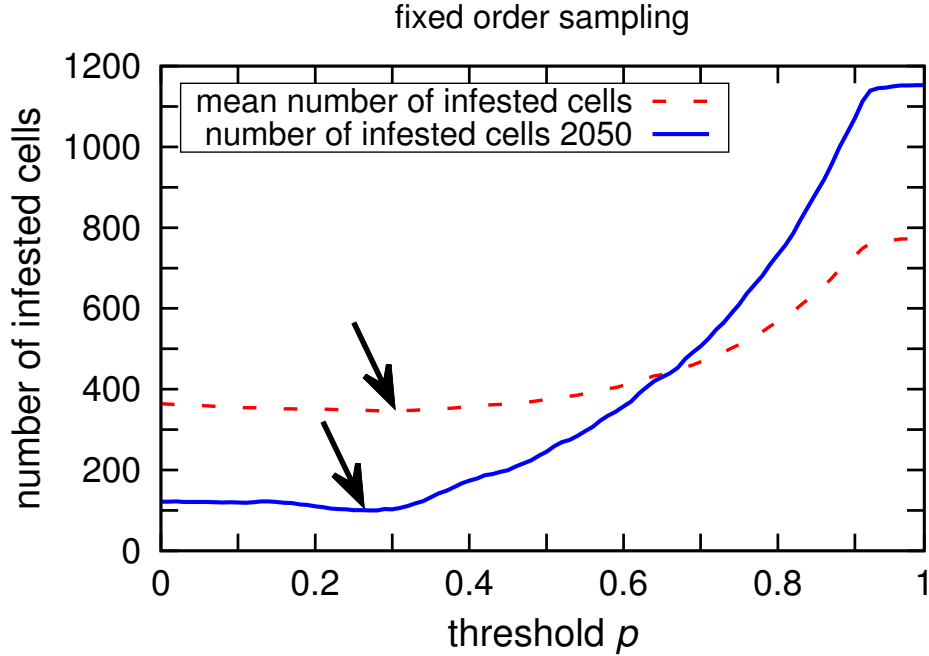


Figure 4.7: Number of infested cells (3×5 geographical minutes, $\sim 35 \text{ km}^2$) by *Ambrosia artemisiifolia* L. for fixed order sampling. The cells to be surveyed and eradicated are defined by the threshold p . The solid line indicates the number of infested cells at the end of the management and simulation period 2050. The dotted line shows the number of mean annual infestations during the management period from 2011 until 2050. The arrows indicate the minima of the curves and, hence, the optimal threshold p . The position of the arrows is given by looking at the calculated data.

Choosing the optimal threshold p by using management with a fixed order sampling becomes more complex. In the first 15 years the management success does not depend on the threshold p (at least for $p < 0.7$), because in the fixed order sampling scheme surveillance always starts in the same cell with the highest habitat suitability (Fig. 4.8). The reason is that it takes this time span to survey and eradicate existing populations of *Ambrosia artemisiifolia* L. down to the habitat suitability corresponding the threshold $p = 0.7$ once. From this point on the trajectories run in different ways. For $p = 0.7$ the number of infested cells increases again, because cells with lower habitat suitability, but still well-suited, are not surveyed. Therefore, *Ambrosia artemisiifolia* L. can spread without limits in those cells. For intermediate values of p like $p = 0.5$ the number of infested cells decreases further until

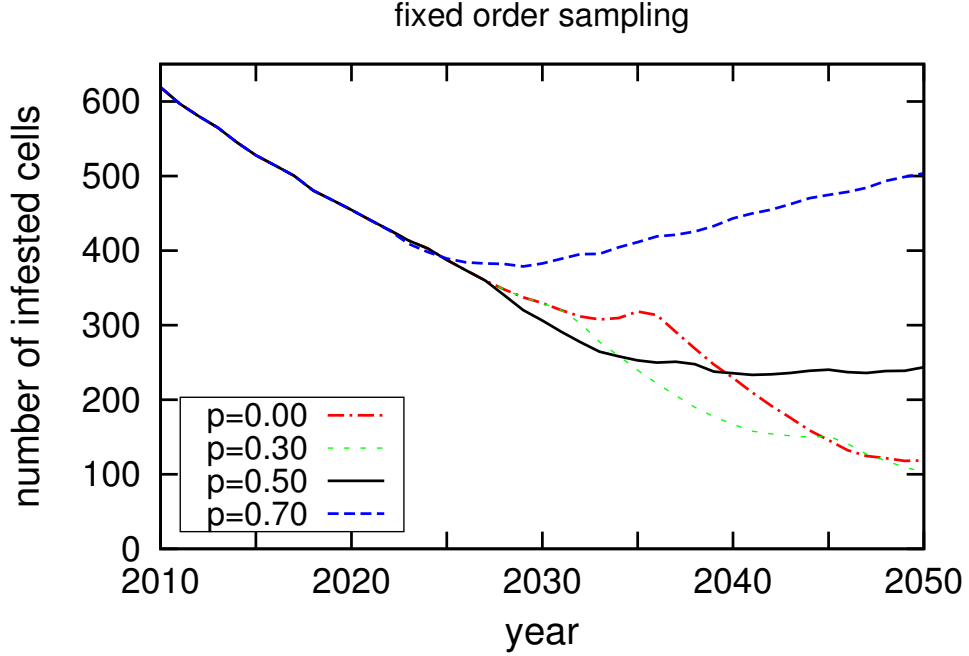


Figure 4.8: Number of infested cells (3×5 geographical minutes, $\sim 35 \text{ km}^2$) by *Ambrosia artemisiifolia* L. for the years 2010 until 2050 for fixed order sampling. Different curves indicate different thresholds p with management only above this value.

it levels off to a nearly constant value. For low values like $p < 0.3$ the number of infested cells decreases further in running through a local maximum. The latter occurs when management reaches the less suitable cells within the set of defined cells by the threshold p . While these cells are surveyed and rarely existing populations are eradicated, the study species can spread in cells with higher habitat suitabilities. After the local maximum surveillance starts again at the cells with the highest habitat suitability. Figure 4.9 also shows this phenomenon: The curve for 2010 shows the percentage of infested cells as a function of the threshold p before management was applied. The line for 2030 shows that surveillance has reached cells with a habitat suitability corresponding threshold $p \sim 0.6$ and cells with a higher suitability are already partly recolonized again. In 2050 management has started already a second time at the beginning and has reached cells corresponding threshold $p \sim 0.8$. All in all a wave-like infestation pattern with a decreasing amplitude can be observed.

