Student thesis series INES nr 444

# Projecting invasive species using remote sensing and spatial explicit models

**Astrid Zimmermann**

2018

Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Astrid Zimmermann (2018).
***Projecting invasive species using remote sensing and spatial explicit models***
***Projektion invasiver Arten mittels Fernerkundung und räumlich expliziten Modellen***
***Förutse invasiva arter med hjälp av fjärranalys och rumsliga modeller***

Master degree thesis, 30 credits in Geomatics
Department of Physical Geography and Ecosystem Science, Lund University

Level: Master of Science (MSc)

Course duration: August 2017 until January 2018

# Projecting invasive species
# using remote sensing and spatial explicit models

---


Astrid Zimmermann


Master thesis, 30 credits, in Geomatics

Supervisors:
Veiko Lehsten and David Tenenbaum
Department of Physical Geography and Ecosystem Science, Lund University

Exam committee:
Lars Eklundh and Karin Larsson
Department of Physical Geography and Ecosystem Science, Lund University

**Abstract (English)**

An evaluation of the current and previous *Rosa rugosa* growth on Kieler Ort, Germany, with the aim to predict the rose coverage in future, under consideration of environmental factors.

Kieler Ort, a rather isolated island in the southwest Baltic Sea is representing a unique environment which is protected for its landscape, nature, flora and fauna and serves as a bird sanctuary. *Rosa rugosa,* as one of the most invasive non-native plant species along northern Europe's coastline, was noted on the island and is therefore endangering the islands unique biotope.

The previous and current extent of *Rosa rugosa* was retrieved from aerial images for the years 1994, 2000, 2007 and 2016. The 2016 outcome was validated by collecting ground truth data. A *Rosa rugosa* coverage of 10.6% was identified for 2016. An analysis of elevation, aspect and wind in relation to the *Rosa rugosa* locations on Kieler Ort showed an aversion to low, near sea level elevations. A *Rosa rugosa* preference of eastern-facing slopes was observed, which corresponded to wind protect aspects on the island. The *Rosa rugosa* coverage of the 4 years had been analyzed by comparing two adjacent years (3 periods). The overall area increase of *Rosa rugosa* had been estimated to 11.5% per annum. For the future prediction a cellular automata, as spatial explicit model, has been implemented; and predicted a *Rosa rugosa* coverage on Kieler Ort of 30.3% in 2036.

*Keywords:* Physical Geography, Ecosystem Analysis, *Rosa rugosa*, invasive species, aerial images, growth rate, modeling, cellular automata.

**Abstrakt (deutsch)**

Eine Bewertung des aktuellen und früheren *Rosa rugosa* Wachstums am Standort Kieler Ort, mit dem Ziel, die Rosenbedeckung in Zukunft vorhersagen zu können unter Berücksichtigung von Umweltfaktoren.

Kieler Ort, eine eher abgelegene Insel in der südwestlichen Ostsee, repräsentiert eine einzigartige Umgebung, die für ihre Landschaft, Natur, Flora und Fauna geschützt ist und als Vogelschutzgebiet dient. *Rosa rugosa*, eine der invasivsten, nicht heimischen Pflanzenarten entlang der Küste Nordeuropas, wurde auf der Insel beobachtet und gefährdet somit das einzigartige Biotop der Inseln.

Die frühere und aktuelle Ausdehnung von *Rosa rugosa* wurde aus Luftbildern für die Jahre 1994, 2000, 2007 und 2016 ermittelt. Das Ergebnis für 2016 wurde durch eine Begehung vor Ort validiert. Für das Jahr 2016 wurde eine *Rosa rugosa* Ausdehnung von 10,6% festgestellt. Eine Analyse von Höhelagen, Aspekten und Wind in Relation zu den *Rosa rugosa* Standorten auf Kieler Ort zeigte eine Abneigung gegen niedrige Höhen, nahe dem Meeresspiegelniveaus. Eine *Rosa rugosa* Präferenz zu Osthängen wurde beobachtet, was Windgeschützen Aspekten auf der Insel entsprach. Die *Rosa rugosa* Entwicklung über den genannten Zeitraum wurde analysiert durch Vergleich zweier benachbarter Jahre (3 Perioden). Der Gesamtflächenzuwachs von Rosa rugosa wurde auf 11,5% pro Jahr geschätzt. Für die Vorhersage wurde ein zellulärer Automat als räumliches explizites Modell implementiert; und prognostizierte eine Ausdehnung der *Rosa rugosa* auf Kieler Ort von 30,3% bei 2036.

*Keywords:* Physische Geographie, Ökosystemanalyse, *Rosa rugosa*, invasive Pflanzenart, Luftbilder, Wachstumsrate, Modeling, zellulärer Automat.

**Acknowledgements**

I would like to express my sincere gratitude to my supervisors Veiko Lehsten and David Tenenbaum for their support, motivation and feedback throughout the whole process.

I am particularly thankful to Bernd Heinze, Horst Zimmermann and the "Verein Langenwerder zum Schutz der Wat- und Wasservögel e. V." for answering questions and helping me finding missing historical information, as well as welcoming me on the premises of Langenwerder and giving me the opportunity to conduct field work on Kieler Ort.

Last but not least, this thesis would not have been possible without the unconditional support from my mom and friends.

## TABLE OF CONTENT

## LIST OF ABBREVIATIONS

| | |
|---|---|
| **DEM** | Digital Elevation Model |
| **DWD** | Deutscher Wetterdienst (eng. German meteorology agency) |
| **GDR** | German Democratic Republic (former eastern Germany 1949 – 1990) |
| **KGB** | Komitet Gosudarstvennoy Bezopasnosti (eng. security agency of the Soviet Union) |
| **LaIV-MV** | Landesamt für Innere Verwaltung - Mecklenburg-Vorpommern (eng. State Agency for Internal Administration of Mecklenburg-Vorpommern) |
| **LUNG** | Landesamt für Umwelt, Naturschutz und Geologie - Mecklenburg-Vorpommern (eng. State Agency for the Environment, Nature Conservation and Geology of Mecklenburg-Vorpommern) |

## LIST OF TABLES

## LIST OF FIGURES

# 1 INTRODUCTION

Since the beginnings of exploring the world, voyagers have brought items of all kind home. Plants were one of them, as they fulfill different purposes, like food, medicine and/or decoration. Through that way many plants were distributed around the world and some adjusted and eventually naturalized in their new environment. A few of those so called "non-native" species even showed a stronger growth compared to native plants, which can be related to a higher robustness against different environmental factors, like salt, drought or temperature (Bruun 2005); but also by taking away needed resources like light, water or pollinators (Kellner et al. 2012) from native species. Furthermore, through hybridization of related native and non-native plants, more sturdy hybrids are created; provoking endangerment and extinction of native species (Kellner et al. 2012). Plant species that have such a drastic effect on native plants are called "invasive species" and on a higher scale also threaten local environments and native biodiversity (Isermann 2008).

*Rosa rugosa* was named one of the most invasive non-native species along the coastlines of northern Europe and North America - endangering the biodiversity of natural dune vegetation (Bruun 2005; Jørgensen and Kollmann 2009; Kellner et al. 2012; Kelager et al. 2013) due to its high dispersal and reproduction potential (clonal and seed spread) (Bruun 2005; Kelager et al. 2013). *Rosa rugosa* was possibly introduced for medicine (Bruun 2005) but it evolved to be used as ornamental in gardens, parks or as hedgerow (Kollmann et al. 2009). In the last one-two decades *Rosa rugosa* was studied intensely to understand the possibilities to manage and/or get control over this plant. Studies focusing on the spatial growth in northern Europe were performed in the United Kingdom (Boardman and Smith 2016) and Denmark (Frederiksen et al. 2006; Kollmann et al. 2006; Jørgensen and Kollmann 2009; Kollmann et al. 2009). Additionally, a large inventory was carried out in the archipelago of south-west Finland (Kunttu and Kunttu 2017).

This study focuses on the German island of Kieler Ort in the southwest Baltic Sea. Kieler Ort as a highly protected area for birds and nature (LUNG 2015a; LUNG 2015b) for decades, with barely any human interaction (Feiler and Feiler 2004) in the last 25 years or more, presents a unique environment that needs to be preserved.

*Rosa rugosa* was noticed to be present and expanding on the island. It also was noticed by bird wardens that certain birds (especially the greenfinch) favor their fruits, which can cause a higher seed spread. Therefore an analysis on the plants expansion rate (clonal and seed) will be performed for the specific environment of Kieler Ort to investigate the following questions (Q):

- Q1: Do wind and topography have an influence on the preferred establishment locations of *Rosa rugosa*?
- Q2: What is the average growth rate of *Rosa rugosa* on Kieler Ort and how will the population of this plant look in 10 and 20 years?
- Q3: Is the growth rate on Kieler Ort comparable to that found in studies in other European coastal regions?

All related studies investigated the extent of *Rosa rugosa* over a specific period of time and used the retrieved values to calculate the growth rate. With the computed average growth rate they made assumptions on the future extent of *Rosa rugosa*. Their approach for future estimation of the *Rosa rugosa* extent did only partially take into account the merging of shrubs or the limitation of space and neglected environmental influences like topography. For this reason this study followed two approaches: First, a non-spatial modeling approach to compare growth rates with previous studies and, second, a spatial modeling approach to take space and environmental limitations into account. For the spatial model a cellular automata was chosen.

The study was approached in 3 steps: First, the extent of *Rosa rugosa* on the island of Kieler Ort was identified for several years, followed by a small analysis on environmental factors that could have an influence on the location of *Rosa rugosa*, and last these outcomes were used to produce an estimate of the *Rosa rugosa* growth per year and possible future placements.

The influences of erosion were excluded from this study, because they can result in a large uncertainty which cannot be properly bounded without extensive work that is beyond the scope of this study.

# 2 BACKGROUND

## 2.1 Study species

The *Rosa rugosa* is a rose shrub also known as potato rose, beach rose, “Kartoffel-Rose” (in German) or “Vresros” (in Swedish). The origin of *Rosa rugosa* was traced back to northern Japan, the Korean Peninsula, north-east China and the far east of Russia. Its introduction to Europe occurred through several routes in the 19$^{th}$ century, and since the beginning of the 20$^{th}$ century the plant has naturalized, especially in coastal regions along the northern and Baltic Sea (Bruun 2005).

The presence of *Rosa rugosa* is often related to human interaction; e.g. being planted as hedgerows, to stabilize dunes or for other landscaping reasons (Weidema 2006; Isermann 2008). This rose shrub can get up to 2 meters high and is expanding by clonal and seed spread; hence it appears as a single plant as well as in colonies. The most important contributors to seed disposal were identified to be seawater currents and birds (Bruun 2005; Weidema 2006). The flower of *Rosa rugosa* can measure between 6-9cm in diameter and its color varies from a purplish-pink to white. The fruit (hip) is bright red when ripe (see Figure 1) and has a globe like form, measuring 1.5-2cm in length and 2-2.5cm in width. The stem is usually densely covered with thin prickles. The rose shrub was noted to have a turnover rate of 5 years in sand dunes in Japan, but individuals maybe become older. Additionally, *Rosa rugosa* is known for its resistance towards salt, drought, heat and frost; but it does not handle flooding or waterlogged soils well. Due to its high reproduction potential, the plant is withdrawing resources (e.g. light) from surrounding species and is now considered an invasive species (Bruun 2005; Nehring et al. 2013) especially in coastal regions.

*Figure 1: photo of the fruit and flower of Rosa rugosa. The image was taken on the 5.9.2017 on Langenwerder (neighboring island of Kieler Ort) by A. Zimmermann.*

## 2.2 *Rosa rugosa* in northern Europe (previous studies)

*Rosa rugosa* was studied worldwide from several different perspectives (e.g. history, DNA, spatial extent). The most relevant studies for this project, were the ones investigating the extent and growing rate of *Rosa rugosa* shrubs along coastal regions in northern Europe, namely in north-west Denmark (Jørgensen and Kollmann 2009; Kollmann et al. 2009) and in north-west England (Boardman and Smith 2016).

The most intensive study of this plant was performed in a near-natural dune system in northwestern Jutland, Denmark by a research group from Copenhagen and Lund. They investigated the correlation of *Rosa rugosa* seedling emergence in disturbed and undisturbed dune systems with habitat and microclimatic characteristics (Kollmann et al. 2006), and the correlation of *Rosa rugosa* patch distribution and size to the proximity of the coastline and human structures, like roads or houses (Jørgensen and Kollmann 2009), as well as the correlation to temperature and precipitation. A calculation of the annual spread and new establishment rate were done to reconstruct the start of invasion and for future predictions (Kollmann et al. 2009). An intensive field campaign was performed between 2003 and 2007, measuring slope and aspect (by clinometer and compass), relative elevation, heat, wind, soil samples, perimeters and location of shrubs (by GPS) as well as a 15 month field experiment by sowing seeds in different dune habitats to estimate the probability of seedling emergence and survival. Additionally, aerial images (1986-2006) and spatial data on human structures (e.g. roads and houses) were included.

The comparison of *Rosa rugosa* emergence and survival in disturbed and undisturbed soils was investigated for the following five dune types: white dune, empetrum dune, grey dune, outer and inner dune heath. This work has shown an establishment probability of 1% or less in grey dunes and undisturbed white dunes after 15 months. The highest probability was found in disturbed outer dune heath (13%). Overall the encountered seedling emergence and survival was higher in disturbed than in undisturbed soil, possibly due to a higher availability of light, water and nutrients. Other soil dependent correlations were found to a high soil moisture value, a high potassium concentration, and a low percentage of bare soil. This sub-study had also encountered a weak but positive correlation between emergence and undisturbed wind facing slopes and that seedlings in low-lying plots had the highest survival rate (Kollmann et al. 2006).

The investigation of a relationship between *Rosa rugosa* and coastline showed that 75% of all patches were within a distance of 257m to the coastline; 50% of all patches were within a distance range of 142m to 257m. The Presence of *Rosa rugosa* was also positively correlated to human structures like roads, tracks and houses, possibly due to a higher nutrient level and disturbed soils. The patch size showed no correlation to the proximity of coastline and human structures (Jørgensen and Kollmann 2009).

The annual lateral clonal spread rate was estimated with three methods, namely GPS measurements from two years, digitizing shrubs from aerial images and digging up shrubs. All methods came to the similar result of 0.42m year$^{-1}$ lateral spread rate. No correlation between lateral spread and patch size was found, therefore smaller patches had a higher relative annual patch size increase than larger patches (2004-2006: patches <100m$^2$ = 19.6% year$^{-1}$; patches >500m$^2$ = 5.0% year$^{-1}$). The average increase in patch size over all years investigated and patch sizes was 16.4 ± 2.1% year$^{-1}$. The large error was mainly due to difficulties in digitizing the exact perimeter, which had a more significant effect on smaller patches. No correlation was found between lateral clonal spread and distance to coastlines or human structures, or to climate variables like average monthly temperature during growing season and minimum temperature during winter, or precipitation. The *Rosa rugosa* invasion was traced back to around 1949-1954, with negative buffers from existing shrubs and the calculated lateral spread rate. Future establishments were predicted by using the previously estimated number of *Rosa rugosa* shrubs from 1949 to 2004, fitting an exponential regression curve and extrapolating it; resulting in nearly 27000 new patches by 2034. To estimate the location of new shrubs, the nearest neighbor distance of existing patches was analyzed, showing that the maximum distance between patches was 190m and 94% of the patches were within a 50m range of one another. The frequency distribution of 7 predefined distance lags was used to distribute the new *Rosa rugosa* shrubs. In 2004 (reference year of their study) 0.33% of the study side were covered with *Rosa rugosa*, according to their prediction 9.51% will be covered in 2034 (Kollmann et al. 2009).

A smaller study was conducted at the Birkdale Sandhills Local Nature Reserve in northwestern England, UK. *Rosa rugosa* shrub perimeter measurements of fourteen patches were sampled in 2013 by GPS, and from aerial images of the years 1989, 1993, 1997, 2000, 2005 and 2010. Only eight of the shrub measurements were used for the analysis. They measured an average increase in patch size of 22% year$^{-1}$. The growth rate was used to estimate the start of the invasion to 1970, supporting the estimates from a previous study in this area. The largest distance between *Rosa rugosa* patches found was 153m, but 93% had less than 50m distance to their nearest neighbor (Boardman and Smith 2016).

## 2.3 Cellular Automata

The Cellular Automata is a dynamic, spatial explicit modeling and simulation technique, which allows us to describe complex processes through simple rules. According to Wolfram (2002) a Cellular Automata can be applied in many sciences, e.g. mathematics, physics, biology, social science, computer science, philosophy. The most famous Cellular Automata was named the “Game of Life” by J. H. Conway (Balzter et al. 1998).

A Cellular Automata is defined by a discrete space, time and state set. A discrete space is usually described in a one- to multi-dimensional array of often rectangular cells, where each cell has a relation to its neighbors - in geography a spatial relationship is often represented. Each cell in this discrete space has a discrete state out of a predefined state set, e.g. dead or alive (0 or 1 respectively). The State of each cell can be changed in a predefined discrete time-step, depending on its neighbors and predefined transition rules (also called transition functions) (Balzter et al. 1998; Adamatzky 2009). The neighbors of a cell, or a cell’s neighborhood, can be of any size, form or content. The most common forms of a 2-dimentional neighborhood are the rectangular form, also known as Moore Neighborhood (see Figure 2a, b), and the cross- or diamond-shape form, also called von Neumann Neighborhood (see Figure 2c-e). Usually a defined neighborhood contains weights (e.g. probabilities), which when applied on a cell and its neighbors, are used to compute (together with the transition rule) the new state of the cell (Balzter et al. 1998).

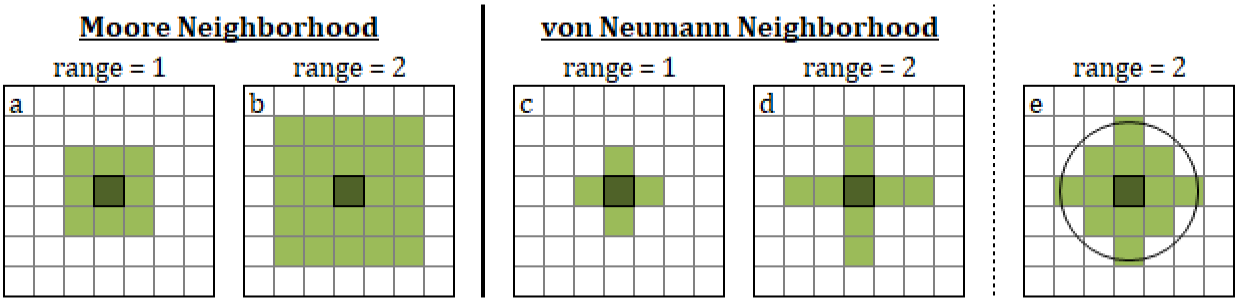
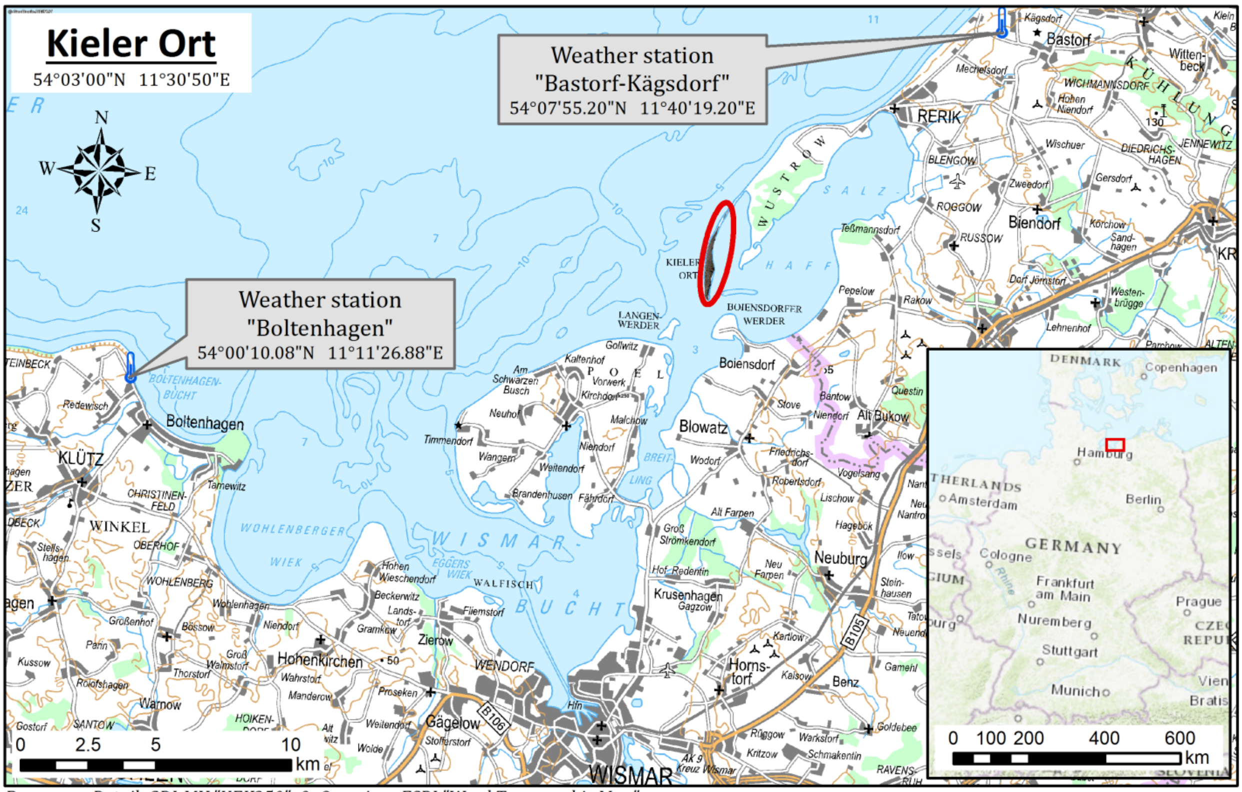



*Figure 2: The most common 2-dimentional neighborhoods for the Cellular Automata: "Moore Neighborhood" and "von Neumann Neighborhood". In the image the center cell, or cell of interest, is shown in dark green, whereas the neighborhood is represented in a lighter green. Each neighborhood type is shown for the range (/size) of one and two cells. The definition of the von Neumann Neighborhood of range 2 and larger varies in literature between figure (d) and (e). Some call (e) a circular or diamond shaped neighborhood, which again vary at larger ranges* (Dutta et al. 2015; Weisstein 2018a; Weisstein 2018b).

## 3 METHOD

### 3.1 Study area

Kieler Ort (54°03'00"N 11°30'50"E - Figure 3) is a German island in the Baltic Sea and used to be connected with the Wustrow peninsula by a thin land bridge in the north of the island. Parts of the bridge were destroyed in the 1980's (estimation from personal observation by H. Zimmermann from March 1991) and another part broke between 2010 and 2012 (estimated by aerial images), creating a small island between Kieler Ort and Wustrow. According to the 2016 aerial image, the main island was 2830m long and 364m wide; measuring an area of 56.5ha.




*Basemaps: Detail: GDI-MV "UEK250" & Overview: ESRI "Word Topographic Map".*
*Reference Coordinate System: ETRS 1989 UTM Zone 33N zE-N | Map created by A. Zimmermann - Sep. 2017*

*Figure 3: Overview map showing the location of "Kieler Ort" in the Baltic Sea (red ellipsoid) as well as the two closest DWD (Deutscher Wetterdienst) weather stations – Boltenhagen (distance: ~22km) and Bastorf-Kägsdorf (distance: ~13.7km).*

The Wustrow peninsula (together with Kieler Ort), once a country estate, became Germany's largest military training base in 1933. After the Second World War, it was used by Soviet military and KGB, who burned down Kieler Ort and the southern part of Wustrow annually till the 1970's, to ensure that no forest would be established. The Russians abandoned the base in 1993, after the GDR (German Democratic Republic) territory was reunited with West Germany (Jeschke et al. 2003; Feiler and Feiler 2004). Since 1990 Kieler Ort has become part of several preservation projects (Jeschke et al. 2003) including: Natura 2000 (LUNG 2015a), Landschaftsschutzgebiet „Salzhaff" (L85 – Eng. landscape conservation area), Naturschutzgebiet "Wustrow" (N141 – Eng. nature conservation area)(LUNG 2015b), Flora-Fauna-Habitat-Gebiet „Wismarbucht" (DE 1934-302 – Eng. flora-fauna habitat area) and Europäisches Vogelschutzgebiet "Wismarbucht & Salzhaff" (DE 1935-401 – Eng. European bird sanctuary)(LUNG 2015a).

The biotope of Kieler Ort has its origin in alluvial sediments from the cliffs of Wustrow and is prone to changes due to erosion (Jeschke et al. 2003). Kieler Ort was described to have barrier beaches all around and formation of white dunes along the Baltic Sea coastline, which turn into grey and brown dunes towards the inland; as well as large areas of wet peat, dry to wet-dry sands and gravel towards the eastern coast (LUNG 1996; Feiler and Feiler 2004). In the south-east of Kieler Ort small lakes enrich the biotope (Jeschke et al. 2003). Kieler Ort is rich in vegetation, the most common plants according to a biotope mapping from 1996 were: *Carex arenaria*, *Phragmites australis*, *Ammophila arenaria*, *Artemisia maritima*, *Aster tripolium*, *Cakile maritima*, *Corynephorus canescens*, *Galium mollugo*, *Hippophaë rhamnoides*, *Polytrichum piliferum, Sedum acre* and *Rosa rugosa* (LUNG 1996).

Due to its history and the conservation projects, the island is un-inhabited and has a year round embargo for entering or landing (Jeschke et al. 2003).

## 3.2 Part 1: Evolution of *Rosa rugosa* on Kieler Ort

### 3.2.1 Data

Several historical aerial and ortho photographs were made available by the Landesamt für Innere Verwaltung Mecklenburg-Vorpommern (LaIV-MV).

The photographs used in this study were from the years: 1994, 2000, 2007, 2010, 2012 and 2016. The years 1994 and 2000 were non-georeferenced panchromatic images, whereas 2007 and later were digitally taken orthorectified images with three or four bands: red, green, blue and sometimes near-infrared. All photos were provided as TIF-files and the orthorectified images had a resolution of 0.2x0.2m.

### 3.2.2 Georeferencing

The panchromatic aerial images of 1994 and 2000 were georeferenced (see Table 1) in ArcMap 10.5. The 2007 image was used as reference image for georeferencing, because it was the oldest available orthorectified image available. The 2$^{nd}$ order polynomial transformation was used to correct for systematic errors and to ensure well-fitting perimeters (Kollmann et al. 2009), as well as the bilinear interpolation resampling technique. An orthorectification was not done, because of the rather flat surface of the island; the highest elevation is 3.6 meters.

*Table 1: Georeferencing parameters of analog taken aerial images (provided by Landesamt für Innere Verwaltung Mecklenburg-Vorpommern) for 1994 and 2000. All images were georeferenced using the oldest available ortho image - 2007. The photographs were transformed with 2$^{nd}$ Order Polynomial and resampled by Bilinear Interpolation (BI) to "ETRS 1989 UTM Zone 33N zE-N".*

| Year | File name | transformation | No. of Points | RMSE | Final resolution |
|---|---|---|---|---|---|
| **1994** | 94_01_49Z_0127_N_32_72_C.tif | 2$^{nd}$ Order Polynomial (BI) | 31 | 0.178 | 0.38 |
| | 94_01_50A_0127_N_32_72_C.tif | 2$^{nd}$ Order Polynomial (BI) | 18 | 0.191 | 0.35 |
| **2000** | 00_02_13_0210_N_32_72_C.tif | 2$^{nd}$ Order Polynomial (BI) | 16 | 0.167 | 0.57 |
| | 00_02_14_0108_N_32_72_C.tif | 2$^{nd}$ Order Polynomial (BI) | 32 | 0.206 | 0.44 |

### 3.2.3 Extent retrieval of *Rosa rugosa* and Kieler Ort / Digitizing

*Rosa rugosa* and the island extent were extracted from the aerial images of 1994, 2000, 2007 and 2016 by digitizing.

Classification was originally intended to be used for extracting size and location of *Rosa rugosa* patches, but no classification strategy resulted in an acceptable result. Different combinations of image enhancement and classification techniques were tried in ArcMap 10.5: masking out the island to reduce area that needed to be classified, image enhancements – like low-pass filter – on each band to highlight differences or segmentation to combine similar spectral signatures, as well as including topographical layers like DEM or aspect. Each of those enhancements and/or a combination of those were used on unsupervised and different supervised classifications (e.g. Maximum Likelihood & ISO classification). It was not possible to extract the perimeter of the roses, due to similar spectral references between vegetation and partially lacking image quality.

Since classification did not produce an acceptable result, the digitizing approach was chosen. Here each visible shrub on the aerial images was digitized to a polygon (one file per year) in ArcMap 10.5. For better identification of shrubs, an enhancement in brightness and contrast was done on the images.

Additionally, the outline of the island was digitized for each year. It had to be assumed that the aerial images were taken at different tidal height over the years, therefore island erosion lines or algae on the beach were used as indicators for highest water level, to map the island perimeter.

### 3.2.4 Field work

Field work was conducted on the 3rd of November 2017 on the Island of Kieler Ort, where all digitized shrubs of 2016 were checked, to separate *Rosa rugosa* from others shrubs. For this task, maps containing the 2016 orthorectified image overlaid by the digitized shrubs were prepared. Each map was printed on A3 format paper and represented one third of the island. The maps were equipped with a one arc second spaced grid for GPS navigation.

In the field, navigation and positioning were performed by using the GPS function on a modern mobile phone and orientation by map (possible due to very detailed map and small island). Shrubs that were falsely identified as *Rosa rugosa* in the digitizing process were marked on the maps. In total, 427 out of 2434 shrubs were miss-classified as *Rosa rugosa* in 2016. The majority of miss-classified shrubs were small shrubs of the following species: *Rosa canina* (Figure 4a), *Genista*, *Salix* and one pine tree. During this field work it was noted that in some locations *Rosa rugosa* appeared in mixed vegetation, as shown in Figure 4b. Additionally, a wild pig and its droppings full of seeds (Figure 4c), prints of roe deer and many opened up fruits with missing seeds (Figure 4d), possibly by birds, were seen by me and my colleagues. The thickest *Rosa rugosa* trunk found was cut out and taken home for age dating.


*Figure 4: photos of field work findings: a) fruits of Rosa canina, b) mixed vegetation incl. Rosa rugosa, c) wild pig droppings with seed and d) opened up Rosa rugosa fruits without seeds. Images were taken on the 3.11.2017 on Kieler Ort by A. Zimmermann (a), E. Lehsten (b+c) and V. Lehsten (d).*

After the field trip, the marked non-*Rosa rugosa* shrubs were removed from the digitized file of 2016. The location of non-*Rosa rugosa* shrubs were also compared to the other digitized images of 1994, 2000 and 2007; and in case of a match, were removed from them as well. The assumption here was that it is more likely that these shrubs were of the same plant species before than they were a *Rosa rugosa*.

## 3.3 Part 2: Environmental factors

### 3.3.1 Data

The wind direction and wind speed data were collected for the two weather stations nearest to Kieler Ort, namely Boltenhagen and Bastort-Käsdorf (see Figure 3), from WESTE-XL - a service provided by the Deutscher Wetterdienst (German meteorology agency); for the period 2000-2016.

The elevation data was made available by the Landesamt für Innere Verwaltung Mecklenburg-Vorpommern (LaIV-MV). It was collected in 2007 with an airborne laser scanner and made available in an ACSCII-file with a 5x5m resolution.

For the comparison of topography and *Rosa rugosa* locations, the digitized output of 2007 from "Part 1: Evolution of *Rosa rugosa* on Kieler Ort" was used. Both datasets were sampled in the same year; therefore no error due to changes on the island had to be considered.

### 3.3.2 Wind

Kieler Ort is located between two weather stations as shown in Figure 3. Since one station is closer than the other, a distance weighted average of wind direction and wind speed was calculated and analyzed in Excel.

At first the mean distance between the weather stations and the island was assessed by measuring the shortest distance (to the nearest point on the island) and longest distance (the furthest point on the island). This resulted in a mean distance of 13.7 kilometers from Bastorf-Kägsdorf (BK) and 22 kilometers from Boltenhagen (B). The mean distances were used to calculate the distance weights with equation (1); resulting in ~0.62 and ~0.38 respectively.

$$weight = 1 - \left(\frac{distance}{(distance_{BK} + distance_{B})}\right) \tag{1}$$

The distance weights were used to determine the distance-weighted average (DWA) of wind direction and wind speed for each hour in the selected time frame. First the absolute differences for wind direction and wind speed between the two stations for each time step were calculated and stored. The values of wind speed or wind direction, the absolute difference and distance weights were used in equation 2 to calculate the distance weighted average per time step for wind speed and wind direction, if the wind directions were not opposite to each other (difference = 180°).

$$DWA = Value_L - (|difference| \times weight_S) \tag{2}$$

*Where:* $Value_L \rightarrow$ *wind speed or direction value from the station with the larger value*
$weight_S \rightarrow$ *distance weight from the station with the smaller wind speed or direction value*

The absolute difference and distance weighted average calculation for wind direction also included a logic (see Appendix A) to ensure the smaller direction angle was used as well as a DWA between 0 and 360 degrees was computed at the end.

Finally, the wind direction was assessed in percentage by occurrence per main and secondary wind direction and the wind speed was given as an average per wind direction.

### 3.3.3 Topography

The received ASCII file was imported into ArcMap 10.5, converted to spatial point data and then into a 5m resolution raster using the "Feature to Raster" tool, to ensure no change of height values. The produced DEM included parts of the Wustrow peninsula and the island surrounding water. The digitized island outline from 2007 was used as a mask to retrieve the DEM for Kieler Ort. To ensure no cells covering the island were deleted the 2007 image was given a 5m (= DEM cell size) buffer extension. From the final DEM the aspect was calculated.

A point raster of the extent of Kieler Ort was created containing information of "Rose" or "no Rose" per point. Additionally, elevation and aspect data were extracted per point and saved in the point's attribute table. A 20cm resolution for the point raster was chosen, to follow the lowest aerial image resolution (20cm) used for digitizing the island and rose shrubs. The attribute table was exported and analyzed in R.

From a statistical perspective *Rosa rugosa* (RR) on Kieler Ort (KO) is representing presence-absence-data. Therefore a comparison of histograms for *Rosa rugosa* and Kieler Ort on elevation and aspect was performed. Additionally, the aspect data of both samples was tested for significant difference with the "Wilcoxon rank sum test" (also known as u-test). The Wilcoxon test was chosen because both samples showed no normal distribution according to the "Anderson-Darling normality test" (p-value <$2.2^{-16}$, $A_{KO\_cos}$ = 61079.3, $A_{KO\_sin}$ = 1279398, $A_{RR\_cos}$ = 3038.393, $A_{RR\_sin}$ = 73522.33). For both tests the aspect value had to be converted to radians to perform a cosines and sines transformation, to linearize the circular values. According to the histogram comparison, suitability probability for aspect and elevation were selected.

## 3.4 Part 3: Average growing rate and prediction of *Rosa rugosa* on Kieler Ort

### 3.4.1 Data

The digitized results of *Rosa rugosa* and Kieler Ort for the years of 1994, 2000, 2007 and 2016 from "Part 1: Evolution of *Rosa rugosa* on Kieler Ort" were used for a deeper analysis, the retrieval of growth rates and modeling. For the spatial model all datasets were converted to "tif"-raster files, with a cell resolution of 10cm. The cell resolution was selected as half of the smallest cell resolution of the aerial images used for digitizing, to prevent adding an additional error to the roses or islands circumference. The changes (form and area) of the northern part of the island over the studied 20 years, and its effect on the *Rosa rugosa* population in this location, would cause a large error to the estimation of the growth rate. Therefore the northern tip of Kieler Ort and its digitized roses were removed (see "Cut-Off Line" in Figure 7 and figure adaptation in Appendix D).