Up to now the management success was only discussed in connection

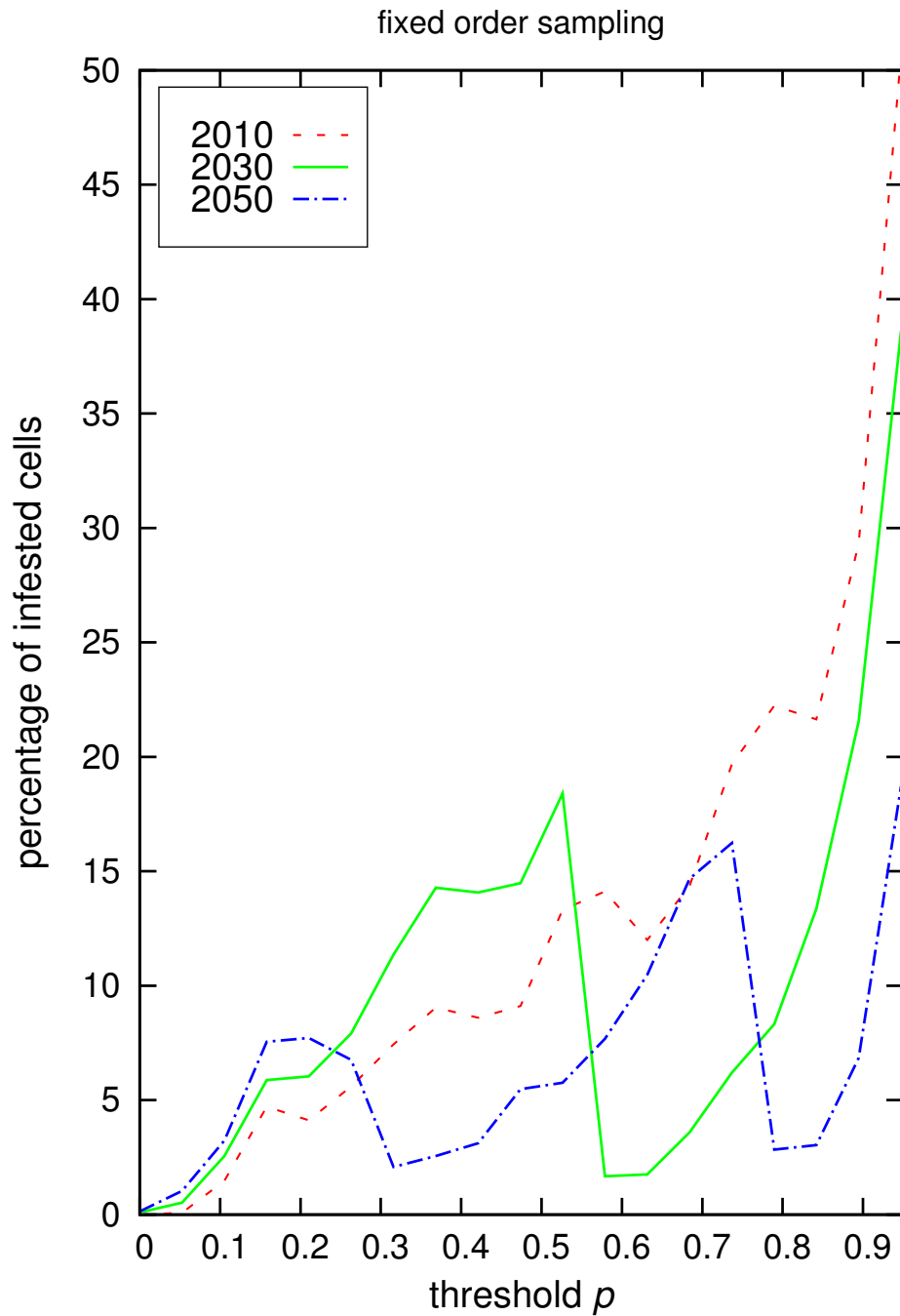


Figure 4.9: Percentage of cells infested by *Ambrosia artemisiifolia* L. as a function of the threshold p for three different years. The dotted line for the year 2010 indicates the percentage of infested cells before the management period begins. The simulations for this figure were run with a threshold of $p = 0.3$ (i.e. 70 % of the study area with the highest habitat suitability was surveyed).

with a management period of 40 years (i.e. from 2011 to 2050). As figure 4.8 shows the management success is best for threshold $p < 0.3$. The exact values are, with regard to minimizing the number of infested cells, at the end of the simulation period in the year 2050 a threshold $p = 0.27$ with 100 infested cells and with regard to minimizing the mean annual infestations a threshold $p = 0.3$ with 318 infested cells. For shorter time spans than 40 years of management higher suitability thresholds can be slightly better with regard to management success. When for example management takes place only half the time and, therefore, already ends in the year 2030, the highest success is achieved when surveying only about half of the study area down to a minimum threshold $p \sim 0.5$ (Fig. 4.8). This can be explained with the total amount of available money over the whole management period. A shorter period is equivalent to less available budget per year as stated in section 4.1.1 ‘Management with random sampling’.

The effect of different available budgets was also considered for fixed order sampling. Figure 4.10 shows the result for 25, 50 and 100 management effort units for (a) the number of infested cells 2050 and (b) the mean number of infested cells over the management period. The threshold p decreases with increasing management effort (see table 4.2). Compared to random sampling the optimal threshold increases for an available budget of 25 management effort units and decreases for 50 and 100 management effort units. Summarizing the two management schemes, random sampling and fixed order

management effort units	25	50	100
optimal value of p (mean annual infestation)	0.67	0.30	0.11
optimal value of p (cells infested in 2050)	0.59	0.27	0.00

Table 4.2: Thresholds p for achieving lowest numbers of infested grid cells for three different available budgets for management with fixed order sampling.

sampling, the latter outreaches the former by far with regard to management success (i.e. lowest number of infested grid cells at the end of the simulation period in the year 2050 as well as mean annual infestations during the management period from 2011 until 2050).

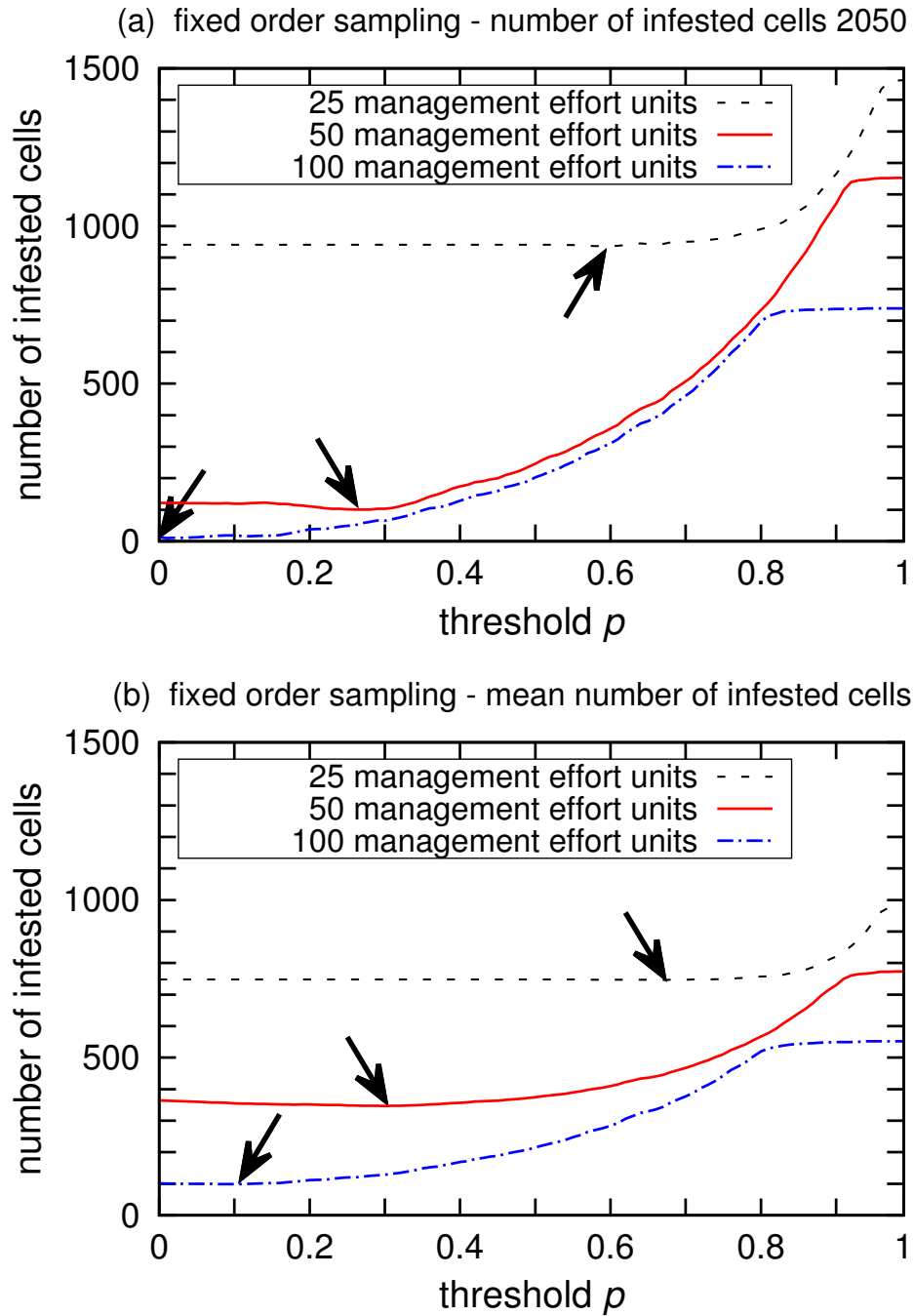


Figure 4.10: (a) Number of infested cells at the end of the simulation period 2050 and (b) mean annual number of infested cells during the management period from 2011 until 2050 as a function of the threshold p for three different available budgets. The higher the available budget, the lower is the optimal threshold p . The arrows indicate the minima of the curves. The position of the arrows is given by looking at the calculated data.

4.2 With climate change

In this section the results of simulations considering a temperature increase of 1.5 °C and 2.4 °C from 1990 until 2050, i.e. 0.025 °C and 0.04 °C per year, respectively, are presented.

Additionally, the results of health cost calculations because of *Ambrosia artemisiifolia* L. pollen allergies are given for the simulations with climate change in comparison to the scenario without temperature increase.

As in the previous chapter 4.1 ‘Without climate change’, management with fixed order sampling proved to be superior to random sampling, the climate change assumptions were simulated only with the fixed order scheme.

4.2.1 Distribution of *Ambrosia artemisiifolia* L.

The simulations show that climate change induced by temperature increase has a dramatic influence on the spread of *Ambrosia artemisiifolia* L. The reason is that the habitat suitabilities of the grid cells increase due to higher temperatures (Fig. 3.10) and, hence, the probability that seeds germinate is higher. In the future without climate change at the end of the simulation period in the year 2050 1 682 cells are infested (Fig. 4.11). This is about one third of the grid cells of the study area. With temperature increase of 0.025 °C per year the number of infested cells until 2050 increases by more than 400 (or about a quarter compared to the assumption without temperature increase) to 2 105 (Fig. 4.12). Assuming the more extreme future with an temperature increase of 0.04 °C per year the number of infested grid cells in the year 2050 increases by even 751 to 2 433 (Fig. 4.13). This equals to more than fifty percent of the cells of the study area.

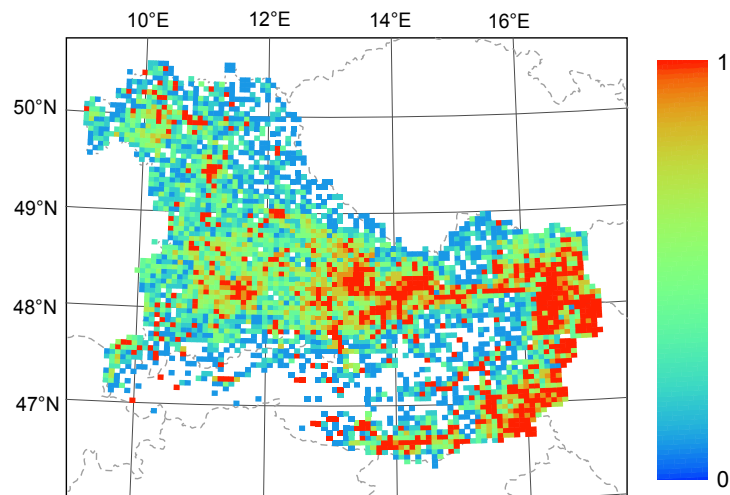


Figure 4.11: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 assuming current climate without management. Different colours indicate the probability of infestation.

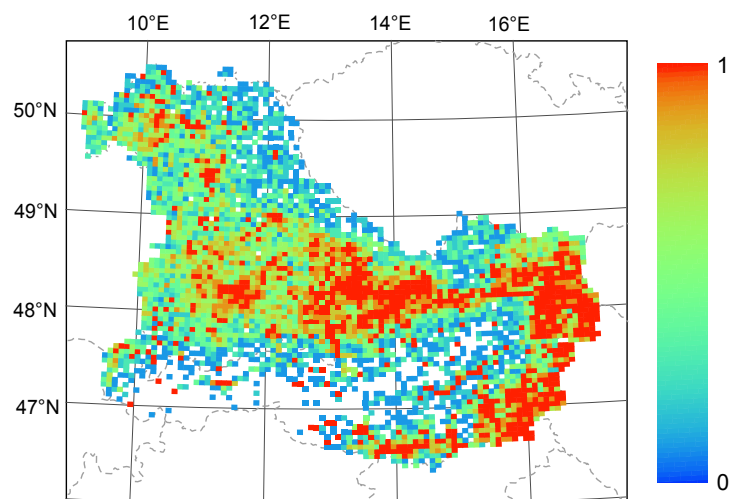


Figure 4.12: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 assuming temperature increase of 0.025 °C per year without management. Different colours indicate the probability of infestation.

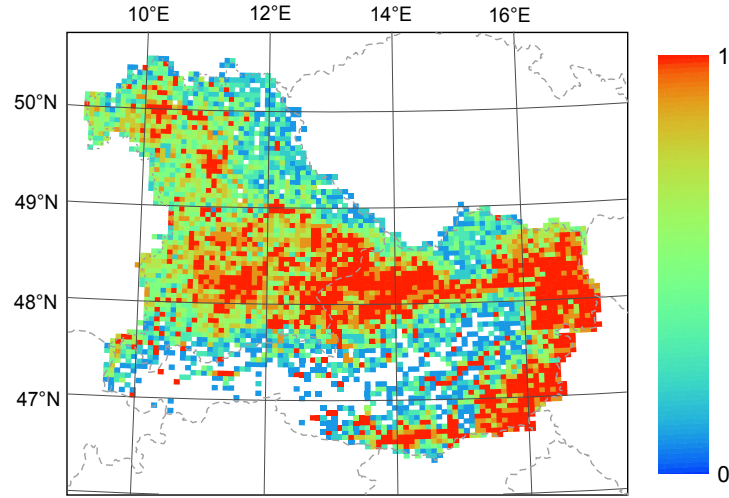


Figure 4.13: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 assuming temperature increase of 0.04°C per year according to the simulation without management. Different colours indicate the probability of infestation.

Management with temperature increase of 0.025°C per year

When applying management for this moderate climate change assumption, the number of infested cells again can be reduced drastically. For an available budget of 50 management effort units the number of infested cells at the end of the simulation period are reduced to 464 when surveying the whole study area and to 377 when choosing the optimal threshold $p = 0.43$ (Fig. 4.14). Although this numbers are clearly below the non-management assumption for this temperature increase, they are more than three times of the best (i.e. lowest) value of the future without climate change. For the mean annual infestations the differences are not so big as the habitat suitabilities increase throughout the management period and reach only in the last year the highest values. The mean annual number of infested cells is 492 when managing the whole study area and 451 when limiting to the optimal threshold $p = 0.46$.