The results from "Part 2: Environmental factors" were used to create aspect and elevation suitability maps for the spatial model. The suitability maps were produced to be in the same file-format with the same spatial and cell resolution (10cm) as the *Rosa rugosa* and Kieler Ort datasets. The aspect related suitability map was created using the density of *Rosa rugosa* placements (/cells) per aspect class (see Figure 9). Wind properties can explain large parts of the preferable slope aspect of *Rosa rugosa*, but due to the encountered uncertainties in Part 2, it was concluded that the density of *Rosa rugosa* placements describe its preferences best (p-value <$2.2^{-16}$, $W_{cos}$ = $4.280122^{+12}$, $W_{sin}$ = $3.151611^{+12}$). The elevation suitability map was based on the 3 identified classes in Part 2: not suitable, medium suitable and suitable. The class breaks were set to 27cm and 57cm (according to analysis of Part 2) and *Rosa rugosa* density per class was used as probability – 0%, 2% and 98% respectively (see Appendix C).

### 3.4.2 Analysis of *Rosa rugosa* evolution on Kieler Ort

The digitized *Rosa rugosa* layers were used to define the rose state at start and end of a period, resulting in three periods that were analyzed; Period 1: 1994 – 2000, period 2: 2000 – 2007, and period 3: 2007 – 2016. The start and end of each period were "overlaid" in ArcMap 10.5 to retrieve shrub changes. The attribute table of the comparison file was enriched with the size of each shrub part and a change indicator: stating if the shrub part disappeared, stayed or is new.

An investigation of all three periods showed the following different cases of change (conceptual overview in Figure 5): The simplest cases found were the eradication (a), new establishment (b) and pure expansion (c) of a shrub. But other cases like a sort of partial die-off (d) of the shrub over time, meaning parts of the shrub died on one side and expanded on the other side; or the merging (e) of several shrubs due to expansion have been identified. The most complex case found, is a special case of partial die-off (d), where two shrubs with partial die-off and expansion of close proximity are overlapping (f). This case had to be examined as one shrub, because it was not possible to separate the single shrubs with the existing data, but it can also be assumed that both original and final shrubs are so close neighbors, that it can be considered very likely that both influence each other.

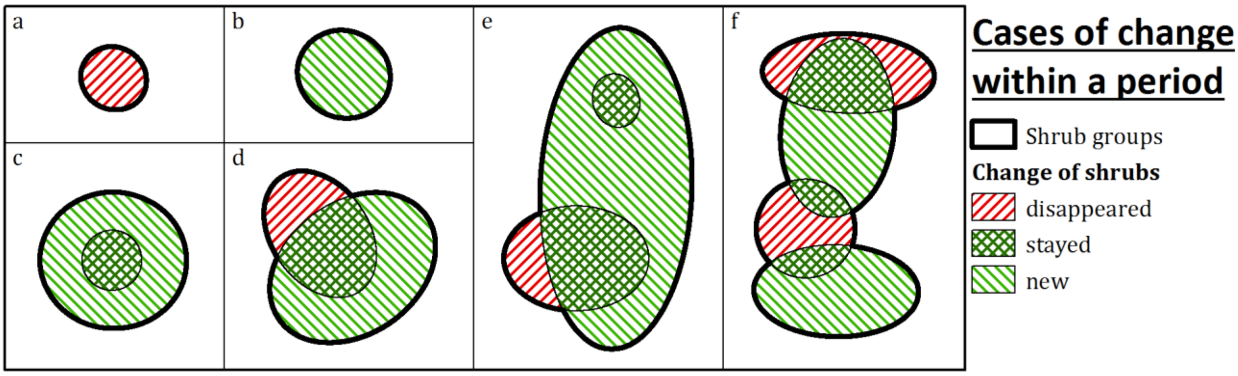



*Figure 5: Identified cases of shrub change on Kieler Ort: a) shrub disappeared/eradicated; b) new shrub establishment; c) expansion of a shrub; d) partial die-off of a shrub (parts have died and others have expanded); e) merging of shrubs due to expansion (with or without shrub die-offs); and f) wandering of close by shrubs, that make it impossible to separate.*

To be able to analyze the development of existing shrubs (Figure 5c-f) as well as to be able to separate them from eradicated (Figure 5a) and new shrubs (Figure 5b), the shrub parts had to be spatially connected to so called shrub groups (thick outline in Figure 5). A shrub group in our case is an imaginary shrub representing one or more shrubs over time. This was done by merging all spatially connected polygons to one polygon in ArcMap ("dissolve") and spatially joining the result back to the shrub parts - therefore giving each shrub part the unique ID of the shrub group.

The final attribute table of each shrub part file/investigated period was imported to Excel and summarized to shrub group level – containing information on total area of stayed (no change), new and died roses per shrub group. This was again summarized; creating an overview per period on total area stayed, shrub expansion, shrub die-off, new shrub establishment and shrub eradication (see Appendix E).

### 3.4.3 Non-spatial model

The total area values per period, retrieved in the previous step, were used to calculate the change rates. It was assumed that the shrub eradication and die-off (Figure 5a and d, respectively) have the same underlying process of parts dying possibly year by year, either connected to the turnover rate of 5 years (Bruun 2005) or due to low suitability. In case of shrub eradication, it was assumed that there was not enough expansion to prevent the whole shrub from dying.

The annual survival rate was calculated with equation (3). The survival rate is the inverse of the die-off rate and was based on the growth factor. The total area of *Rosa rugosa* coverage at the start ($A(t_0)$) and the total area that had stayed ($A_S(t_n)$) over the investigated period were used as input.

$$survival\ rate\colon\ r_S = \left(\frac{A_S(t_n)}{A(t_0)}\right)^{\frac{1}{(t_n - t_0)}} \qquad (3)$$

*Where:* $A(t_0) \rightarrow$ *Area of Rosa rugosa at the start of the period investigated*
$A_S(t_n) \rightarrow$ *Area of Rosa rugosa that had survived (stayed) by the end of the period investigated*
$(t_n - t_0) \rightarrow$ *number of years investigated per period*

The annual expansion rate was calculated with equation (4) and was based on the growth rate. The expansion rate formula follows the assumption that roses that are about to die, will not contribute to the expansion. The total area that had survived ($A_S(t_n)$) and the total area that had expanded ($A_E(t_n)$) over the investigated period were used as input.

$$expansion\ rate:\ r_E = \left(\frac{A_S(t_n) + A_E(t_n)}{A_S(t_n)}\right)^{\frac{1}{(t_n - t_0)}} - 1 \tag{4}$$

*Where:* $A_E(t_n) \rightarrow$ *Area of Rosa rugosa that had expanded by the end of the period investigated*

The annual new establishment rate was calculated with equation (5) and was based on the growth rate. The new establishment rate follows the same assumption as the expansion rate and takes into account that the identified new establishments are a combination of new establishment and expansion. The total area that had survived ($A_S(t_n)$), the total area that had expanded ($A_E(t_n)$) and the total area of new establishments ($A_N(t_n)$) over the investigated period were used as input. The sum of $A_S(t_n)$, $A_E(t_n)$ and $A_N(t_n)$ is equal to the area of *Rosa rugosa* coverage at the end of the investigated period, which could be used instead.

$$new\ establishment\ rate:\ r_N = \left(\frac{A_S(t_n) + A_E(t_n) + A_N(t_n)}{A_S(t_n)}\right)^{\frac{1}{(t_n - t_0)}} - 1 - r_E \tag{5}$$

*Where:* $A_N(t_n) \rightarrow$ *Area of Rosa rugosa that had expanded by the end of the period investigated*

Furthermore, the lateral expansion (equation 6) and die-off (equation 7) rates had been calculated per shrub group and investigated period; and averaged afterwards. Both rates were based on the area of a circle formula.

$$lateral\ expansion\ rate:\ r_{lE} = \frac{\left(\frac{A_S(t_n)+A_E(t_n)}{\pi}\right)^{\frac{1}{2}} - \left(\frac{A_S(t_n)}{\pi}\right)^{\frac{1}{2}}}{(t_n - t_0)} \quad (for\ A_E(t_n) > 0) \tag{6}$$

$$lateral\ die\text{-}off\ rate:\ r_{lD} = \frac{\left(\frac{A_S(t_n)}{\pi}\right)^{\frac{1}{2}} - \left(\frac{A_S(t_n)+A_D(t_n)}{\pi}\right)^{\frac{1}{2}}}{(t_n - t_0)} \quad (for\ A_D(t_n) > 0) \tag{7}$$

*Where:* $A_D(t_n) \rightarrow$ *Area of Rosa rugosa that had died by the end of the period investigated*

The future prediction of *Rosa rugosa* on Kieler Ort was based on the survival, expansion and new establishment rate (equation 3-5). First an average of each rate was calculated over periods 1 and 2 (1994-2007) and over periods 1, 2 and 3 (1994-2016). Equation 8 was developed to calculate the area of *Rosa rugosa* covering the island of Kieler Ort. The formula was based on equations 3-5 and that the sum of the area of survived, expanded and new establishments equals the new total area of *Rosa rugosa* coverage.

$$Area\ of\ Rosa\ rugosa:\ A(t_n) = A(t_0) \times \left(r_S \times (1 + r_E + r_N)\right)^{(t_n - t_0)} \tag{8}$$

*Where:* $A(t_n) \rightarrow$ *Area of Rosa rugosa at the end of a selected period*

### 3.4.4 Spatial model

The spatial model was implemented as Cellular Automata in Matlab. Input data were the Boolean presence-absence rasters for *Rosa rugosa* and Kieler Ort at the start of the period to be investigated; the two suitability maps for elevation and aspect; and the information of how many years shall be investigated. Because erosion or similar changes were not taken into account in this study, the island outline of the starting year was considered static and therefore used as spatial limitation for *Rosa rugosa* growth over all years investigated.

The main set-up for this Cellular Automata was:

- The discrete space was defined by the island raster (1 = island; 0 = no island),
- The state set (to be changed by the transition rules) was defined as 1 = rose and 0 = no rose to follow the *Rosa rugosa* raster, and
- The time step (to be iterated by) was set to 1 year. 1 year was seen as a sufficient time where the changes of the rose are big enough to be projected on a 10cm cell resolution grid.

The general structure of the Cellular Automata model (as shown in Figure 6) consists of a set of rules for new establishments, die-offs and expansion; which were defined in a loop, to iterate through the to be investigated time period. Each rule changes the *Rosa rugosa* states of the current year depending on pre-set configuration values. The *Rosa rugosa* states per year were collected in a 3-dimentional matrix (row, column, year).

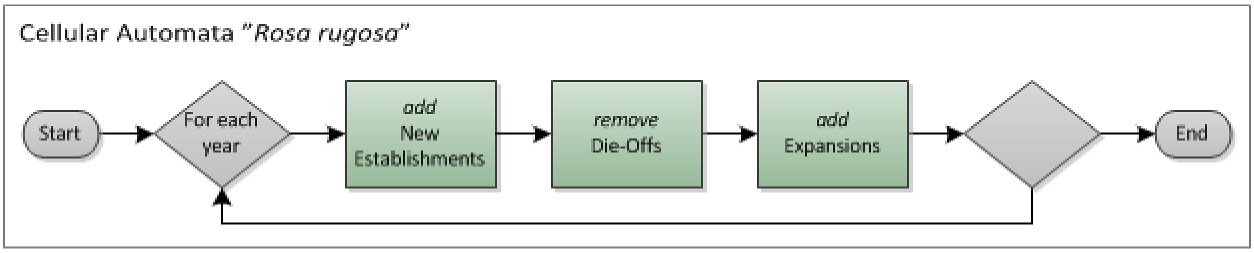



*Figure 6: General outline of the Cellular Automata for Rosa rugosa prediction.*

The general order of rule sets (green boxes in Figure 6) had been defined according to the following assumptions:

- The cell resolution of the *Rosa rugosa* matrix was 10cm. A new seedling will not automatically have this size, but smaller. Same accounts for the digitized input: a new seedling is due to size not identifiable on a 20cm resolution image. Hence it is needed to be assumed that a seedling of a size 10-by-10cm is actually from an earlier time, e.g. the previous year. This means all rules that run for the current year have to be applied on the new established shrubs, and therefore the establishment is done first.
- Like in the Non-spatial model it is assumes that roses that are in such a bad state that they die off in the current year, will not contribute to the expansion, and therefore are removed before the expansion.

The complete Matlab code can be found in Appendix G.

**"New Establishment" rule:**

At first the probability of non-rose cells becoming rose cells was computed by applying a pre-defined kernel on the current year's *Rosa rugosa* matrix. The kernel was defined as a circular inversed squared distance probability window with a radius of 50m. The 50m radius was chosen because the Danish study estimated 94% of all patches being within a 50m distance to one another (Jørgensen and Kollmann 2009) and the British study noted 93% (Boardman and Smith 2016). The kernel values were based on the Euclidean distance in order to implement Tobler's first Law of geography, and have been squared because it was assumed it is rather an exponential than linear relationship. The assumption is based on undisturbed birds being known to discharge when they start flying (personal statement by bird wardens) and considering the size of the fruits and seeds, wind possibly does not carry them far. Therefore the distance probability has been seen much stronger for close distances, than a linear relationship would represent. The kernel was applied on the rose matrix with a convolution function in Matlab, and afterwards element-wise divided by its highest value to retrieve the probability in every cell. The probability for rose cells was removed, because existing rose cells cannot become new establishments.

In the next step, a pre-selection of possible new establishments for the current year was performed over the whole discrete space based on the distance probability and suitability (elevation and aspect) using a random generator (random values between 0 and 1; different values for each cell). The pre-selection is a combination of 4 simple selections, where only those cells are considered further that were selected in each simple selection:

- All locations that are within the specified distance of a shrub (distance probability > 0).
- All locations where the random value is smaller than the distance probability (random < probability). A pre-selection of possible locations based on the distance to existing shrubs; where the closer the next shrub(s), the higher the distance probability and therefore the higher the chance to be pre-selected.
- All locations where the aspect probability multiplied by random is larger than half the lowest aspect probability ((aspect probability .* random) >= 0.02). A pre-selection of possible locations based on the aspect suitability, where the lowest aspect suitability (0.0408) was given a 50% chance (random >= 0.5) to be pre-selected.
- All locations where the elevation probability multiplied by random is larger than half the lowest possible elevation probability ((elevation probability .* random) >= 0.01). A pre-selection of possible locations based on the elevation suitability, where the lowest elevation suitability (0.02) was given a 50% chance (random >= 0.5) to be pre-selected.

The lowest suitability was given a 50% chance for new establishments, because so far it cannot be said for certain that there is no chance for new establishments to develop in less suitable locations. But it can be assumed that it is less likely due to the findings of the Danish study, which showed that in locations with a higher suitability, more new establishments were found (Kollmann et al. 2006). By multiplying the suitability probability with random and defining that this value has to be larger than half the lowest probability, locations of low suitability are given a possibility to have a new establishment, but it is less likely than at high suitable locations.

The result of the pre-selected location was captured as Boolean value, if the distance probability would have been kept only the direct neighbors would have had a change. The result was multiplied by random and had to be larger than a configuration value (see Appendix F). Afterwards the new establishments were added to the current *Rosa rugosa* matrix.

**“Die-off” rules:**

Only little is known about the die-off of *Rosa rugosa*, especially because this phenomenon was not noted in the found previous studies. Facts that can be contributed to the found behavior on Kieler Ort (Figure 5) are the annual turnover rate of 0.2 in Japan and the lack of establishment on waterlogged soil (Bruun 2005).

The die-off behavior was split into three rules according to encountered behavior in this study and documented observations in literature: 1) the partial shrub die-off (see Figure 5d), 2) bad suitability and 3) random. The last rule accounts for turnover with no instant back growth and possible other influences. Shrub die-off was only modeled at the edge of shrubs, because it was the only behavior this study was able to analyze due to the large time span per period and the resolution of the aerial images, used for digitizing.

The partial shrub die-off (1) calculates a die-off probability based on previous die-off. The previous die-off was collected by comparing the previous two years, and was then used in a direct neighbor analysis with a previously defined adopted Moore-neighborhood (range = 1, see Figure 2a) as kernel, to find clustered die-off. The adopted Moore-neighborhood was defined as having the value 1 in the center cell, 0.5 in direct adjacent cells (left, right, top, bottom) and 0.25 at the corner cells, because the corner cells were seen as having slightly less impact on the center cell than direct adjacent. The weighted neighbor matrix (applied kernel on previous die-off) was element-wise divided by the sum of the kernel to retrieve the probability, which is the highest if the center cell and all neighbors had died previously. The die-off probability in non-rose cells was removed, because non-rose cells cannot die.

The rose-cells with a probability to die were multiplied by a random value and had to be larger than a configuration value (see Appendix F). Afterwards the die-offs were removed from the current *Rosa rugosa* matrix.

In the first loop run there is no information on previous die-off available, therefore clustered die-off had to be placed randomly on shrub edges. The random placement was done, because it is not known why the rose shows this partial die-off behavior, therefore it cannot be predicted where this appears. At first, all rose-cells with at least 1 non-rose neighbor (shrub edges) were collected and a few of those were selected at random as die-off. A linear inversed distance kernel (similar to new establishments, but not squared) of a 50cm radius was used to retrieve all neighboring cells from the selected die-off. A 50cm radius was picked to generate a clustered die-off without being too large. Those neighbors combined with the already selected die-off were masked out by all rose-cells that had at least one non-rose-cell neighbor (all shrub edges). The result was then removed from the current *Rosa rugosa* matrix.

After the partial shrub die-off, die-off based on bad suitability (2) was removed. Bad suitability die-off was selected based on amount of neighbors and suitability (elevation and aspect). At first, an inversed neighbor probability based on the amount of direct rose neighbors was computed (few neighbors = high probability) per cell. The direct neighbors were selected and weighted by an adopted Moore-neighborhood - defined by the value 0 in the center cell, 1 in direct adjacent cells (left, right, top, bottom) and 0.75 at the corner cells, because the corner cells were seen as having slightly less impact on the center cell than direct adjacent. The retrieved direct neighbor matrix was then element-wise divided by the maximum amount of possible neighbors, to compute the inversed neighbor probability per cell. As a pre-selection, first, all non-rose cells and all rose cells with 8 neighbors were removed from the probability matrix, because only shrub edges were considered.