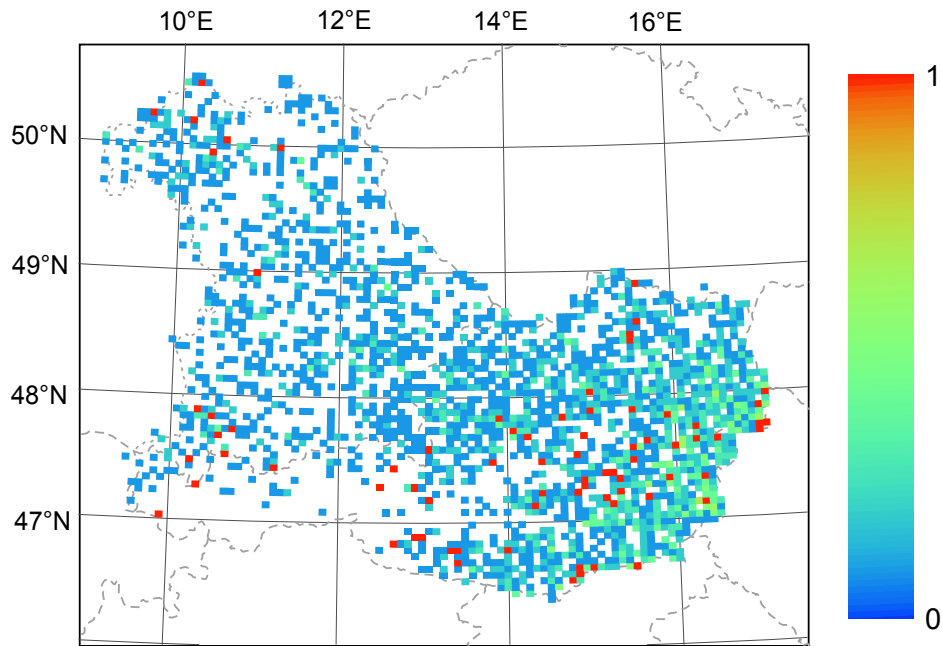


Figure 4.14: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 assuming temperature increase of 0.025 °C per year. Management was carried out with available budget of 50 management effort units down to a threshold $p = 0.43$ (equivalent to surveying 57% of the best suitable cells). Different colours indicate the probability of infestation. Red squares indicate cells infested until the year 2005, that are not surveyed due to the chosen threshold.

Management with temperature increase of 0.04°C per year

In this more extreme future the number of infested cells is also drastically reduced compared to the business-as-usual scenario. However, compared to the assumption without climate change this number is considerably higher. When surveying the whole study area and eradicating detected populations using 50 management effort units per year, the number of infested cells in the year 2050 is 915 compared to 800 for the optimal threshold $p = 0.36$ (Fig. 4.15). The mean annual infestations are about double the number of the future without climate change. For managing all grid cells the mean annual infestations are 643, and 601 for surveying only down to the optimal threshold $p = 0.45$.

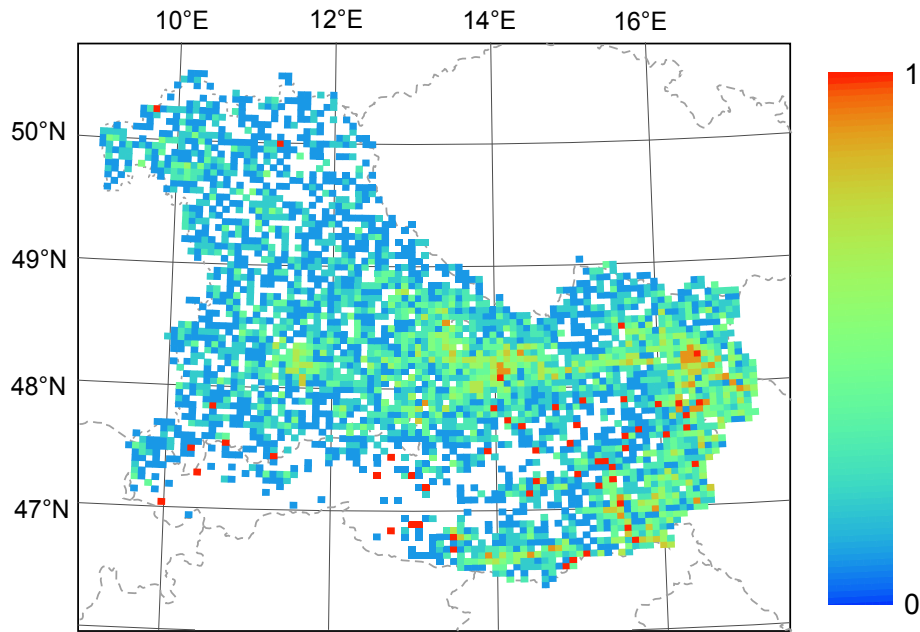


Figure 4.15: Distribution of grid cells infested by *Ambrosia artemisiifolia* L. in the year 2050 assuming temperature increase of 0.04°C . Management was carried out with available budget of 50 management effort units down to a threshold $p = 0.36$ (equivalent to surveying 64% of the best suitable cells). Different colours indicate the probability of infestation. Red squares indicate cells infested until the year 2005, that are not surveyed due to the chosen threshold.

The number of cells infested by *Ambrosia artemisiifolia* L. without management increases from 1990 until 2050 for the two climate change assumptions more dramatically in comparison to the future without climate change (Fig. 4.16). For the first 16 years (from 1990 until 2005) the numbers from the presence absence data and from 2006 onwards the mean of the simulated values are plotted. The transition from collected data to simulated data (2005 to 2006) shows a sharp bend (Fig. 4.16). This can be explained with the increased number of sightings in the year 2005 (see also Fig. 3.8). The reason may not be the more severe dispersion of *Ambrosia artemisiifolia* L., but the higher awareness of the population. The simulated spread shows again the more slower increase of the first 15 years.

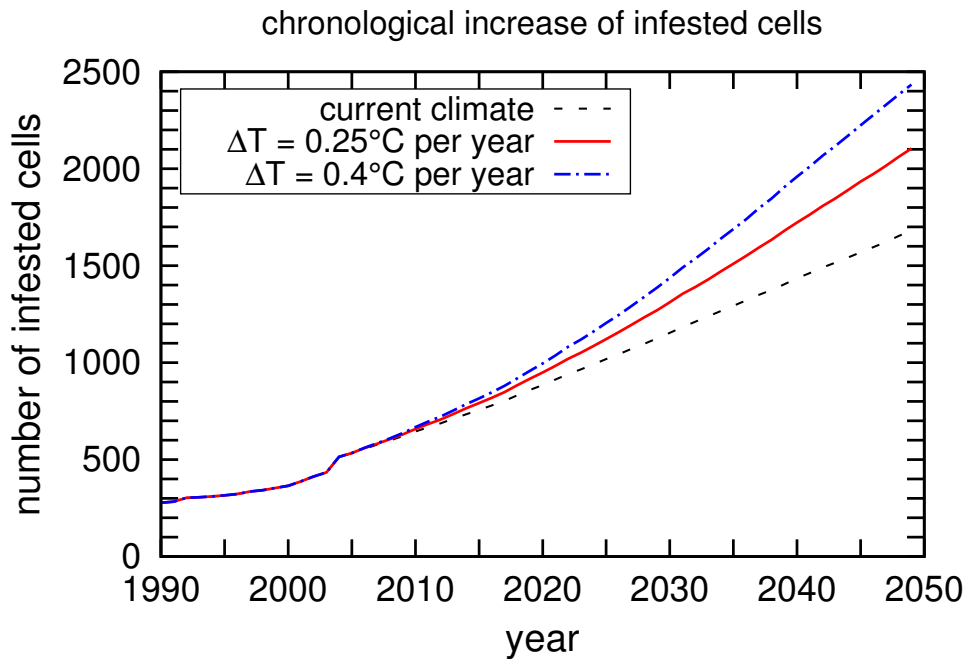


Figure 4.16: Number of cells infested by *Ambrosia artemisiifolia* L. as a function of the year for current climate as well as for two climate change assumptions without management. For the years 1990 until 2005 the numbers of presence absence data are plotted. From 2006 onwards the mean of the simulated values is plotted.

4.2.2 Pollen spread and costs

One of the main achievements of this thesis is the calculation of costs arising due to allergies against *Ambrosia artemisiifolia* L. pollen and possible savings when applying management. The hitherto calculated management effort units are converted into the currency Euro based on the estimation carried out in section 3.7 ‘Estimation of management costs’. Therefore, one management effort unit is equivalent to 300 000 € or the amount to survey ten grid cells or eradicate (including subsequent monitoring) one grid cell, respectively.

The optimal threshold p may differ from the section 4.2 ‘With climate change’, because in the calculation with pollen spread also the population density is included. Furthermore the pollen does not only stay in the infested cell, but is also transported to uninfested ones.

In the business-as-usual scenario (i.e. without management) the mean annual allergy costs from 2011 until 2050 are calculated to be 291 million € (Fig. 4.17). Whereas the costs at the beginning of the simulation period (2005) had been 133 million € (see section 3.6 ‘Pollen dispersion and health costs’), at the end of the simulation period (2050) the costs have increased to 422 million €. When carrying out management, those costs can be reduced drastically (Fig. 4.17). With applying management using 50 management effort units (i.e. 15 million €) per year the mean annual allergy costs can be reduced to 82 million € per year (when surveying cells with a higher threshold than $p = 0.41$) and the costs in the year 2050 drop even to 29 million € (when surveying down to a threshold $p = 0.3$). With higher investment in management the result can even be improved: The mean annual allergy costs drop to 45 million € (for a threshold $p = 0.16$), 32 million € (for a threshold $p = 0.11$), 26 million € (for a threshold $p = 0.11$) and 22 million € (for a threshold $p = 0.11$) when investing 75 (22.5 million €), 100 (30 million €), 125 (37.5 million €) and 150 (45 million €) management effort units per year, respectively. These results show the dependence of the optimal threshold p of the available budget. Whereas for a budget of 15 million € (i.e. 50 management effort units) about 60% of the area are surveyed (threshold $p = 0.41$), for higher budgets (30 million € or 100 management effort units) nearly 90% are surveyed (threshold $p = 0.11$) and existing populations of *Ambrosia artemisiifolia* L. detected and eradicated. This increase of manageable area seems logic as with higher budget every year more cells can be surveyed, but this drastic increase was surprising. The same increase of manageable area for higher available budget can also be seen when evaluating the costs at the end of the management period only. The costs in 2050 drop to 14 million € (for a threshold $p = 0.06$) for applying management using

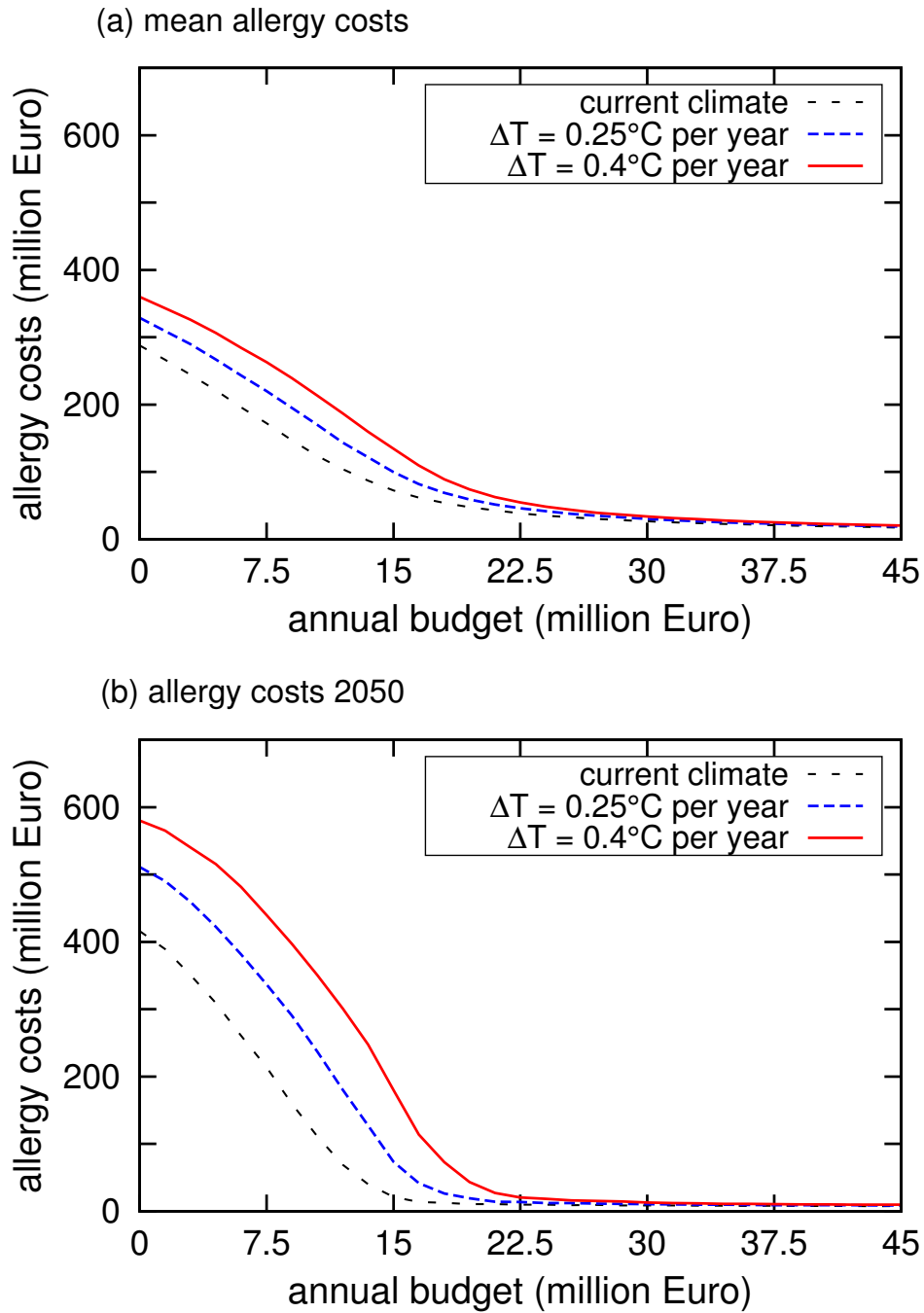


Figure 4.17: (a) Mean allergy costs during the management period from 2011 until 2050 and (b) allergy costs at the end of the simulation period in the year 2050 for current climate as well as for two climate change assumptions as a function of available budget.

22.5 million € (i.e. 75 management effort units) and stay approximately at this level also for higher investment.

Costs with temperature increase of 0.025 °C per year

With an increase of the mean annual temperature, the spread of *Ambrosia artemisiifolia* L. is faster. The reason is that under climate change the number of cells suitable for the study species also increases. Under climate change assuming 0.025 °C per year corresponding to a temperature increase of 1.5 °C from 1990 until 2050 the annual allergy costs increase by about 15% compared to the future without climate change. For this moderate assumption the mean annual allergy costs increase to 333 million € (Fig. 4.17 a) with an annual budget of 0 €, i.e. without management. The costs at the end of the management period 2050 increase even by nearly a quarter corresponding to 522 million € (Fig. 4.17 b).

Management can also drastically reduce costs under climate change. Investing 50 management effort units (i.e. 15 million €) per year, the mean annual allergy costs from 2011 to 2050 will decrease to 105 million € (for a threshold $p = 0.51$) for the climate change assumption with a temperature increase of 1.5 °C from 1990 to 2050 compared to 82 million € (for a threshold $p = 0.41$) without climate change. The allergy costs at the end of the simulation period 2050 decrease to 81 million € (for a threshold $p = 0.43$) compared to 29 million € (for a threshold $p = 0.3$) without climate change.

With the double amount of money applying for management (i.e. using 100 management effort units or 30 million €), the mean annual allergy costs decrease to 37 million € (for a threshold $p = 0.15$) for the moderate climate change assumption compared with 32 million € (for a threshold $p = 0.11$) without climate change (Fig. 4.17a). When applying this 100 management effort units per year the allergy costs at the end of the simulation period 2050 decrease to 18 million € (for a threshold $p = 0.06$) compared to 16 million € (for a threshold $p = 0.01$) without climate change (Fig. 4.17 b).