Followed by a removal of probabilities based on suitability, where only neighbor probabilities where kept in locations that had medium or low suitability. These locations were selected by either having an elevation probability of 0.02 or lower and/or an Aspect probability of less than 0.1 (see Part 2: Environmental factors). The remaining rose-cells with a probability to die were multiplied by random and had to be larger than a configuration value (see Appendix F). Afterwards the die-offs were removed from the current *Rosa rugosa* matrix.

The random die-off (3) was selected by an inversed neighbor probability based on the amount of direct neighbors (like bad suitability die-off). From the resulting probability matrix all non-rose cells and all rose cells with 8 neighbors were removed, because only shrub edges were considered. The probability matrix was then element-wise multiplies by random and the result had to be larger than a configuration value (see Appendix F). Afterwards the die-offs were removed from the current *Rosa rugosa* matrix.

**"Expansion" rules:**
To model the partial die-off, it had to be assumed that there is no or considerably less expansion on shrub edges affected by partial die-off, compared to those not affected. Therefore the expansion was split into two rules to account for both cases. First, two probabilities were computed. One based on recent die-offs to limit the expansion and one general expansion probability based on existing rose neighbors. The recent die-off probability was calculated by first collecting the locations of the current year's die-off and applying the same kernel as for the partial shrub die-off, to retrieve the amount of recent and neighboring die-offs per cell. This was used to compute an inverse probability (close die-offs = low probability for expansion). The general expansion probability was based on spatial autocorrelation using an inverse squared distance kernel (similar to the new establishment rule) with a radius of 50cm. For the radius, first, double the value of the largest lateral growth rate (40cm; computed in "Analysis of *Rosa rugosa* evolution") was used, but this proved to be too small. Therefore the radius was extended to 50cm. From both resulting expansion probability matrixes all probabilities in the location of rose cells were removed, because already existing rose cells cannot become rose cell. From this, two subsets for possible expansion were created. One for all possible locations that have died-off neighbors and one for all locations that are not effected by nearby die-off. The subset (Boolean) affected by die-off was element-wise multiplied by the general expansion probability, the probability based on amount of nearby die-off, and random. The subset not effected by die-off was element-wise multiplied by the general expansion probability and random. Both results had to be larger than a configuration value (each; see Appendix F). The retrieved new rose cells were both added to the current *Rosa rugosa* matrix.

**Calibration of the rules - "configuration values":**
The calibration of the rules "configuration values" to fit the model outcome to the encountered growth was done with an optimization function in Matlab. The used optimization function was the peer-reviewed "fminsearchbnd" (D'Errico 2012); which is an enhanced version of the Matlab "fminsearch" function. "Fminsearch" and "fminsearchbnd", both need starting seeds for the to be optimized values, meaning values where the function will start with the optimization. Ideally those starting seeds should already be set to close estimates to speed up the optimization process. "Fminsearchbnd" additionally allows to specify boundaries (= ranges) to those values.

The starting seeds for the “configuration values” (shown in Table 2), were estimated by a few manual model runs for each period. Here, it was tried to set the configuration values in a way to produce a similar area coverage of the roses by the end of each period, compared to the encountered behavior seen in 3.4.2 “Analysis of *Rosa rugosa* evolution” (exact values can be found in Appendix E). The die-off parameters had been pre-calibrated to fit the seen areal lose, resulting in the most die-off due to partial die-off (incl. eradication), followed by bad suitability and only very little according to random die-off. The expansion parameters were pre-calibrated to have most of the areas gain resulting from the general expansion (not partial die-off effected location); and only very little at locations with partial die-off.

*Table 2: Starting seeds for the “configuration values” in the spatial model for the periods 1, 2 and 3. The last column shows the lower and upper bounds for each configuration value*

| | 1994–2000 | 2000–2007 | 2007–2016 | lower – upper bound |
|---|---|---|---|---|
| **New establishments** | 0.99994 | 0.999979 | 0.999942 | 0.9 – 1.0 |
| **Die-off** | | | | |
| Partial die-off (1st year) | 0.99 | 0.99 | 0.99 | 0.0 – 1.0 |
| Partial die-off (other years) | 0.054 | 0.050 | 0.103 | 0.0 – 1.0 |
| Suitability die-off | 0.40 | 0.40 | 0.44 | 0.0 – 0.893 |
| Random die-off | 0.725 | 0.725 | 0.725 | 0.0 – 0.893 |
| **Expansion** | | | | |
| Partial die-off | 0.45 | 0.45 | 0.45 | 0.0 – 1.0 |
| General | 0.035 | 0.104 | 0.0375 | 0.0 – 1.0 |

For the use of the optimization function in Matlab, the Cellular Automata had to be designed as a function with a scalar return value. Since the used optimization was performed with a function minimizer, the return value had to be “0”, if the optimization reached an optimum. Equation 9 was implemented at the end of the Cellular Automata, to compare the simulated total area values with the retrieved (/measured) values under 3.4.2 Analysis of *Rosa rugosa* evolution (Appendix E).

$$f(x) = \left(1 - \frac{simulated\ DO}{measured\ DO}\right)^2 + \left(1 - \frac{simulated\ EXP}{measured\ EXP}\right)^2 + \left(1 - \frac{simulated\ NE}{measured\ NE}\right)^2 \quad (9)$$

*Where*: $f(x) \rightarrow$ *Return value of the Cellular Automata*
$DO \rightarrow$ *total area of Die-off*
$EXP \rightarrow$ *total area of Expansion*
$NE \rightarrow$ *total area of New Establishments*

**Parameter configuration for the future prediction:**
The prediction was performed by running the Cellular Automata with two different sets of configuration values. The configuration values for the prediction were calculated averages of the configuration values (see Appendix F) over the first two periods and all three periods. Additionally, a possible range of uncertainty was estimated by using the configuration of the period with the highest (period 3:2007-2016) and the lowest (period 2: 2000-2007) increase of *Rosa rugosa* on Kieler Ort.

### 3.4.5 Model validation

The retrieved configuration averages - of 2 (1994-2007) and 3 (1994-2016) periods – used for the prediction, were run on the spatial and non-spatial model for the period 2007-2016 (third period). The results were compared to the digitized outcome of 2016.

The resulting images of the spatial model for the final configuration of period 1, 2 and 3 have been compared to their digitized equivalent. The comparison was performed by computing a confusion matrix for each pair of modeled and digitized (ground truth) images. Additionally, the distance between the nearest neighbors for each rose cell between both images had been assessed to understand the accuracy of the model.

# 4 RESULTS

## 4.1 Part 1: Evolution of *Rosa rugosa* on Kieler Ort

*Rosa rugosa* coverage on Kieler Ort has increased from 1.4% in 1994 to 10.6% in 2016. In Figure 7, one can see a clear increase in amount and size of *Rosa rugosa* patches (green) in the 4 years analyzed. The increase has not been equally continuous, between 1994-2000 (6 year period) and 2007-2016 (9 year period) the area doubled or tripled, respectively; but the area increased very little in comparison in 2000-2007 (7 year period). Furthermore, drastic changes in the size and form of the island can be seen in the northern part of Kieler Ort – especially in 2016. According to not further analyzed aerial images the landmass had vanished in this location between 2010 and 2012. A similar change can be observed on the rose population - decay of *Rosa rugosa* just north of the "Cut-Off Line" in Figure 7, between 2000 and 2007.

The "Cut-Off Line" in Figure 7 shows the location where the northern tip of Kieler Ort was removed for further analysis. A similar map as Figure 7 with the removed northern part can be seen in Appendix D.

The collected *Rosa rugosa* trunk was estimated to be 5 years old.

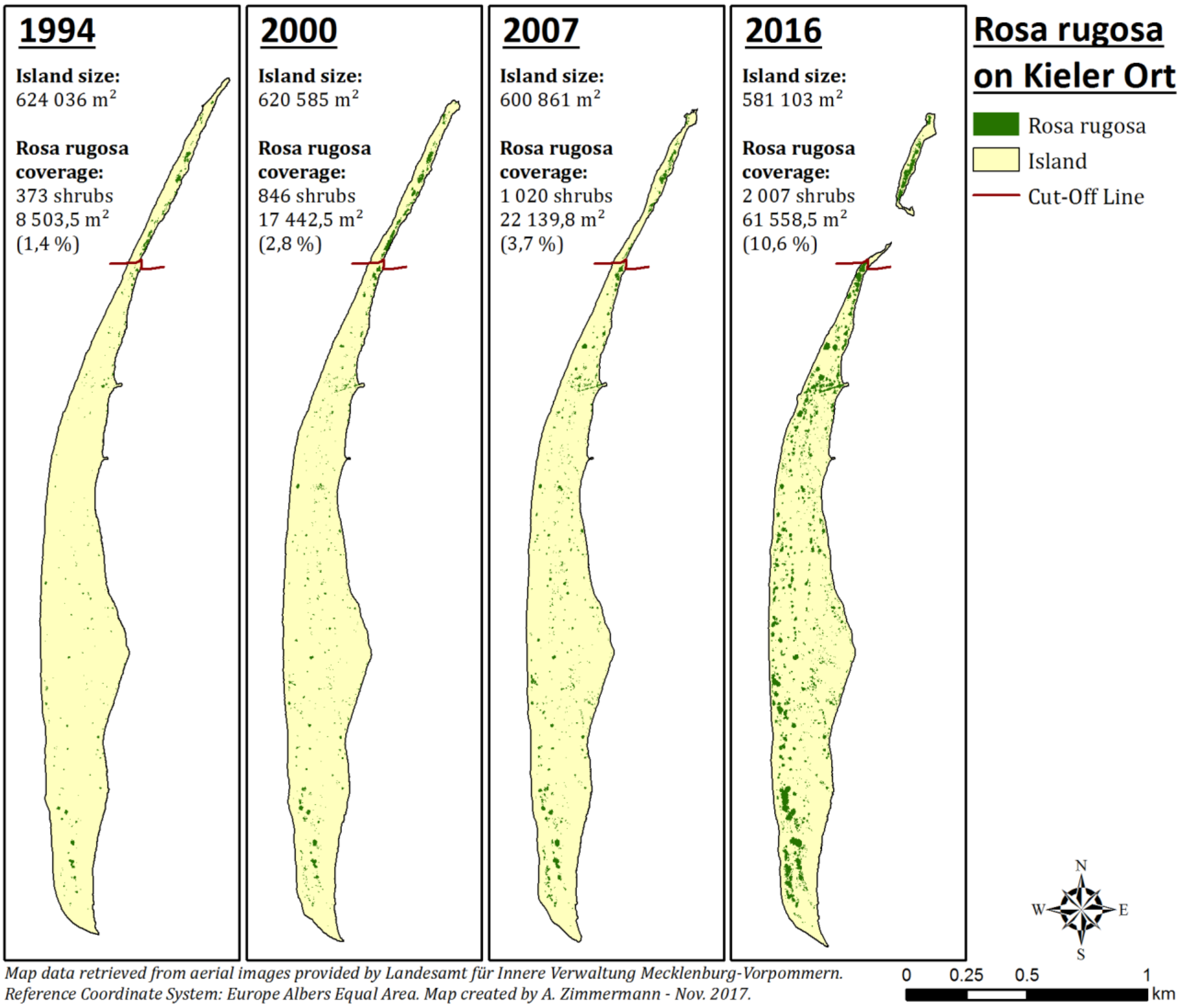



*Figure 7: Kieler Ort and Rosa rugosa extent for the years 1994, 2000, 2007 and 2016. The "Cut-Off Line" serves as an indicator of the location where the northern part of the island has been removed for further analysis.*

## 4.2 Part 2: Environmental factors

**Wind**

The analyzed wind data shows that the major wind direction (Figure 8 – left) is south-west, when including the neighboring directions south and west; these sum up to 55% of time.

The average wind speed per wind direction (Figure 8 – right), shows that on average the stronger winds (> 6ms$^{-1}$) come from west and southwest direction, closely follow by winds from north-west (5,81ms$^{-1}$). When looking more closely at the data, one can see measured (hourly averaged) maximum wind speed values (see Appendix B) higher than 100ms$^{-1}$ for NE, S, SW and NW (in comparison: wind speeds over 32.7ms$^{-1}$ are considered a hurricane). The maximum difference of the average value between calculations with and without outliers (larger than 40ms$^{-1}$) was observed for the southern wind direction of Bastorf-Kägsdorf and resulted in a difference of 0.08ms$^{-1}$.

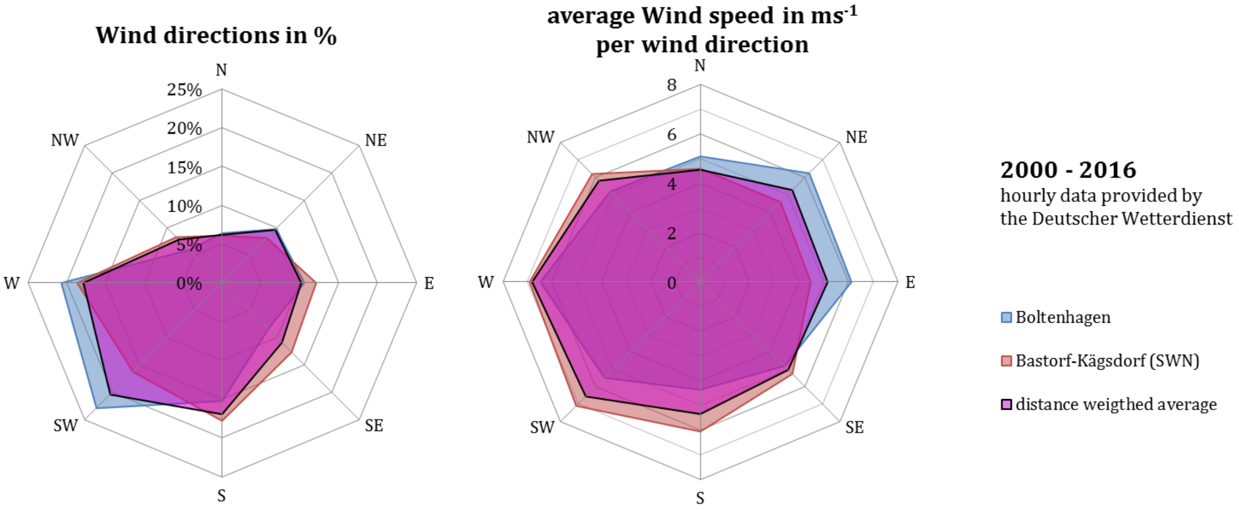



*Figure 8: Retrieved Wind properties for the time frame 2000-2016 of the weather stations Boltenhagen (blue) and Bastorf-Kägsdorf (red) as well as the calculated distance weighted average (pink) for Kieler Ort.*

**Aspect**

Nearly 30% of the slope aspects on Kieler Ort (yellow fill in Figure 9) are facing east, followed by ca. 20% facing west. Their neighboring aspects are covering each around 10% of the island; and north and south facing slopes are least common.

Over 40% of all *Rosa rugosa* locations (green fill in Figure 9) are growing on eastern slopes, followed by 20% on southeastern slopes and around 10% on northeastern slopes. This results in over 70% of all roses growing on those 3 neighboring slope aspects. The remaining 30% are distributed over the other aspects and no roses were identified to grow on flat surfaces.

A comparison of slope aspect availability on Kieler Ort and aspect of *Rosa rugosa* growth shows that the rose density is close to equal or higher on north, north-eastern, east and south-eastern slopes; whereas the other aspects have a lower rose density compared to aspect availability. The u-test has shown a significant difference (p-value $<2.2^{-16}$, $W_{cos} = 4.280122^{+12}$, $W_{sin} = 3.151611^{+12}$) between both datasets.

The wind probability and wind speed per direction from Figure 8 had been added in Figure 9 for comparison. It stands out in Figure 9 that a higher wind probability and wind speed responds to a lower rose probability (south, south-west, and west aspect) per available aspect.

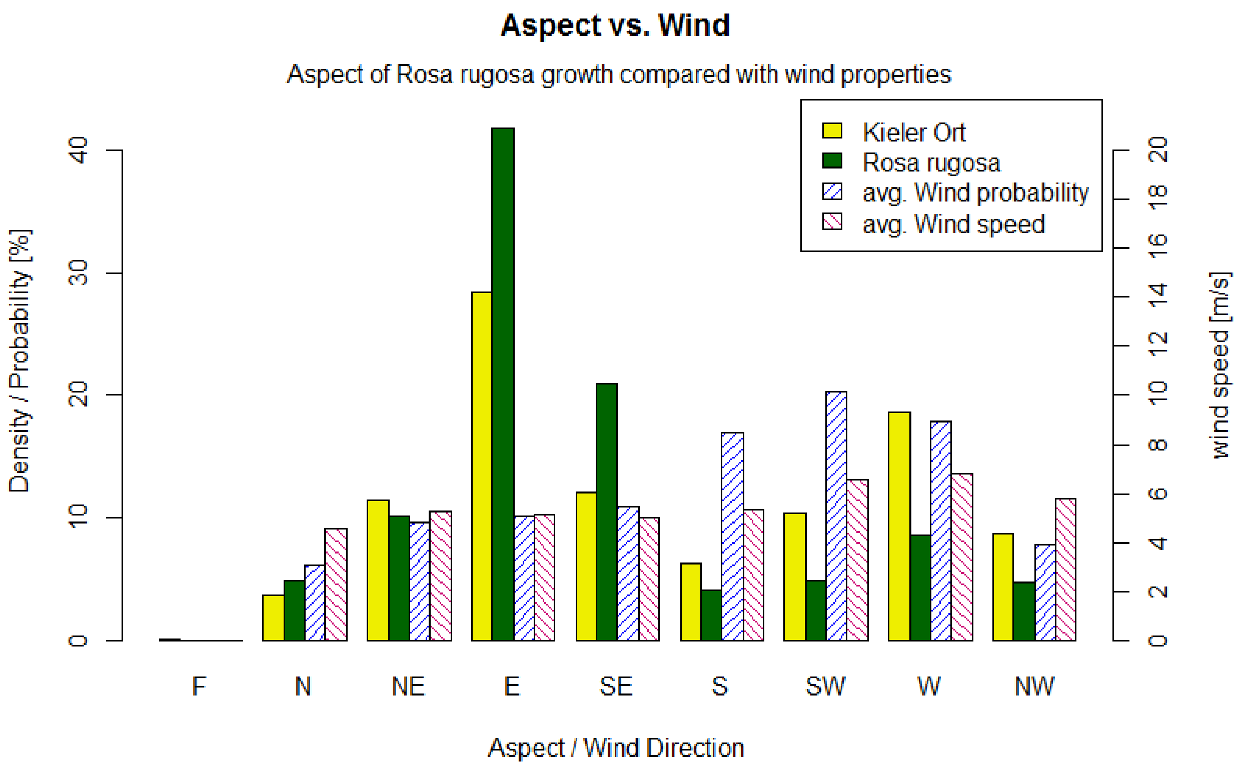



*Figure 9: Aspect comparison of density on Kieler Ort (yellow fill), Rosa rugosa density (green fill), average wind probability (blue pattern) and average wind speed (red pattern). Data of Aspect, Kieler Ort and Rosa rugosa had been sampled in 2007, whereas wind properties show an average of 2000-2016 and where sampled in Boltenhagen and Bastorf-Kägsdorf (a distance weighted average was used for Kieler Ort).*

**Elevation**

The *Rosa rugosa* distribution over elevation follows the elevation density on Kieler Ort, with the exception of low elevation. A comparison of elevation density between the island and its *Rosa rugosa* locations is shown in the overlaid histogram in Figure 10. The island (blue) has considerably large areas around 0cm elevation. Hereafter it starts at a very low density (~0%) that increases linear up to around 60cm (~0.006%) of elevation, followed by a plateau until ca. 170cm, and a decrease of density. It can be said that the majority of the Island has an elevation between 50 – 180cm and only a few areas below and above. In comparison, Figure 10 indicates that *Rosa rugosa* (red) has only very little placements on the island below 27cm of elevation, which slowly increase afterwards till 57cm, followed by a strong increase to around 130cm of elevation. The decease of *Rosa rugosa* placements per elevation follows the decrease of the island. Appendix C shows a figure highlighting the breaks.

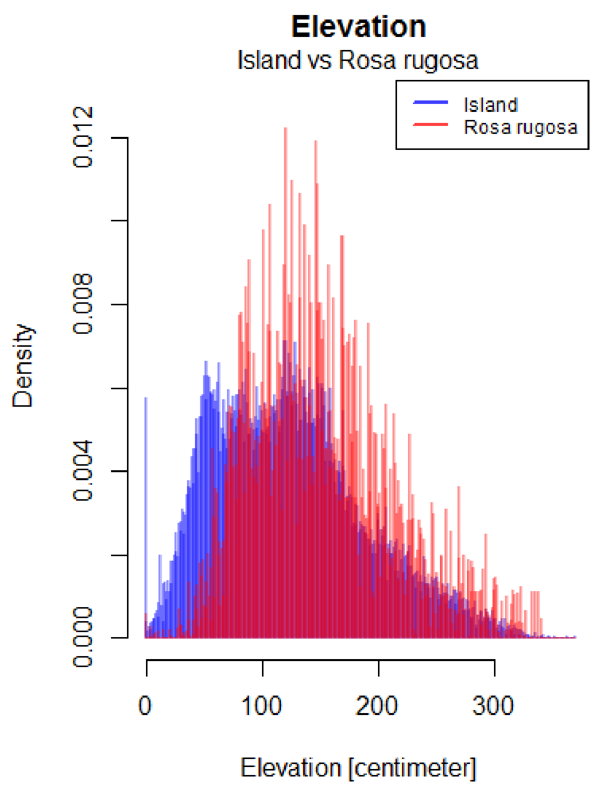



*Figure 10: Comparison of elevation density (per cm height) on Kieler Ort (blue) and Rosa rugosa locations on Kieler Ort (red). All data had been sampled in 2007.*

## 4.3 Part 3: Average growing rate and prediction of *Rosa rugosa* on Kieler Ort

**Growth Rates:**

Table 3 shows the retrieved rates per period as well as their combined averages used for the non-spatial future prediction model. A comparison of the survival, expansion and establishment rate of the investigated periods shows that the second period from 2000 to 2007 had the lowest rates, indicating the most die-off, and the least expansion and new establishment per year. The third period from 2007 to 2016 shows the highest survival whereas the first period from 1994 to 2000 shows the highest expansion and new establishment rate. This has the effect that the average rates calculated from all 3 periods have a higher survival and expansion rate but the average of the first two periods has a higher new establishment rate.

The 3rd period has the lowest lateral die-off rate and the highest lateral expansion rate, whereas period 1 shows the lowest lateral die-off rate and period 2 the lowest lateral expansion rate.

*Table 3: Calculated change rates for Rosa rugosa on Kieler Ort. Survival, expansion and establishment rates have been calculated on the overall areas per period, whereas the lateral rates have been calculated on shrub/group level and were averaged afterwards.*

| **Rates:** | **Survival [% $y^{-1}$]** | **Expansion [% $y^{-1}$]** | **Establishment [% $y^{-1}$]** | **Lateral die-off [cm $y^{-1}$]** | **Lateral expansion [cm $y^{-1}$]** |
|---|---|---|---|---|---|
| **per Period:** | | | | | |
| **1994-2000** | 95.3 | 13.0 | 7.6 | -6.1 | 16.4 |
| **2000-2007** | 96.6 | 9.0 | 1.4 | -3.9 | 12.2 |
| **2007-2016** | 98.6 | 12.0 | 2.7 | -2.2 | 20.9 |
| **Averages:** | | | | | |
| **1994 - 2007** | 95.9 | 11.0 | 4.5 | -5.0 | 14.3 |
| **1994 - 2016** | 96.8 | 11.3 | 3.9 | -4.1 | 16.5 |

Additionally, the overall average increase of *Rosa rugosa* coverage per annum had been noted to be of 11.5% per year over the whole investigated period.

**Prediction:**

The prediction with the non-spatial model (Figure 11) resulted in a *Rosa rugosa* coverage in 20 years of 449000m² for the 2-period average, and 514000m² for the 3-period average. The possible range (min – max in Figure 11) of 200000m² to nearly 700000m² was computed with the configuration of the lowest (period 2 -> Table 3) and the highest (period 3 -> Table 3) increase.

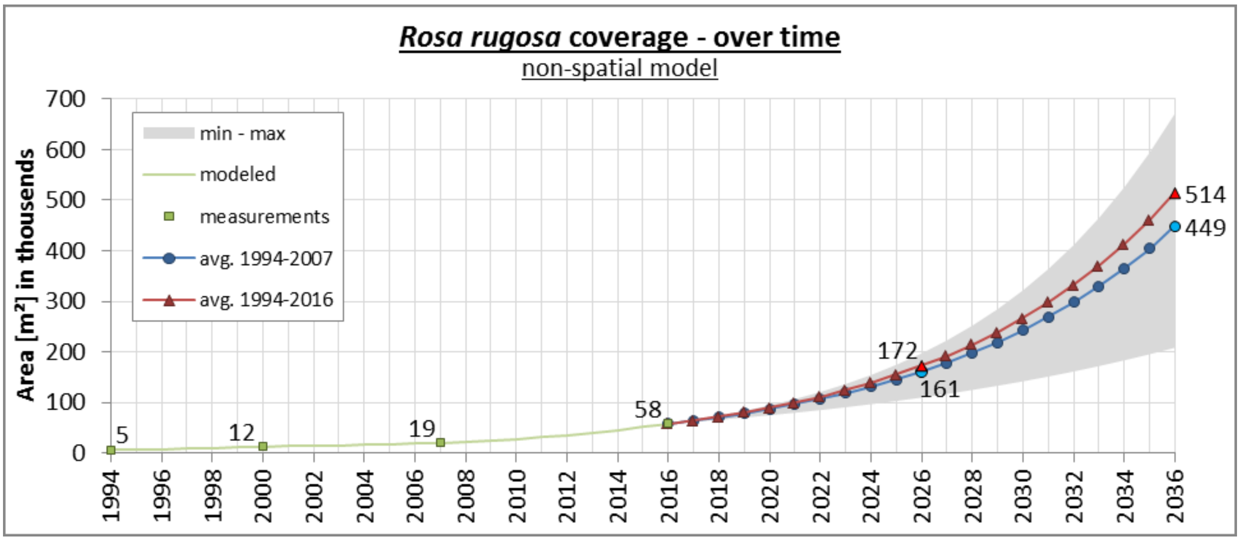



*Figure 11: Future prediction of Rosa rugosa coverage on Kieler Ort up to the year 2036 (20 years) retrieved by a non-spatial model based on growth rate. The blue (circle) line presents the computed future estimates by the 2-period-average, whereas the red (triangle) line shows the result by 3-period-average. The grey range indicates the uncertainty estimated with the configuration of the measured period with the lowest (2nd period) and the highest (3rd period) area growth.*

The prediction with the spatial model resulted (Figure 12) in a *Rosa rugosa* coverage in 20 years of 121000m² for the 2-period average, and 170000m² for the 3-period average. The possible range (min – max in Figure 12) of 98000m² to 240000m² was computed with the configuration of the lowest (period 2) and the highest (period 3) increase.

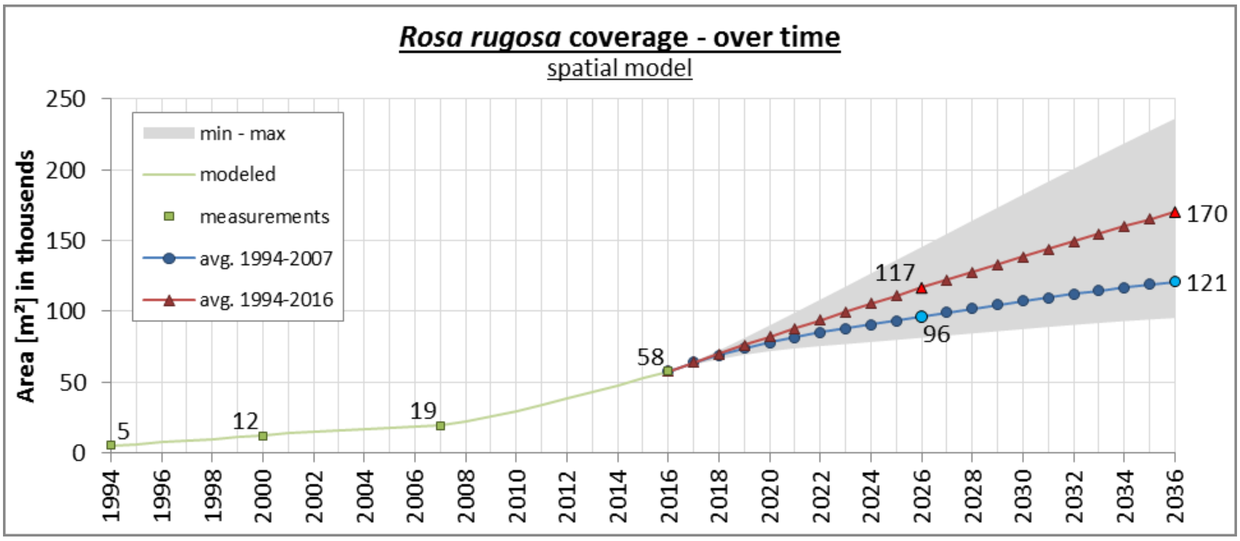



*Figure 12: Future prediction of Rosa rugosa coverage on Kieler Ort up to the year 2036 (20 years) retrieved by a spatial model based on a cellular automata. The blue (circle) line presents the computed future estimates by the 2-period-average, whereas the red (triangle) line shows the result by 3-period-average. The grey range indicates the uncertainty estimated with the configuration of the measured period with the lowest (2nd period) and the highest (3rd period) area growth.*

The retrieved rose coverage of both models shows large differences in size, furthermore does the form of the coverage curve differ. The non-spatial coverage curves show a clear exponential increase, whereas the curves of the spatial model indicate a linear to exponential increase till 2016 but a rather logarithmic increase after 2016.

Figure 13 shows the resulting images of the spatial model for 2026 (10 year prediction) and 2036 (20 year prediction) for both averages (2- and 3-period average). The increase in *Rosa rugosa* coverage as seen in the graph of Figure 12, can also be noted in Figure 13, where the 3-period average (Figure 13 – right) shows a larger increase of *Rosa rugosa* (green) in both years (2026, 2036) compared to the 2-period average (Figure 13 – middle). According to the 2-period average, *Rosa rugosa* will cover 21.5% of the island by 2036; the 3-period average estimates a 30.3% coverage of *Rosa rugosa* by that time.

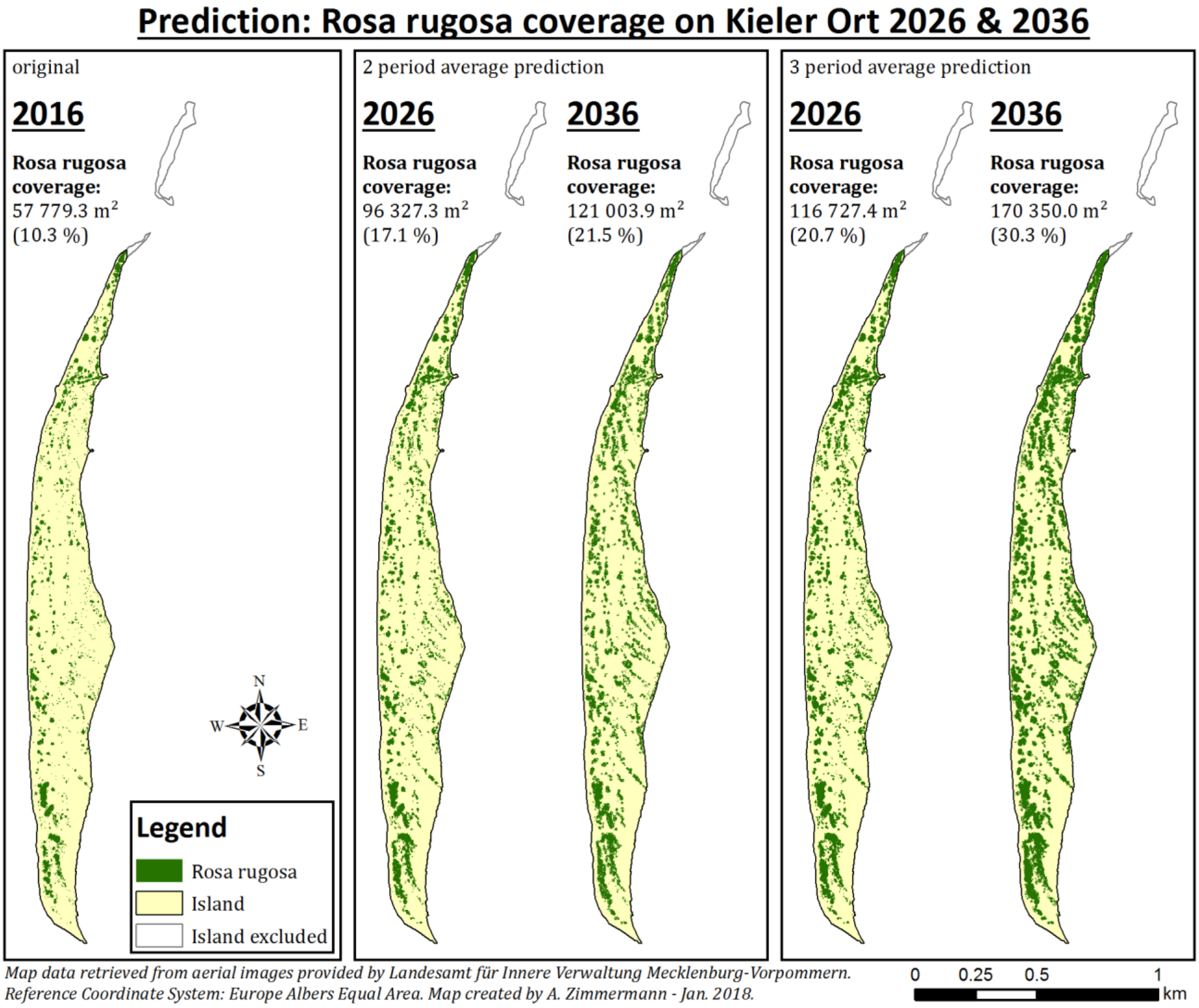



*Figure 13: Future prediction of Rosa rugosa coverage (green) on Kieler Ort (yellow) for the years 2026 (10 years) and 2036 (20 years) retrieved by a spatial model based on a cellular automata. The possible Rosa rugosa coverage (green) is presented for both, the 2-period (middle) and 3-period average (right). The island shape for all years is represented by the Islands outline from 2016. The coverage given in percentage is based on the size of the island in 2016.*

**Validation:**

The comparison of the two averages (2-period and 3-period) used for the prediction in both models (non-spatial and spatial), with the digitizing result of period 3 showed that both averages in both models under-estimates the *Rosa rugosa* coverage in 2016. The 3-period average (Figure 14: red-triangles) has a higher coverage increase in both models, and is therefore closer to the measured value (Figure 14: green-squares). The non-spatial model (Figure 14 - left) with a predicted coverage of 51000m² and 48000m² for the 3-period and 2-period average respectively, showed a better fit than the predicted coverage of 45000m² and 38000m² for the spatial model (Figure 14 - right).