Costs with temperature increase of 0.04 °C per year

For this more extreme climate change assumption with a temperature increase of 2.4 °C from 1990 until 2050 the annual allergy costs increase by more than 25% to 365 million € compared to the future without climate change and nearly 10% compared to the moderate assumption (Fig. 4.17 a) with an annual budget of 0 €, i.e. without management. The costs at the end of the management period 2050 increase even by more than 40% to 596 million € compared to the assumption without climate change and by nearly

15% compared to the moderate temperature increase (Fig. 4.17 b).

With management investing 50 management effort units (i.e. 15 million €) per year, the mean annual allergy costs from 2011 to 2050 will decrease to 140 million € (for a threshold $p = 0.58$) compared to 82 million € (for a threshold $p = 0.41$) without climate change. At the end of the simulation period 2050 the costs decrease to 187 million € (for a threshold $p = 0.52$) compared to 29 million € (for a threshold $p = 0.3$) without climate change.

When the available budget is doubled to 30 million € per year (equivalent to 100 management effort units), the mean annual allergy costs decrease to 41 million € (for a threshold $p = 0.15$) compared to 32 million € (for a threshold $p = 0.11$) without climate change. At the end of the management period 2050 the costs decrease to 20 million € (for a threshold $p = 0.12$) compared to 16 million € (threshold $p = 0.06$) for the moderate climate change assumption and to 16 million € (for a threshold $p = 0.01$) without climate change. This shows that if the investment in management is high enough, the impact of climate change (induced by temperature increase) on health costs is negligible (Fig. 4.17).

4.3 Management at its best

The best strategy would be to use unconstrained budget and hence eradicate as much *Ambrosia artemisiifolia* L. population as can be found. Of course this is not feasible as in real life the budget is always limited.

In the section 4.1 ‘Without climate change’ it is discussed which management strategy, with regard to how to select the grid cells for surveillance, is the best. The simulation showed that selecting the cells from a subset in the order of their habitat suitability is superior to selecting them at random. Furthermore, there exists an optimal threshold p for dividing the cells to be managed from cells without management, where the success is highest.

Whereas in the section 4.2 ‘With climate change’ also the arising allergy and management costs are calculated. Therefore, a benefit-cost calculation is possible. For people allergic to *Ambrosia artemisiifolia* L. pollen, the optimal management strategy is of course using as much management effort units as possible. From the economic side the effort has to be compared with the gained benefit - the benefit-cost ratio. The costs here are from carrying out management and the benefit is the reduction of allergy costs. For current climate and moderate climate change there is a threshold of investing 100 management effort units beyond which no additional reduction in health costs are gained. With the more extreme climate change assumption this threshold

increases to about 125 management effort units. Therefore, the cumulative savings over the whole management period (2011-2050) amount to about 9 billion € under current climate, to about 11 billion € under moderate climate change and to about 12 billion € under the more extreme climate change future (Fig. 4.18) From the economic side of view it would be best to invest between 30 and 40 million € per year depending on the actual climatic future.

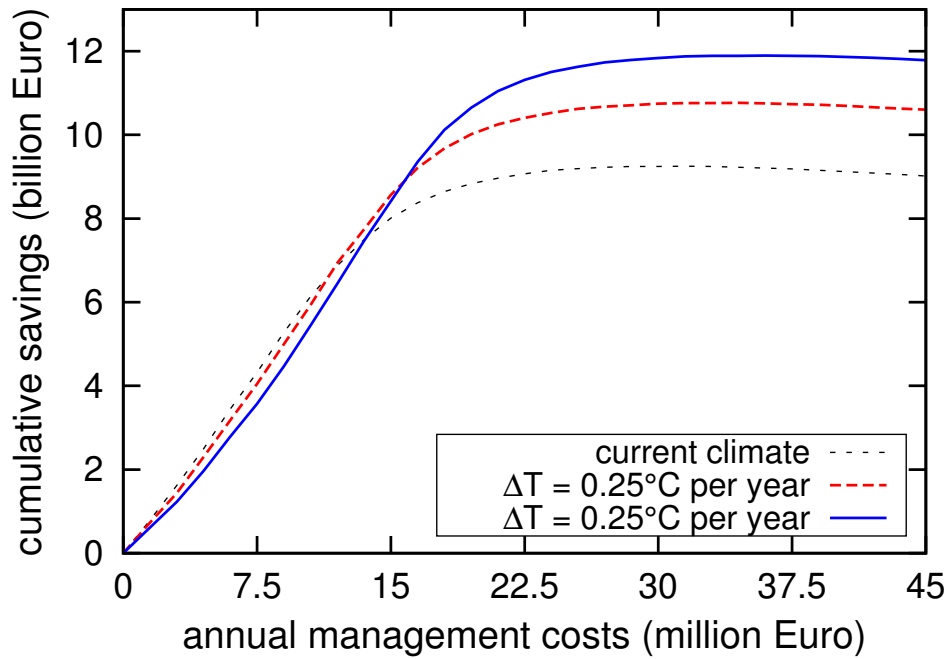


Figure 4.18: Savings accumulated over the management period from 2011 until 2050 for current climate as well as two climate change assumptions as a function of available budget.

Chapter 5

Discussion

In times of increasing trade, due to globalisation, more and more plants are introduced to new territories [Hulme et al., 2009, Essl et al., 2011a, Essl et al., 2011b], of which about 0.1% become invasive [Hulme, 2003]. To fight against such alien species, which can destabilise the ecosystems, only limited budgets are available [Epanchin-Niell and Hastings, 2010]. Usually eradication is carried out in selective areas where the problems already became severe [Hulme, 2003, Myers and Bazely, 2003], instead of large scale management. The disadvantage of such an approach is the ongoing spread in suitable areas without notice for a long time until the population size is big enough to be detected as problematic [Hulme, 2003]. It is obvious that for efficient control it is necessary to survey a wide area, irrespective if it is known to be already infested or not. It is evident that in such a global surveillance scheme the species habitat suitability should be considered [Fox et al., 2009]. Otherwise the available management budgets will be wasted in surveying areas where the chance of germination is nearly zero.

In this thesis the spread of invasive species is simulated by using grid cell sizes of 3 x 5 geographical minutes (about 35 km²). The reason for this relatively large cell size is the resolution of the distribution data of the study species (*Ambrosia artemisiifolia* L.). This is also true for many other species where in lack of finer resolutions cell sizes of 10 x 10 or 3 x 5 geographical minutes are necessary [Kühn et al., 2013]. However, compared with other studies [Skjæth et al., 2010, Bullock et al., 2012, Hamaoui-Laguel et al., 2015] the cell size here seems to be of suitable size as they use cell sizes in the same range or bigger. The cell size also has an influence on the percentage of the study area that is infested, the coarser the resolution the higher the infestation percentage [Hulme, 2003]. For a real life implementation on a smaller scale it should be possible to use smaller grid cells. Locally the environmental variables used in the model usually are known with a higher

resolution and the same is true for species presence absence data. However, the qualitative results from these simulation will not change.