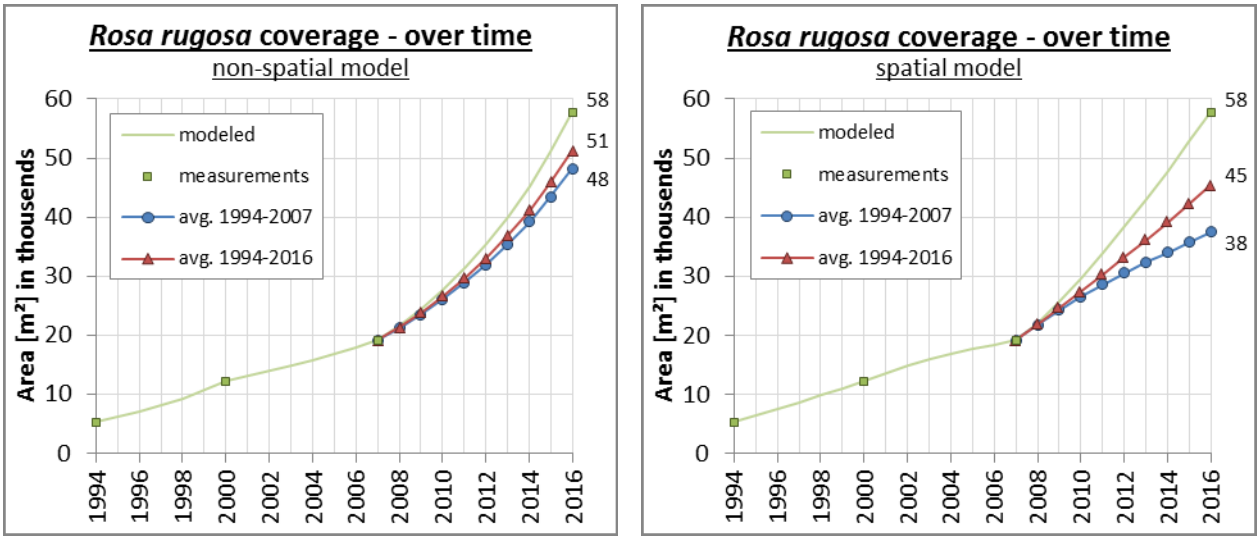



*Figure 14: Comparison of fit of both averages (used for the prediction) with the 3rd period (2007-2016) result; for both the non-spatial model (left) and spatial-model (right).*

The resulting images of the spatial model, retrieved with the optimized configuration values, have been tested against the measured (digitized) images for all 3 periods. The user and producer accuracy (see Table 4) show comparable values for all three periods, where 2000 has the lowest rose-cell accuracy and 2007 the highest. The Kappa value of agreement indicates that all three configurations are at least 50% better than Change, where again the year 2000 has the worst fit and 2007 shows the best fit.

The nearest neighbor distance between the modeled and measured image (Table 4 – last column), shows the average and maximum distance between the closest rose-cells. 2007 shows the best fit because it has the lowest average nearest neighbor distance, which is related to the highest user and producer accuracy (64.3%). The nearest neighbor analysis indicates that 2016 has the least good fit with an average distance between rose-cells of 1.6m.

Overall, 2007 (the outcome from the 2nd period) shows the best fit in the confusion matrix and nearest neighbor distance.

*Table 4: Accuracy assessment of the resulting images from the spatial model for each configured period. The table shows an extract from the confusion matrix (user, producer and overall accuracy, and kappa) and the nearest neighbor distance. The comparison has been done on the final year of each period, namely 2000 for period 1, 2007 for period 2 and 2016 for period 3. The digitized image was used as Ground Truth data for the comparison with the model output.*

| Year | User Accuracy rose / non-rose | Producer Accuracy rose / non-rose | Overall Accuracy | Kappa | Nearest Neighbor average (max) |
|---|---|---|---|---|---|
| **2000** | 51.2% / 99.5% | 51.2% / 99.5% | 99.0% | 50.7% | 1.6m (40.4m) |
| **2007** | 64.3% / 99.5% | 64.3% / 99.5% | 98.9% | 63.8% | 0.8m (49.4m) |
| **2016** | 60.7% / 98.1% | 60.8% / 98.1% | 96.4% | 58.9% | 1.6m (33.7m) |

# 5 DISCUSSION

## 5.1 Part 1: Evolution of *Rosa rugosa* on Kieler Ort

The *Rosa rugosa* coverage increased over the investigated time span from 1994 to 2016, which was expected because the more plants exist, the more base for expansion; but also more fruits are produced and therefore the more seeds are available to be distributed and the more likely it is for new plants to develop - expansion by clonal and seed spread (Bruun 2005). The comparable low increase between 2000 and 2007 to the other two periods could have been caused by floods or very high tides, since *Rosa rugosa* was reported to have an aversion to waterlogged soil (Bruun 2005). Another possible factor could be an increase in hunting and therefore decrease in pigs on the island; or less birds to distribute seeds. Precipitation and temperature could be a reason, but appears to be less likely, because *Rosa rugosa* was reported to be resistant to those factors (Bruun 2005) which was confirmed by Kollmann et al. (2009).

The change of the form and size of Kieler Ort in the northern part can be contributed to erosion. First, a visible reduction of *Rosa rugosa* population (2000-2007; Figure 7 north of the "Cut-off line"), possibly due to wash over (e.g. high tides) and therefore waterlogged soils (Bruun 2005). The eradication of *Rosa rugosa* and possibly other plants might have destabilized the landmass, that caused strong erosion by water to which Kieler Ort was reported to be prone to (Jeschke et al. 2003).

The seed distribution sources found during the field work align with and add to the ones reported by Bruun (2005). The opened up fruits can be contributed to birds, since Kieler Ort is a protected bird sanctuary; and the animal droppings, assigned to the encountered wild pig due to its size, were full with seeds. Hence the existing seed distribution sources on Kieler Ort can be summarized to sea currents, birds, wild pig and possibly wind.

The thickest *Rosa rugosa* stem found on Kieler Ort was dated to be 5 years old. This agrees with the reported turnover rate in Japan (Bruun 2005).

**Error evaluation:**

The low number of georeferencing points was due to a lack of usable markers. The form of the island and its vegetation were changing constantly, and therefore could not be used for georeferencing. The island itself has barely any human made infrastructures, hence only a limited amount of markers, like an old vehicle, track crossings or ruins, were considered persistent over time and could be used. The low number of georeferencing points could have caused a shift of shrubs placements in locations with fewer points, which would result in an error in the later analysis.

Reasons for the classification failure were the variations in spectral signature range of *Rosa rugosa*, caused by light reflections and shadows in the aerial images, as well as the differences in spectral signature of old shrubs (darker green) and young colonies. Young plant colonies cover partially large areas but appear as mixed spectral reference with soil and/or other vegetation (as encountered during the field work - Figure 4b). This in combination with the fact that the island is completely covered with vegetation (similar spectral reference) and partially bad image quality - merged images with different brightness values between former mosaics, made it impossible to extract all *Rosa rugosa* patches by classification.

Digitizing, besides being very time consuming, is very subjective. The drawing of the perimeters fully depends on human selection, together with light reflections and shadows on plants in the aerial images, as well as the shrub density (as explained before) make it difficult to get a 100% correct rose outline. This introduces an error, which has a more significant effect on smaller shrubs sizes. The islands perimeter depends fully on the human selection as well, and therefore an error can be expected. The different cell resolution of the images introduces an additional uncertainty.

The mapping of wrongly identified shrubs in the field was done using detailed maps of the 2016 aerial image with the digitized perimeter of shrubs and GPS. Since the maps allowed for orientation and localization of shrubs compared to its surroundings; GPS was mainly used for general orientation. Therefore an error related to GPS uncertainties can be neglected.

During fieldwork I had the assistance of 3 additional people for the mapping, who were all well aware of the plant species and the environment on Kieler Ort. Still, it needs to be taken into account that people work differently and that some might have worked more precise than others.

**Summary:**
Georeferencing and digitizing were done by the same person for all years investigated; therefore the same source of subjectivity was in place in all cases, hence this cannot explain the large difference in growth as encountered in the three periods. A comparison (eyeballing) of the results towards form and location of shrubs did not show an overall or partially similar shift in a certain direction, therefore an error due to low number of referencing points can be minimized. Consequently, *Rosa rugosa* growth in combination with one or several environmental factors is likely to be the driving reason for the encountered phenomena during the investigated periods.

## 5.2 Part 2: Environmental factors

An investigation of aspect on Kieler Ort showed that *Rosa rugosa* were not growing on flat surfaces. This can be due to flat surfaces on Kieler Ort were mainly water like the encountered lakes or the sea, or areas on the beach. Under consideration that Bruun (2005) noted that the investigated rose does not prefer waterlogged soil, the finding appears reasonable.

The aspect of *Rosa rugosa* was found to be significantly different to the island's aspect density, allowing the assumption that there must be factors influencing the aspect preference of the rose. The aspect comparison showed (Figure 9) that a higher wind probability and stronger wind speeds per wind direction relate to a lower *Rosa rugosa* probability compared to the existing aspect density on Kieler Ort; resulting in the assumption that *Rosa rugosa* prefers wind sheltered locations. In contrary to this study's finding was the reported weak but positive correlation between *Rosa rugosa* emergence and wind facing slopes by Kollmann et al. (2006). The different study outcomes can be caused by accurateness of the wind, aspect and *Rosa rugosa* dataset. The study of Kollmann et al. (2006) has not stated how, where and over which period the wind data was collected, therefore it is difficult to judge how precise it is for their study area. However, in this study an error due to the distance between weather stations and study area can be expected (as explained later in detail). The *Rosa rugosa* and aspect dataset used by Kollmann et al. (2006) were collected in the field but focusing only on emergence of *Rosa rugosa*, whereas this study worked with much coarser data collected with airborne instruments not allowing an investigation in this detail. Therefore Kollmann et al. (2006) dataset can be considered more accurate, but without any further information on their wind data and under consideration that only a weak correlation was found, as well as the possibility of local environment differences; this studies outcome should be considered critical and possibly be investigated in finer detail. But it is certain that there is a preference of *Rosa rugosa* towards aspect, therefore other environmental factors could be considered being the source.

The investigation of elevation on Kieler Ort showed that the island has considerably large areas at around 0 cm elevation, and only very few areas with an elevation just above 0 cm. The areas of 0 cm elevation can be explained by the ponds, sea and possibly some beach areas.

The considerably lower *Rosa rugosa* density compared to the overall elevation density on Kieler Ort at low elevations can be explained by the aversion of waterlogged soil of the rose (Bruun 2005). The breaks of 27cm and 57cm indicate the elevation, where the gradient of the density curve changes. Since the Baltic Sea has tidal water height changed during the course of a day; the lowest parts (0-27cm) on the island are most likely regularly (normal tides) affected by wet soil and therefore can be considered not preferred areas of *Rosa rugosa*. Occasional higher tides would affect areas of higher elevations, but since these do not appear on a daily basis, *Rosa rugosa* expanse or establishes there. Due to a higher probability of wet soils, the *Rosa rugosa* density increases only slowly with elevation.

**Error evaluation:**

The wind probability per weather station showed a rather large difference in SW and SE direction. A large difference between measurements per weather station can also be seen for wind speed per wind direction in S, SW and E, NE direction. Considering the distance between both weather stations, those differences can be explained by local weather differences. Therefore, an interpolation to retrieve the local weather on Kieler Ort will contain uncertainties. The here applied distance weighted average accounts for Bastorf-Kägsdorf being closer than Boltenhagen but since both weather stations are on the coast of the main land and Kieler Ort is an island, differences between the calculated and actual wind properties can be expected.

The encountered very high wind speed values seem unrealistic, especially since these were hourly averaged values; therefore an error in the overall dataset needs to be considered. Outliers were defined as larger than $40ms^{-1}$, because values larger than $32.7ms^{-1}$ are considered a hurricane. Those outliers were found in 3 measurements per station and each being in a different wind direction. Therefore max two outliers per wind direction (one per station) out of 16 years of hourly measurements affect the computed distance weighted average for Kieler Ort. Hence an introduced error due to outliers will be very small and can be neglected.

The received DEM had a resolution of 5m and a reported height accuracy between 0.25m and 1m. Under consideration that the highest point on Kieler Ort is only 3.6m, it has to be considered that smaller details like depressions or peaks are smoothed out. Therefore it has to be noted that some of the elevation and aspect values were wrong.

Both sources datasets – DEM and aerial image – were taken in 2007 with possibly only a few months apart. Therefore no significant error can be expected due to differences in the time.

**Summary:**

The analysis has shown that *Rosa rugosa* avoids low elevations and has a preference towards east facing slopes. The preference of elevation could be explained by literature, but the aspect preference caused by wind contradicts to previous studies. Therefore an investigation with more detailed meteorological and other environmental data, as well as a more precise DEM is recommended.

## 5.3 Part 3: Average growing rate and prediction of *Rosa rugosa* on Kieler Ort

The analysis of growth rates showed an overall increasing trend in *Rosa rugosa* coverage by 11.5% per annum. Compared to the Danish study with 16.4% year$^{-1}$ (Kollmann et al. 2009) and the study in England with 22% year$^{-1}$ (Boardman and Smith 2016), this studys's outcome is considerably lower (half of the UK study). The UK study had retrieved their growth rate from a sample size of 8 shrubs on two different sites (4 shrubs per site), hence their growth rate appears less representable. Kollmann et al. (2009) investigated the period 1986-2006, which is a shift of one decade to this study (1994-2016), but covers the least suitable times of this investigation: largest die-off rate in 1994-2000 and lowest expansion rate in 2000-2007. The Danish study did not identified any die-off or eradication, which in combination with the larger overall coverage increase and a larger lateral spread (0.42m year$^{-1}$ (Kollmann et al. 2009) to 0.16m year$^{-1}$ (this study)), indicates that the Danish study site is a more suitable environment for *Rosa rugosa* than Kieler Ort.

Both models – non-spatial and spatial –showed an increase of *Rosa rugosa* coverage, but under-estimated the measurement of 2016. This can be attributed to the low amount of investigated periods, where one (period 2) out of three showed a significantly lower increase than the other two. A larger amount of periods (with possibly smaller time spans) would average a very low or high value out and give a more reliable estimation.

The large differences in estimated future *Rosa rugosa* coverage between the non-spatial and spatial model can be associated to the missing spatial component in the non-spatial model. The non-spatial model did not take into account merging of plants (due to growth), instead it will consider overlapping areas twice; and limitations in space and suitability. Therefore it can be assumed that the non-spatial model has a large error in its future prediction, and that the spatial model's estimate is more accurate.

The spatial result of future *Rosa rugosa* locations showed that between half and two-third of all rose locations were correctly placed (user and producer accuracy), but this comparison included all rose-cells that have not changed, which indicates a much lower kappa for new placements (expansion and new establishments). The best fit according to the confusion matrix and nearest neighbor distance had period 2 (Table 4), but that result can be related to a medium die-off and very low expansion and new establishment rate (Table 3; Appendix E). Therefore a larger amount of cells had not changed compared to the other 2 periods investigated, and hence results in a higher percentage of similarity. An average of 1.33m as nearest neighbor distance at a raster resolution of 10cm, dismisses the argument of near miss (close by placement). Therefore it has to be assumed that the Cellular Automata places new roses rather by random, which was expected since it is a random model.

**Error evaluation:**

In *Rosa rugosa* related studies, a turnover rate and an aversion to waterlogged soils (Bruun 2005) was reported, but none of the spatial related studies had identified any sort of natural eradication on existing plants. Here it has to be noted, that the UK study only used 8 shrubs (Boardman and Smith 2016), which does not appear very representative in this context; and the Danish study did only use a distinct sub-set of shrubs in their study area. Therefore it cannot be said for certain, that there are no die-offs in their study environment. As for this study, an error due to the low number of reference points and manual digitizing has to be expected (see 5.1 “Part 1: Evolution of *Rosa rugosa* on Kieler Ort"), but does not explain the amount, size and distribution of die-offs.

The spatial model uses a large number of assumptions, which is due to the lack of knowledge, mainly related to the die-off behavior; and missing information, that possibly could have been retrieved with more time. Therefore, a large error due to the used assumptions has to be expected.

For a scientific model, all parameters used have to be optimized and verified by a high number of model runs with different values per parameter. Due to limitations in time and hardware, this was only done for the configuration values.

**Summary:**
For both models (non-spatial and spatial) an uncertainty was introduced by the low number of samples (3 periods) and their large difference in growth. It had to be considered that the non-spatial model’s future prediction was over-estimated, due to the lack of spatial and environmental factors. The spatial model had a large uncertainty as a result of the number of assumptions. Consequently, it can be said that the non-spatial model can be used to retrieve existing growth rates, but was not suitable for future predictions. The spatial model is at a prototype stage, which gives a possible spatial future prediction but still has many knowledge gaps.

For a more precise spatial model, the die-off behavior, specifically the partial die-off and its related expansion; and the preferred locations of *Rosa rugosa* (for new placements) needs to be better understood. One attempt could be the investigation of more suitability factors, liked an analysis of a biotope map or soil properties, because Kollmann et al. (2006) found a correlation to soil and between different dune types and the establishment probability. Unfortunately, this biotope map does not currently exist, and has to be created.

# 6 CONCLUSION

**Q1: Do wind and topography have an influence on the preferred establishment locations of *Rosa rugosa* (investigated from a GIS perspective)?**

This study had identified a *Rosa rugosa* preference of east-facing slopes on Kieler Ort. This does correspond to wind sheltered slopes, but due to contrary reports in other studies, an analysis with more detailed data would be recommended.

Additionally, a very low presence at low, near sea level elevations had been found, supporting the statement of aversion of waterlogged soils.

**Q2: What is the average growth rate of *Rosa rugosa* on Kieler Ort and how will the population of this plant look in 10 and 20 years?**

An overall increase of *Rosa rugosa* on Kieler Ort was estimated to 11.5% per annum. Because of the identified shrub die-off during the investigated period, the average growth rate was split to account for die-off and expansion, as well as new establishments. An average survival rate of 96.8% per year, expansion rate of 11.3% per year and a new establishment rate of 3.9% per year was extracted.

The highest prediction with the spatial explicit model was found to reach a *Rosa rugosa* coverage of 170 350m$^2$ by 2036 (116 727.4m$^2$ by 2026), which corresponds to 30.3% of the area of Kieler Ort in 2036. But because of the large number of assumptions used for the modeling, the result should not be considered very explanatory.

**Q3: Is the growth rate on Kieler Ort comparable to that found in studies in other European coastal regions?**

The retrieved *Rosa rugosa* growth rate on Kieler Ort was smaller to comparable studies in Denmark and United Kingdom, which could be related to the found shrub die-off, the other studies did not encounter; or the fact that the other studies had a very small sample size or used just a sub-set and not all shrubs. Another reason is also the difference in the environment; both studies were on the mainland, whereas Kieler Ort is a small island.

# 7 REFERENCES


Adamatzky, A. 2009. Identification of Cellular Automata. In *Encyclopedia of Complexity and Systems Science*, 4739–4751. New York, NY: Springer New York. doi:10.1007/978-0-387-30440-3_280.

Balzter, H., P. W. Braun, and W. Köhler. 1998. Cellular automata models for vegetation dynamics. *Ecological Modelling* 107: 113–125.

Boardman, C., and P. H. Smith. 2016. Rates of spread of Rosa rugosa (Japanese Rose) determined by GIS on a coastal sand-dune system in Northwest England. *Journal of Coastal Conservation* 20. Journal of Coastal Conservation: 281–287. doi:10.1007/s11852-016-0439-7.

Bruun, H. H. 2005. Rosa rugosa Thunb. ex Murray. *Journal of Ecology* 93: 441–470.

D'Errico, J. 2012. fminsearchbnd, fminsearchcon v1.4. *MathWorks*. Retrieved 2017-12-30, from https://se.mathworks.com/matlabcentral/fileexchange/8277-fminsearchbnd--fminsearchcon?requestedDomain=www.mathworks.com

Dutta, A., S. Kar, A. Apte, I. Nopens, and D. Constales. 2015. A generalized cellular automata approach to modeling first order enzyme kinetics. *Sadhana* 40: 411–423. doi:10.1007/s12046-015-0336-z.

Feiler, E., and K. Feiler. 2004. *Die verbotene Halbinsel Wustrow: Flakschule, Militärbasis, Spionagevorposten*. Berlin: Ch. Links Verlag.

Frederiksen, L., J. Kollmann, P. Vestergaard, and H. H. Bruun. 2006. A multivariate approach to plant community distribution in the coastal dune zonation of NW Denmark. *Phytocoenologia* 36: 321–342. doi:10.1127/0340-269X/2006/0036-0321.

Isermann, M. 2008. Classification and habitat characteristics of plant communities invaded by the non-native Rosa rugosa Thunb. in NW Europe. *Phytocoenologia* 38: 133–150. doi:10.1127/0340-269X/2008/0038-0133.

Jeschke, L., U. Lenschow, and H. Zimmermann. 2003. *Die Naturschutzgebiete in Mecklenburg-Vorpommern*. Schwerin: Demmler Verlag GmbH.

Jørgensen, R. H., and J. Kollmann. 2009. Invasion of coastal dunes by the alien shrub Rosa rugosa is associated with roads, tracks and houses. *Flora - Morphology, Distribution, Functional Ecology of Plants* 204: 289–297. doi:10.1016/j.flora.2008.03.002.

Kelager, A., J. S. Pedersen, and H. H. Bruun. 2013. Multiple introductions and no loss of genetic diversity: invasion history of Japanese Rose, Rosa rugosa, in Europe. *Biological Invasions* 15: 1125–1141. doi:10.1007/s10530-012-0356-0.

Kellner, A., C. M. Ritz, and V. Wissemann. 2012. Hybridization with invasive Rosa rugosa threatens the genetic integrity of native Rosa mollis. *Botanical Journal of the Linnean Society* 170: 472–484. doi:10.1111/j.1095-8339.2012.01298.x.

Kollmann, J., L. Frederiksen, P. Vestergaard, and H. H. Bruun. 2006. Limiting factors for seedling emergence and establishment of the invasive non-native Rosa rugosa in a coastal dune system. *Biological Invasions* 9: 31–42. doi:10.1007/s10530-006-9003-y.

Kollmann, J., R. H. Jørgensen, J. Roelsgaard, and H. Skov-Petersen. 2009. Establishment and clonal spread of the alien shrub Rosa rugosa in coastal dunes-A method for reconstructing and predicting invasion patterns. *Landscape and Urban Planning* 93: 194–200. doi:10.1016/j.landurbplan.2009.07.006.

Kunttu, P., and S.-M. Kunttu. 2017. Distribution and Habitat Preferences of the Invasive Alien Rosa rugosa (Rosaceae) in Archipelago Sea National Park, SW Finland. *Polish Botanical Journal* 62: 99–115. doi:10.1515/pbj-2017-0009.

LUNG. 1996. Biotopkartierung: Kieler Ort. *Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern*. Retrieved 2017-09-04, from https://www.umweltkarten.mv-regierung.de/meta/boegen/bk/0305-331B4004.PDF

LUNG. 2015a. Übersichtskarten der Schutzgebiete nach europäischem Recht. *Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern*. Retrieved 2017-09-12, from http://www.lung.mv-regierung.de/insite/cms/umwelt/natur/schutzgebiete_portal/schutzgebiete_karten.htm

LUNG. 2015b. Übersichtskarten der Schutzgebiete nach nationalem Recht. *Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern*. Retrieved 2017-09-12, from http://www.lung.mv-regierung.de/insite/cms/umwelt/natur/schutzgebiete_portal/schutzgebiete_karten.htm

Nehring, S., I. Kowarik, W. Rabitsch, and F. Essl. 2013. *Naturschutzfachliche Invasivitätsbewertungen für in Deutschland wild lebende gebietsfremde Gefäßpflanzen*. *BfN-Skripten 352*. Bundesamt für Naturschutz.

Weidema, I. 2006. NOBANIS – Invasive Alien Species Fact Sheet - Rosa rugosa. *Online Database of the European Network of Invasive Alien Species*. Retrieved 2017-09-12, from https://www.nobanis.org/globalassets/speciesinfo/r/rosa-rugosa/rosa_rugosa.pdf

Weisstein, E. W. 2018a. "Moore Neighborhood." *MathWorld - A Wolfram Web Resource*. Retrieved 2018-01-02, from http://mathworld.wolfram.com/MooreNeighborhood.html

Weisstein, E. W. 2018b. "von Neumann Neighborhood." *MathWorld - A Wolfram Web Resource*. Retrieved 2018-01-02, from http://mathworld.wolfram.com/vonNeumannNeighborhood.html

Wolfram, S. 2002. A New Kind of Science. *Wolfram Media, Inc.* Retrieved 2018-01-02, from http://www.wolframscience.com/nks/

# APPENDIX – TABLE OF CONTENT

# APPENDIX A WIND DIRECTION LOGIC BEHIND THE DISTANCE WEIGHTED AVERAGE CALCULATION

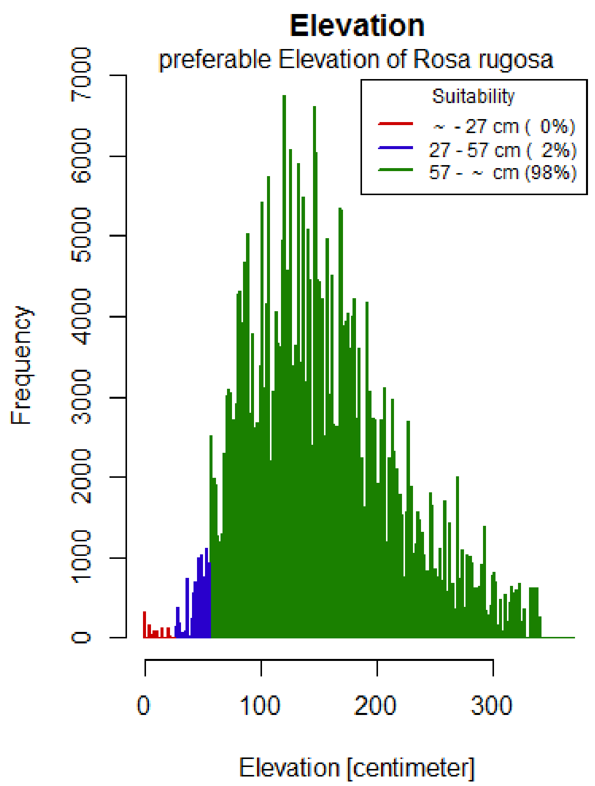
```
# BK/B == wind direction of Bastorf-Kägsdorf (BK)/Boltenhagen (B) in degrees
# weightBK/weightB == calculated weight for the distance to Bastorf-Kägsdorf/Boltenhagen

# diff (Difference of the wind direction between both stations in degrees)
IF (BK <> "" & B <> "")
  IF (|BK - B| <= 180)
    diff = |BK - B|
  ELSE
    IF (|(BK - 360) - B| < 180)
      diff = |(BK - 360) - B|
    ELSE
      diff = |BK - (B - 360)|
ELSE
  diff = ""

# preDWA (distance weighted average - without adjustment)
IF (BK <> "" & B <> "" & diff <> 180)
  IF (|BK - B| < 180)
    IF (BK > B)
      preDWA = BK - (diff * weightB)
    ELSE
      preDWA = B - (diff * weightBK)
  ELSE
    IF (BK > B)
      preDWA = BK + (diff * weightBK)
    ELSE
      preDWA = B + (diff * weightB)
ELSE
  preDWA = ""

# DWA (distance weighted average - with adjustment: value between 0 and 360 degrees)
IF (preDWA = "")
  DAW = ""
ELSE
  IF (preDWA > 360)
    DWA = preDAW - 360
  ELSE
    IF (preDWA < 0)
      DWA = preDWA + 360
    ELSE
      DWA = preDWA
```

# APPENDIX B WIND SPEED IN $MS^{-1}$ PER WIND DIRECTION

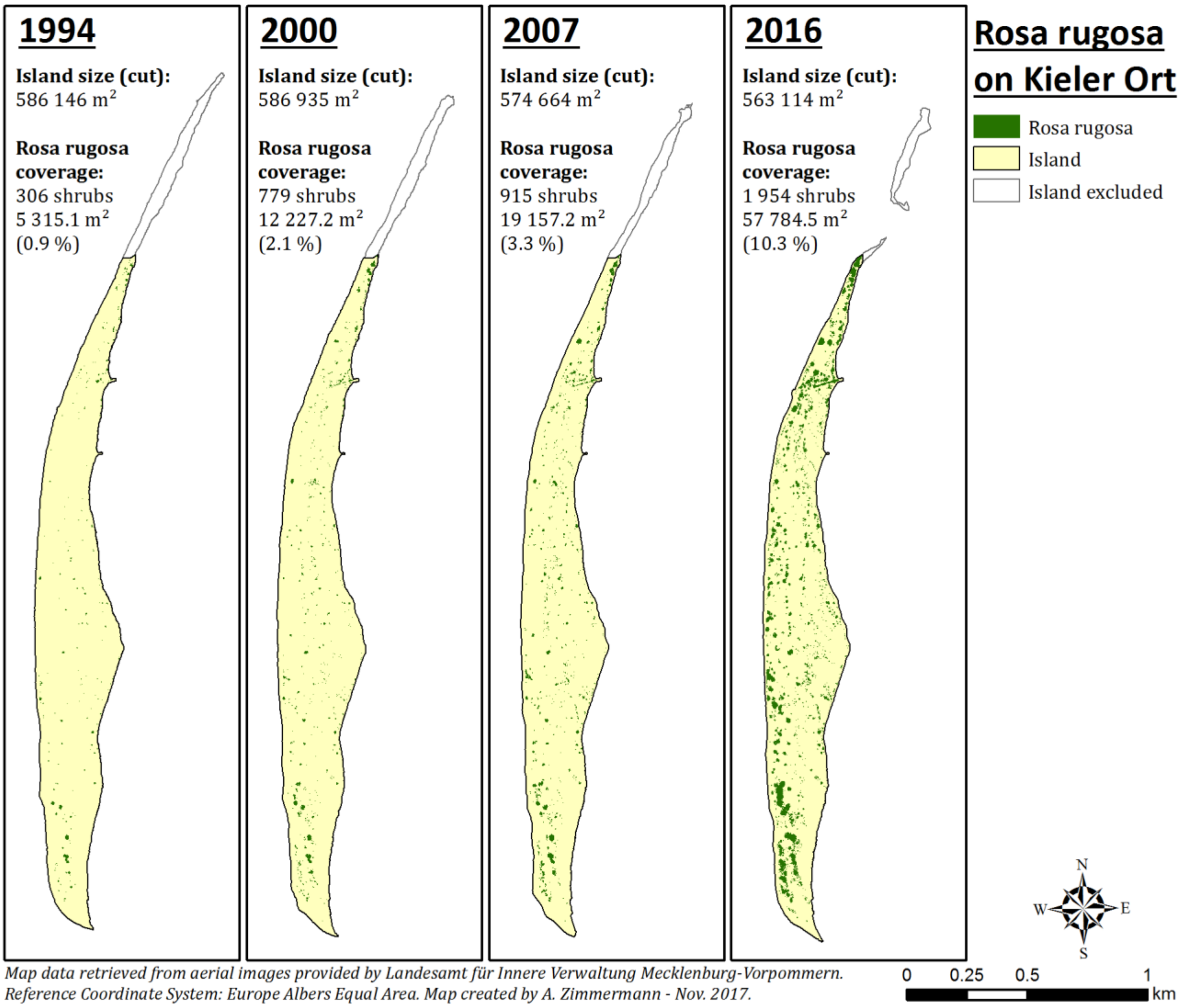
| wind direction | | Bastorf-Kägsdorf (SWN) | | | Boltenhagen | | | distance weigthed average | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2000 - 2016 | | min | average | max | min | average | max | min | average | max |
| **N** | (337.5° - 22.5°) | 0.00 | 4.59 | 19.70 | 0.00 | 5.09 | 21.10 | 0.00 | 4.55 | 18.89 |
| **NE** | (22.5° - 67.5°) | 0.10 | 4.59 | 16.90 | 0.10 | 6.24 | 120.00 | 0.04 | 5.27 | 48.15 |
| **E** | (67.5° - 112.5°) | 0.10 | 4.47 | 13.70 | 0.10 | 6.12 | 16.60 | 0.06 | 5.15 | 13.89 |
| **SE** | (112.5° - 157.5°) | 0.10 | 5.27 | 14.70 | 0.10 | 4.82 | 13.90 | 0.14 | 5.04 | 13.44 |
| **S** | (157.5° - 202.5°) | 0.10 | 6.06 | 1102.00 | 0.10 | 4.37 | 13.30 | 0.14 | 5.35 | 682.63 |
| **SW** | (202.5° - 247.5°) | 0.10 | 7.11 | 23.10 | 0.10 | 5.50 | 230.00 | 0.33 | 6.56 | 94.80 |
| **W** | (247.5° - 292.5°) | 0.10 | 6.92 | 23.90 | 0.10 | 6.47 | 24.10 | 0.08 | 6.81 | 23.82 |
| **NW** | (292.5° - 337.5°) | 0.10 | 6.20 | 310.00 | 0.10 | 5.18 | 18.30 | 0.12 | 5.81 | 192.30 |
| **Average** | | **0.09** | **5.65** | **190.50** | **0.09** | **5.47** | **57.16** | **0.11** | **5.57** | **135.99** |

## APPENDIX C SELECTED ELEVATION SUITABILITY

Classification of elevation suitability of *Rosa rugosa* – below 27cm (red): not suitable; between 27 and 57cm (blue): medium suitable (transition zone); and above 57cm (green): suitable. The legend shows the density of each class.



## APPENDIX D THE *ROSA RUGOSA* EVOLUTION WITH THE NORTHERN TIP EXCLUDED




*Map data retrieved from aerial images provided by Landesamt für Innere Verwaltung Mecklenburg-Vorpommern. Reference Coordinate System: Europe Albers Equal Area. Map created by A. Zimmermann - Nov. 2017.*

# APPENDIX E ANALYSIS OF *ROSA RUGOSA* EVOLUTION SUMMARY

| | 1994 – 2000 | | 2000 – 2007 | | 2007 – 2016 | |
|---|---|---|---|---|---|---|
| | **shrubs** | **area [m²]** | **shrubs** | **area [m²]** | **shrubs** | **area [m²]** |
| **Overall** | | | | | | |
| **start of period** | 306 | 5,315.1 | 779 | 12,227.2 | 915 | 19,157.2 |
| **end of period** | 779 | 12,227.2 | 915 | 19,157.2 | 1954 | 57,784.5 |
| **died RR** | | 1,332.8 | | 2,653.3 | | 2,288.7 |
| **eradicated** | 59 | 368.8 | 139 | 773.6 | 224 | 1,208.4 |
| **died-off** | | 964.0 | | 1,879.7 | | 1,080.3 |
| **survived RR** | | | | | | |
| **stayed** | | 3,982.2 | | 9,573.9 | | 16,868.5 |
| **new RR** | | 8,245.0 | | 9,583.3 | | 40,916.0 |
| **expanded** | | 4,286.8 | | 7,950.6 | | 29,703.7 |
| **new established** | 542 | 3,958.1 | 339 | 1,632.7 | 1465 | 11,212.3 |

## APPENDIX F "CONFIGURATION VALUES" OF THE SPATIAL MODEL

| | Period 1<br>1994–2000 | Period 2<br>2000–2007 | Period 3<br>2007–2016 | Period 1 and 2<br>average | Period 1, 2 and 3<br>average |
|---|---|---|---|---|---|
| **New establishments** | 0.999940747928239 | 0.999979038497002 | 0.999945278319768 | 0.9999598932126205 | 0.9999550215816697 |
| **Die-off** | | | | | |
| Partial die-off (1st year) | 0.997597647506009 | 0.999992716680657 | 0.989709583694277 | 0.998795182093333 | 0.9957666492936477 |
| Partial die-off (other years) | 0.053780776490364 | 0.044277826221544 | 0.105403469037398 | 0.049029301355954 | 0.067820690583102 |
| Suitability die-off | 0.393858156664439 | 0.398062489274172 | 0.441171274193036 | 0.3959603229693055 | 0.4110306400438823 |
| Random die-off | 0.735666477448442 | 0.744324868180380 | 0.799507550443914 | 0.739995672814411 | 0.7598329653575787 |
| **Expansion** | | | | | |
| Partial die-off | 0.461696528616394 | 0.475923263426088 | 0.484655908986509 | 0.468809896021241 | 0.474091900342997 |
| General | 0.035847115156184 | 0.105947026299379 | 0.041488994521594 | 0.0708970707277815 | 0.0610943786590523 |