This thesis shows that surveillance, particularly with regard to the species habitat suitability, makes sense when aiming for best management success. Although the way to do so is tricky and not self-evident. Here a study species (*Ambrosia artemisiifolia* L.) is used that has not reached its equilibrium, but is still spreading to suitable areas [Dullinger et al., 2009]. Therefore, it was expected that the optimizing management success under constrained budget depends on minimizing search costs including cells with quite low habitat suitabilities. The threshold p indicates below which value no cells are surveyed. The simulations suggest rather surveying the whole study area than focussing only on a few highly suitable cells. In the latter case exists the risk that the invasive alien species spreads in cells, that are not surveyed, without limit and induces higher allergy costs and less management success. With this study the long-standing discussion can be put to an end, whether control should focus on core or satellite populations [Moody and Mack, 1988, Hulme, 2003, Epanchin-Niell and Hastings, 2010] by recommending rather to manage a too large area than concentrating only on few sites. However, it is admitted that this result may lie in the special character of the habitat distribution (i.e. continuous distribution of suitable habitats) for *Ambrosia artemisiifolia* L. (Fig. 3.5) and may be different for irregular distributed suitable cells. The strong positive effect regarding management success of the fixed order sampling scheme was surprising. It can be explained with the fact that in the beginning management takes place in areas where it is most urgent, in cells with highest habitat suitabilities. After eradicating the populations in those cells, surveillance continues in cells with just a little bit lower habitat suitabilities. This is achieved by arranging the cells in decreasing order regarding habitat suitability. This procedure is carried out until a preset threshold p is reached and starts then again in the cell with the highest suitability. When it is doubtful where to set the threshold, the simulations show that it is better to select a too low threshold p than a too high one. Generally it can be said that for higher available budgets the threshold can be set drastically lower (Fig. 4.10). When doing so, this does also imply to accept the fact that, under more constrained budget, a higher percentage of grid cells are not managed and, hence, people living there are exposed to the pollen without control. The optimum threshold p is the one which leads to start surveillance just in the right time at the cell with the highest suitability to eradicate recolonized cells. The right moment is, when the percentage of recolonized cells in highly suitable cells has reached the same percentage as the infested cells in regions with lower habitat suitability. In practice, when habitat suitability is the only information available, such

a ranking regarding cells suitability is chosen intuitively [Underwood et al., 2004, Fox et al., 2009, Giljohann et al., 2011].

One may argue that the approach, using only the habitat suitability as the only determining factor for selecting cells to be surveyed, is not the best choice. Usually management will begin by eradicating known populations of the invasive alien species and then concentrate on locations near once infested sites. In reality one will of course first eradicate known infestations to maximize management success in the beginning. The simulations should be understood how to act after these early eradications. To concentrate now on the surrounding of these known infested sites seems to be wise on first sight, however, the analyses here shows that the best management success is achieved with the fixed order scheme. When concentrating on known infested sites, it can be expected that the management success is bigger in the beginning. Later it can be assumed that the success decreases because the species had the chance to spread without limits in unnoticed highly suitable areas. However, this may also lie in the fact that *Ambrosia artemisiifolia* L. is already widespread and spreads over large distances. For invasive alien species that spread only over small distances and spread with a well defined invasion front it may improve management success.

A main statement of this thesis is the prediction of allergy costs. In a first step the costs are calculated in management effort units without saying how they corresponded to real currencies. In a second step the actual costs in Euro are calculated. Of course this can be seen only as a rough estimation because (a) the costs are different in every country, (b) no professional employer dealing with such work has been contacted and (c) the kind of eradication is not specified. Also inflation during the management period was not considered.

Nevertheless the simulations indicate that management of *Ambrosia artemisiifolia* L. in Austria and Bavaria is of high success. From an economic point of view one can only begin as soon as possible with surveillance: one invested Euro in management yields in 10 saved Euros for our health system. Hence, the costs of management are clearly below the costs arising because of pollen allergies attributed to *Ambrosia artemisiifolia* L. This is the case for current climate and even more for climate change assumptions. The savings using available budget for surveillance and eradication including subsequent monitoring of once infested sites of 30 million € reduces the mean annual allergy costs by 258, 295 and 325 million € for current climate, moderate temperature increase (i.e. an annual temperature increase of 0.025 °C) and more extreme temperature increase (i.e. an annual temperature increase of 0.04 °C), respectively. Over the management period of 40 years (from 2011 until 2050) the savings amount to about 12 billion € in the case of an annual

temperature increase of 0.04°C (Fig. 4.18).

Therefore, on the example of *Ambrosia artemisiifolia* L. it is shown that management of invasive alien species has an economic benefit in addition to nature conservation. The intention of scientific studies like this is that decision makers consider the results as basis in their work. Unfortunately the fact is, that only a few people in charge of roadside mowing know about problems of *Ambrosia artemisiifolia* L. and how to deal with them [Joly et al., 2011]. To overcome this problem it is necessary to instruct people in charge on a wider basis.

A critical factor in the benefit-cost analyses is the costs arising due to persons allergic to *Ambrosia artemisiifolia* L. It is difficult to find information regarding costs in literature. Based on a calculation for the costs in Austria for the year 2005 [Jäger, 2006] the costs for Austria and Bavaria (i.e. the study area) were calculated to be 133 million € in 2005. Comparing this figure for a study area with about 21 million inhabitants with the Canadian province of Quebec (155 million CAD equal to about 110 million € for 8 million inhabitants) is in a similar range [Ngom and Gosselin, 2013]. Also the benefit-cost ratio with about 10:1 is in the same range as in other management scenarios: e.g. benefit-cost ratio of 2.3:1 to 20.7:1 for terrestrial weeds [McConnachie et al., 2003]. Other studies for different alien plants yielded as well in the statement that the benefit outweighs the costs [Currie et al., 2009, Yokomizo et al., 2011, Wise et al., 2012]. In the study region (i.e. Austria and Bavaria) *Ambrosia artemisiifolia* L. is already widespread and local eradication is quite expensive. The main reason why management anyway pays off are the high health costs due to persons allergic to the pollen of *Ambrosia artemisiifolia* L. In regions where it has (nearly) reached its saturation like in south-eastern Europe [Bullock et al., 2012] and central North America [Ziska et al., 2011, Ngom and Gosselin, 2013] the costs for management per cell will be much higher. Of course in such heavily populated areas also the health costs will be much higher and hence savings will also increase. Complete eradication may be unfeasible in such densely populated regions, but even curtailing the spread will turn to account and, therefore, will be economically justifiable.

Climate change assuming temperature increase of 0.025°C and 0.04°C per year for the moderate and more extreme assumption, respectively, as used for the simulations yields in faster spread of *Ambrosia artemisiifolia* L. Whereas under current climate at the end of the simulation period about a third of the study area will be infested without management, for the more extreme future (i.e. a temperature increase of 2.4°C from 1990 until 2050) the number of infested cells increases to more than fifty percent of the study area.

The number of persons that suffer from *Ambrosia artemisiifolia* L. pollen allergies will increase in future due to its spread as people that are sensitised with no pollen contact current will live in infested areas in future. The arising costs as have been calculated for climate change may be a lower limit of actual health costs, because with higher temperatures also the time span of pollen flight may expand [Bullock et al., 2012]. Also agricultural losses were not incorporated in the cost estimations.

The reason for carrying out benefit-cost analyses are to weigh the costs and benefits of management and non-management of alien species [Currie et al., 2009, Frid et al., 2013]. Such analyses, unavoidably, always include some simplifications and assumptions [Keller et al., 2006, Sahlin et al., 2011, Yokomizo et al., 2011]. This may also influence decision makers in planning the allocation of resources [Regan et al., 2005, Yokomizo et al., 2011]. The simulation here is no exception of these facts. For a future work some ideas for improvements are listed in the following:

(1) Cell transition from 1 to 0 (beside management), i.e. self-extinction of species within a cell was not considered. The reason is that at the moment no information is available how big such a mortality rate is, if it exists at all. The population size within a cell is neglected as well. Therefore, it was not calculated with different eradication costs for different cells. Also perfect surveillance and eradication was presumed by defining uninfested as negligible population size.

(2) Calculating allergy costs is based on a few assumptions. The exact number of persons allergic to pollen of *Ambrosia artemisiifolia* L. is unknown and even more the distribution to different cells. Of course the health costs are not the same for each person concerned, depending on the individual case the range of costs can be quite big (e.g. 24 € to 8 060 € per person and year in the case of Switzerland) [Bullock et al., 2012]. Supposedly the percentage of allergic persons may even rise with climate change due to increased pollen concentrations [Taramarcaz et al., 2005]. Though this will even increase the savings and make management more profitable. There are also studies that have shown that higher rates of CO_2 could lead to increased pollen production and, therefore, increase the number of pollen per plant [Ziello et al., 2011]. The reason is that higher concentrations of CO_2 affect plant functions and so plants grow faster, are larger and produce more pollen [Ziska and Caulfield, 2000, Wayne et al., 2002]. Even so those facts were not considered in the calculations as quantitative data are missing.

(3) Homogenous cells regarding habitat suitability were assumed. Of course this is not true for the majority of the cells as most contain unsuitable locations such as water bodies, grassland, forests and area covered by buildings. Hence, the calculated benefit may be a conservative estimate and

the actual benefit might be higher.

All in all the analyses confirm the expectations that surveillance based on the habitat suitability will improve the management success of invasive alien species. The habitat suitability was predicted by using a species distribution model (i.e. a model that describes the spread of plants based on the habitat suitability and presence absence data). Such an approach is wise when allocating resources for invasive alien species management. Naturally it depends on the accuracy of the model if it is a reasonable tool to use. A high accuracy was implicitly assumed in the simulations, because the same species distribution model was used for simulating the spread and for selecting the cells to be managed. However, it can be assumed, that species distribution models that are parametrized by using data from the native or introduced range [Kriticos et al., 2003, Dullinger et al., 2009] measure suitabilities not so accurately, either because species' spread is far from reaching equilibrium with the environmental conditions in the new range [Williamson et al., 2009], or because of niche shifts between introduced and native ranges [Broennimann et al., 2007]. Another reason is, that variables, unknown to be a driving force regarding habitat suitability, are not accounted for in the species distribution models [Guisan and Thuiller, 2005].

One may argue that the results are sugarcoated because the same distribution model is used to simulate the spread and management. It is true that the infested cells are known as predicted by the model, but this information is not used to take decisions which cells to survey next.

As mentioned above background mortality and different population sizes are not considered. The optimum threshold p received by the simulations may be changed when incorporating some of those facts [Krug et al., 2010, Regan et al., 2011]. Probably it would reduce management success when surveying marginally suitable cells if in those cells the background mortality is higher and the growth rate of the population is lower than in cells with high habitat suitability. It also is possible that the fixed order management scheme is less pronounced with imperfect *Ambrosia artemisiifolia* L. detection. However, it does not change anything on the fact, that cells with high habitat suitabilities have the highest chances to become infested if they have not been surveyed recently. Hence, it can be assumed that the result (i.e. best management success by using the fixed order sampling) will, nevertheless, hold true qualitatively.

Chapter 6

Conclusion

The number of alien species introduced to Europe is rising since decades with a certain percentage being invasive. Hence, it is necessary to introduce a management strategy to curtail them on transnational scales [Hulme et al., 2009, Essl et al., 2011a, Essl et al., 2011b]. This thesis shows that the benefit-cost ratio of management strategies can be increased by considering the habitat suitability of surveyed grid cells. The results suggest to select a threshold p below which no cells are managed. Where to set this threshold for optimum management success, depends on the management scheme and the budget available. A fixed order scheme, where cells are surveyed in order of decreasing habitat suitability, yielded better results than selecting cells to be surveyed at random. The higher the available budget, the lower the threshold p has to be chosen. Unconstrained budget, therefore, leads to a threshold $p = 0$, i.e. all cells should be surveyed. If the threshold is set too high, only cells with highest suitabilities are managed, with the result that in the beginning the success is large as the percentage of infested cells, where populations of *Ambrosia artemisiifolia* L. are eradicated, is high. What follows is that the success decreases drastically, because cells below this threshold with still high suitabilities will be infested without limits as they are not surveyed. When setting the threshold too low the management success decreases only marginally in the fixed order scheme. Therefore, it is generally better to select a threshold that is too low than a too high one when uncertain about the position of the optimal limit.

According to the simulations it can be expected that *Ambrosia artemisiifolia* L. will be spread more widely in the next decades when no action will be taken to curtail this invasive alien species. This will even be worse when implying climate change due to temperature increase. Although locally there already exist some management programmes against *Ambrosia artemisiifolia* L. [Karrer et al., 2011, StMUG, 2012], they do not consider

strategies planned by scientists. One issue is ignoring preparing benefit-cost analyses of such management schemes [Kettenring and Adams, 2011]. The reason could be missing information on negative effects of invasive species on native biodiversity or ecosystems [Hulme, 2011]. For those benefit-cost analyses it is necessary to calculate the human health costs, although this is a challenging task. One may expect that they should be easy to quantify in Central Europe as it can be assumed that the health care system in this region collects and files a lot of data. However, it is very difficult to get access to such data, because of privacy protection and no analysis exists at all. Nevertheless, different studies achieve similar results [Reinhardt et al., 2003, Jäger, 2006, Bullock et al., 2012]. Not only the health costs, but also the calculation of costs for surveillance and eradication including monitoring contain several assumptions and simplifications. Especially one has to be aware of the fact that in different countries those costs can be completely different. For further studies it is worthwhile to work closely with people in charge of management activities to gain more precise benefit-cost ratios.

Despite all these problems, qualitatively it does not change the basic conclusion that long-term management strategies pay off even for such widespread species like *Ambrosia artemisiifolia* L. The reason for the assertion is that the health costs will more likely rise rather than decrease as generally the percentage of allergies rises [Hemmer et al., 2011]. The management costs would have to increase tenfold compared to the calculation so that the costs outnumber the benefit.

Of course this result can be transferred also to other invasive alien species, although some parameters will have to be adapted to the specific kind of the plant. Applying the simulations to other invasive species can demonstrate, that the results are in a similar range and can be used to convince the public and politicians to really invest in long-term management schemes.

Chapter 7

Outlook

Finally, further steps, that would be worth considering, are presented. This shall lead to higher acceptance of this model by practitioners.

(1) For an implementation in real life, cell sizes of about 35 km² are probably too big. To be able to use smaller units, it is necessary to know the exact position of *Ambrosia artemisiifolia* L. within the grid cells. This will be possible for some presence absence data, but unfortunately, not for all. The same is true for implementing the population size of this invasive alien species. When this is known the model can be changed from a binary system (i.e. infested and uninfested) into one with values in-between.

(2) To be able to make a better benefit-cost calculation it will be necessary to get data on how many people are allergic to *Ambrosia artemisiifolia* L. and what their symptoms are and hence what the health costs are. This is a task that is feasible, but takes time. Although it has to be guaranteed that the privacy of patients stays protected.

(3) Another uncertainty is the pollen flight as today nobody can say for sure which percentage travels how far. To overcome this problem field tests can be carried out. In an area with only a limited number of *Ambrosia artemisiifolia* L. populations numerous pollen traps can be arranged in several directions and distances from the source. With additional documented wind data the traps can be evaluated. With such information it will be possible to implement a more accurate kernel for pollen flight. Of course such an experiment delivers only information regarding short distance travel.

(4) Last but not least it would be worth checking the accuracy of this model by comparing the predictions with real data. Therefore, it is necessary to survey wide areas to get newer presence absence data. When doing so, present management activities, that have been implemented in the last years, have to be considered as well.

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Curriculum Vitae

Personal data

name: Robert Richter
date of birth: 14.02.1975
place of birth: Vienna
nationality: Austria

Education

June 1993: Matura (school leaving examination)
1993 - 1999: studies of Technical Physics, Vienna University of Technology
2010 - 2014: studies of teacher accreditation for physics and mathematics, Vienna University of Technology and the University of Vienna
2010 - 2015: doctoral studies of physics, University of Vienna

Work experience

2000 - 2005: Support and Training Manager, Brother International Austria GesmbH
2006 - 2009: Development Abrasives, Tyrolit Schleifmittelwerke Swarovski K.G.
2010 - 2013: ÖAW project scientist, University of Vienna
2012 - 2013: teacher for physics and mathematics, BRG Klosterneuburg
2013 - today: teacher for physics and mathematics, GRG7