# APPENDIX G CELLULAR AUTOMATA – MATLAB CODE

```
function compValue = CARosaRugosa(ConfValue)
% Function to predict Rosa rugosa coverage over a certain amount of years.
% The program uses the "Cellular Automata" method.
%
% Input:
%   - ConfValue: Array of 7 configuration values
%
% Output:
%   - compValue: scalar comparison value for optimization

%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

% SET-UP:
%---------
% Path to images, which shall be used as initial state:
% All images have to have the same row & column count and the same extent!
Rose_F = 'D:\RosaRugosaModel\InputFiles\RR1994cut.tif';  % rose = 1 | no rose = 0
Island_F = 'D:\RosaRugosaModel\InputFiles\I1994cut.tif';  % island = 1 | no island = 0
DEM_F = 'D:\RosaRugosaModel\InputFiles\DEM_suit.tif';  % suitability values between 0 - 1
Aspect_F = 'D:\RosaRugosaModel\InputFiles\Aspect_suit.tif';  % suitability values between 0 - 1

% output path:
Output_F = 'D:\RosaRugosaModel\OutputFiles\';

% year of initial image:
InitialYear = 1994;

% amount of years to process:
AmountOfYears = 6;

% radius (in cell count) to consider for new establishment of roses
NEradius = 500;

% detailed Summary (yes = 1 | no = 0)
detailedSummary = 1;

% perform comparison (yes = 1 | no = 0)
comp = 1;

% measured values
%        overall die-offs  expanded  new est.
% 1994:  5315.05
% 2000: 12227.19  1332.81   8244.96    542
% 2007: 19157.17  2653.30   9583.28    339
% 2016: 57784.48  2288.68  40916.00   1465
if InitialYear == 1994
    mShrubDieOff = 133281;
    mShrubExpansion = 824484;
    mShrubEstablishment = 542;
elseif InitialYear == 2000
    mShrubDieOff = 265330;
    mShrubExpansion = 958328;
    mShrubEstablishment = 339;
elseif InitialYear == 2007
    mShrubDieOff = 228868;
    mShrubExpansion = 4091600;
    mShrubEstablishment = 1465;
else
    comp = 0;
    mShrubDieOff = 0;
    mShrubExpansion = 0;
    mShrubEstablishment = 0;
end

%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

% Initialization
%----------------
% randomize random number generator
%rng(0,'combRecursive');

% set up year counter/array
YearCount = 1;

Years = zeros(1, (AmountOfYears+1), 'uint16');
Years(1) = InitialYear;
```

```
for i = 2:(AmountOfYears+1)
    Years(i) = Years(i-1) + 1;
end

% load additional images
DEM = imread(DEM_F);
Aspect = imread(Aspect_F);

[r,c] = size(DEM);

Island = false(r, c);
Island(:,:) = imread(Island_F);

Roses = false(r, c, (AmountOfYears+1));
Roses(:,:,YearCount) = imread(Rose_F);

% create Shrub counter
ShrubTotalC = zeros(1, (AmountOfYears+1), 'int32');
ShrubDieOffC = zeros(1, (AmountOfYears+1), 'int32');
ShrubExpansionC = zeros(1, (AmountOfYears+1), 'int32');
ShrubEstablishmentC = zeros(1, (AmountOfYears+1), 'int32');

ShrubTotalC(YearCount) = sum(sum(Roses(:,:,YearCount)));

% create Kernels:
% New Establishments Kernel (neighborhood based on Tobler's 1st Law)
CoI = false((2 * NEradius + 1));
CoI((NEradius+1), (NEradius+1)) = 1;
distanceKernel = bwdist(CoI, 'euclidean');
distanceKernel = distanceKernel.* (distanceKernel <= NEradius);
% exponential (squared)
NEkernel = ( (((NEradius.^2)+1) - (distanceKernel.^2)) ./ ((NEradius.^2)+1) );
NEkernel = NEkernel .* (NEkernel < 1);

% direct Neighbor Kernel (adopted Moor Neighborhood)
NBkernel = [0.75, 1.00, 0.75;
            1.00, 0.00, 1.00;
            0.75, 1.00, 0.75];

% Die-Offs Kernel (adopted Moor Neighborhood)
DOkernel = [0.25, 0.50, 0.25;
            0.50, 1.00, 0.50;
            0.25, 0.50, 0.25];

% Expansion Kernel (neighborhood based on Tobler's 1st Law)
NBradius = 5; % max radius (cell count) of neighbors that should be considered
CoI = false((2 * NBradius) + 1);
CoI((NBradius+1), (NBradius+1)) = 1;
distanceKernel = bwdist(CoI, 'euclidean');
distanceKernel = distanceKernel.* (distanceKernel <= NBradius);
% exponential (squared)
EXkernel = ( (((NBradius.^2)+1) - (distanceKernel.^2)) ./ ((NBradius.^2)+1) );
EXkernel = EXkernel .* (EXkernel < 1);

% clean up
clear Island_F DEM_F Aspect_F Rose_F InitialYear i CoI NBradius NEradius distanceKernel;

% show original image
imshow(Roses(:,:,YearCount),'InitialMagnification','fit');
title(sprintf('Rosa rugosa coverage for %d', Years(YearCount)))
drawnow;

% print heading and first row of detailed output (if detailed Summary was selected)
if detailedSummary
    fprintf(' year |     total [m²] | survived [m²] | expanded [m²] |    new [shrub] |\n');
    fprintf('------|---------------|---------------|---------------|---------------|\n');
    fprintf(' %d | %13.2f |               |               |               |\n', ) ...
            Years(YearCount), (cast(ShrubTotalC(YearCount), 'single')/100));
end

%--------------------------------------------------------------------------
% Cellular Automaton
%--------------------
YearCount = YearCount + 1;

while (YearCount <= AmountOfYears+1) % repeat for all years

    % copy data from previous year into this year
    Roses(:,:,YearCount) = Roses(:,:,YearCount-1);
    ShrubTotalC(YearCount) = ShrubTotalC(YearCount-1);
```

```
    ShrubDyingType = [0,0,0];
    ShrubExpansionType = [0,0];

    %----------------------------------------------------------------------
    % NEW ESTABLISHMENTS
    %--------------------
    % Get amount of rose neighbors per cell (distance weighted).
    neighbors = conv2(Roses(:,:,YearCount), NEkernel, 'same');

    % Get neighbor probability (a lot or close roses = high probability |
    %                            a few or further way roses = low probability)
    neighbors = (neighbors ./ max(max(neighbors)));

    % Get possible new establishments locations.
    % ... eliminate probability in rose cells (rose cells become 0) (keep neighbor probability)
    % Roses: 1 or 0
    % neighbors: 0 - 1 (low value - low chance | high value - high chance)
    NEprobability = ( (Roses(:,:,YearCount) == 0) .* neighbors);

    % ... eliminate/pre-select locations by suitability and random
    % Roses: 1 or 0
    % NEprobability: 0 - 1 (low value - low chance | high value - high chance)
    % Aspect (RRDenisty): 0/0.0408/0.0478/0.0486/0.0490/0.0857/0.1010/0.2096/0.4175
    % DEM: 0.00/0.02/0.98
    % RM: 0 - 1 (random)
    RM = rand(size(Roses(:,:,YearCount)));
    NEprobability = (( (NEprobability > 0) ... % for all locations that are within the specified
distance of a shrub
                        + (RM < NEprobability) ... % for all locations where random is smaller
than the probability
                        + ((Aspect .* RM) >= 0.02) ... % for all locations that are suitable (and
selected by random)
                        + ((DEM .* RM) >= 0.01) ) == 4); % for all locations that are suitable
(and selected by random)

    % Consider only a few make it.
    % NEprobability: 0 or 1 (if probability value was kept,
    %                        only the closest cells would have had a chance)
    % RM: 0 - 1 (random)
    RM = rand(size(Roses(:,:,YearCount)));
    NEprobability = ( (NEprobability .* RM) > ConfValue(1));

    % Maintain collectors
    Roses(:,:,YearCount) = Roses(:,:,YearCount) + NEprobability;

    ShrubEstablishmentC(YearCount) = sum(sum(NEprobability));
    ShrubTotalC(YearCount) = ShrubTotalC(YearCount) + ShrubEstablishmentC(YearCount);

    %----------------------------------------------------------------------
    % DIE-OFFs |
    %-----------
    % Die-Off: partial - if a neighbor had died, chances are high this one might die as well
    %------------------------------------------------------------------------------------------
    % If it is the first period, place random die-offs,
    % as there is no information on previous die-offs.
    if (YearCount == 2)
        % Get amount of direct rose neighbors per cell
        neighbors = conv2(Roses(:,:,YearCount), NBkernel, 'same');

        % Get possible die-offs
        % ... roses cells that have at least one neighboring cell that is not a rose.
        % Roses: 1 or 0
        % neighbors: 0 - 7
        DOpartial = ( (Roses(:,:,YearCount) == 1) .* (neighbors < 7) );

        % Pick a few to die
        % DOpartial: 0 or 1 (probability value was not kept, to keep it random)
        % RM: 0 - 1 (random)
        RM = rand(size(Roses(:,:,YearCount)));
        DOpartial = ( (DOpartial .* RM) > ConfValue(2));

        % Expand those die-offs along the shrub edge (less than 7 neighbors)
        % (neighborhood based on Tobler's 1st Law)
        NBradius = 5; % max radius (cell count) of neighbors that should be considered
        CoI = false((2 * NBradius) + 1);
        CoI((NBradius+1), (NBradius+1)) = 1;
        kernel = bwdist(CoI, 'euclidean');
        kernel = kernel .* (kernel <= NBradius);
        % linear
```

```
    kernel = ( ((NBradius+1) - kernel) ./ (NBradius+1) );
    kernel = kernel .* (kernel < 1);
    kernel((NBradius+1), (NBradius+1)) = 1;

    % get all cells around the picked die-off that has less than 7 neighbors (shrub edge).
    DOpartial = conv2(DOpartial, kernel, 'same');
    DOpartial = (DOpartial .* ( (Roses(:,:,YearCount) == 1) .* (neighbors < 7) ) > 0);

else
    % Get previous die-offs.
    previousDieOffs = ( (Roses(:,:,YearCount-1) - Roses(:,:,YearCount-2)) < 0);

    % Get amount of direct died-off neighbors per cell.
    DOneighbors = conv2(previousDieOffs, DOkernel, 'same');

    % Get die-off probability (a lot or close die-offs = high value)
    DOneighbors = (DOneighbors ./ sum(sum(DOkernel)));

    % Get possible die-offs
    % ... roses cells which have at least one neighboring cell that has died recently.
    %     (keep DOneighbors probability)
    % Roses: 1 or 0
    % DOneighbors: 0 - 1 (low value - little previous die-off - low chance |
    %                      high value - alot previous die-off - high chance)
    DOpartial = ((Roses(:,:,YearCount) == 1) .* DOneighbors);

    % Consider some will still survive.
    % DOneighbors: 0 - 1 (0.25/4=0.063) (1/4=0.25)
    % RM: 0 - 1 (random)
    RM = rand(size(Roses(:,:,YearCount)));
    DOpartial = ( (DOpartial .* RM) > ConfValue(3));
end

% Maintain collectors
Roses(:,:,YearCount) = Roses(:,:,YearCount) - DOpartial;
ShrubDyingType(1) = sum(sum(DOpartial));

% Die-Off: Suitablility
%-----------------------
% Get amount of direct rose neighbors per cell
neighbors = conv2(Roses(:,:,YearCount), NBkernel, 'same');

% Get neighbor probability (inverse: least neighbors = highest probability)
neighbors = 1 - (neighbors ./ sum(sum(NBkernel)));

% Get possible die-offs
% ... roses cells which have at least one neighboring cell that is not a rose.
%     (keep probability)
% Roses: 1 or 0
% neighbors: (0) 0.107 - 0.893 (0.107 most nb; 0.893 least nb)
DOsuitablility = ( (Roses(:,:,YearCount) == 1) .* (neighbors .* (neighbors < 1)) );

% ... edge of shrubs that are within not so suitable locations. (keep probability)
% DOsuitablility: (0) 0.107 - 0.893 (0.107 most nb; 0.893 least nb)
% DEM: 0.00/0.02/0.98
% Aspect (RRDenisty): 0/0.0408/0.0478/0.0486/0.0490/0.0857/0.1010/0.2096/0.4175
DOsuitablility = (DOsuitablility .* ( ((DEM <= 0.02) + (Aspect < 0.1)) >= 1 ));

% Consider some will still survive.
% DOsuitablility: (0) 0.107 - 0.893 (0.107 most nb; 0.893 least nb)
% RM: 0 - 1 (random)
RM = rand(size(Roses(:,:,YearCount)));
DOsuitablility = ( (DOsuitablility .* RM) > ConfValue(4));

% Maintain collectors
Roses(:,:,YearCount) = Roses(:,:,YearCount) - DOsuitablility;
ShrubDyingType(2) = sum(sum(DOsuitablility));

% Die-Off: random
%-----------------
% Get amount of rose neighbors per cell
neighbors = conv2(Roses(:,:,YearCount), NBkernel, 'same');

% Get neighbor probability (inverse: least neighbors = highest value)
neighbors = 1 - (neighbors ./ sum(sum(NBkernel)));

% Get possible die-offs
% ... roses cells which have at least one neighboring cell that is not a rose.
%     (keep neighbor probability)
% Roses: 1 or 0
```

```
    % neighbors: (0) 0.107 - 0.893 (0.107 most nb; 0.893 least nb)
    DOrandom = (Roses(:,:,YearCount) == 1) .* (neighbors .* (neighbors < 1));

    % Consider some will still survive.
    % DOrandom: (0) 0.107 - 0.893 (0.107 most nb; 0.893 least nb)
    % RM: 0 - 1 (random)
    RM = rand(size(Roses(:,:,YearCount)));
    DOrandom = ( (DOrandom .* RM) > ConfValue(5));

    % Maintain collectors
    Roses(:,:,YearCount) = Roses(:,:,YearCount) - DOrandom;
    ShrubDyingType(3) = sum(sum(DOrandom));

    ShrubDieOffC(YearCount) = sum(ShrubDyingType);
    ShrubTotalC(YearCount) = ShrubTotalC(YearCount) - ShrubDieOffC(YearCount);

    %-----------------------------------------------------------------------
    % EXPANSION |
    %------------
    % Get amount of rose neighbors per cell (distance weighted).
    neighbors = conv2(Roses(:,:,YearCount), EXkernel, 'same');

    % Get neighbor probability (a lot or close roses = high probability |
    %                            a few or further way roses = low probability)
    neighbors = (neighbors ./ (sum(sum(EXkernel))));

    % Get recent die-offs.
    recentDieOffs=( (Roses(:,:,YearCount) - Roses(:,:,YearCount-1)) < 0);

    % Get amount of direct died-off neighbors per cell.
    DOneighbors = conv2(recentDieOffs, DOkernel, 'same');

    % Get die-off probability (inverse: a lot or close die-offs = low probability)
    DOneighbors = (1 - (DOneighbors ./ sum(sum(DOkernel))));

    % Get possible expansions
    % ... non roses cells which have at nearby cell that is a rose. (keep neighbor probability)
    % Roses: 1 or 0
    % neighbors: 0 - 1 (low value - low chance | high value - high chance)
    neighbors = ( (Roses(:,:,YearCount) == 0) .* (neighbors .* (neighbors < 1)) );

    % ... roses cells which have at least one neighboring cell that has died recently.
    %     (keep DOneighbors probability)
    % Roses: 1 or 0
    % DOneighbors: 0 - 1 (high value - little previous die-off - high chance |
    %                     low value - alot of previous die-off - low chance)
    DOneighbors = ( (Roses(:,:,YearCount) == 0) .* DOneighbors );

    % neighbors: 0 - 1 (the higher the value, the higher the chance for expansion)
    % DOneighbors: 0 - 1 (the higher the value, the higher the chance for expansion)

    % Expansion: wandering
    %----------------------
    % If there had been recent die-off round a location, chances are lower that it will expand.
    EXPwandering = (( (neighbors > 0) ... % for all locations that are within the specified
distance of a shrub
                      + (DOneighbors < 1) ) == 2); % for all locations that are effected by
shrub wandering

    % Expansion: random
    %-------------------
    %  Except locations effected by wandering.
    EXPrandom = (( (neighbors > 0) ... % for all locations that are within the specified distance
of a shrub
                   + (DOneighbors == 1) ) == 2); % for all locations that are not effected by
shrub wandering

    % Consider not all will make it.
    % EXPwandering: 0 or 1
    % EXPrandom: 0 or 1
    % neighbors: 0 - 1 (low value - low chance | high value - high chance)
    % DOneighbors: 0 - 1 (4-0.25/4=0.938) (4-0.50/4=0.875) (4-1.00/4=0.750)
    % RM: 0 - 1 (random)
    RM = rand(size(Roses(:,:,YearCount)));
    EXPwandering = ( (EXPwandering .* DOneighbors .* neighbors .* RM) > ConfValue(6));
    EXPrandom = ( (EXPrandom .* neighbors .* RM) > ConfValue(7));

    expansionRR = ( ( EXPwandering + EXPrandom) >= 1);

    % Maintain collectors
```

```
    Roses(:,:,YearCount) = Roses(:,:,YearCount) + expansionRR;

    ShrubExpansionType(1) = sum(sum(EXPwandering));
    ShrubExpansionType(2) = sum(sum(EXPrandom));

    ShrubExpansionC(YearCount) = sum(ShrubExpansionType);
    ShrubTotalC(YearCount) = ShrubTotalC(YearCount) + ShrubExpansionC(YearCount);

    %-----------------------------------------------------------------------

    % show image of current year
    imshow(Roses(:,:,YearCount),'InitialMagnification','fit');
    title(sprintf('Rosa rugosa coverage for %d', Years(YearCount)))
    drawnow;

    % print detailed summary of current year (if detailed Summary was selected)
    if detailedSummary
        fprintf('      |               | %13.2f | %13.2f | %13d |\n', ...
                (cast(ShrubTotalC(YearCount-1)-ShrubDieOffC(YearCount), 'single')/100), ...
                (cast(ShrubExpansionC(YearCount), 'single')/100), ...
                ShrubEstablishmentC(YearCount));
        fprintf(' %d | %13.2f |               |               |               |\n', ...
                Years(YearCount), (cast(ShrubTotalC(YearCount), 'single')/100));
    end

    % increase year
    YearCount = YearCount + 1;
end
%-----------------------------------------------------------------------

% print final shrub size (if detailed Summary was deselected)
if detailedSummary
    fprintf('------|---------------|---------------|---------------|---------------|\n');
    fprintf('total |               | %13.2f | %13.2f | %13d |\n', ...
            sum(ShrubDieOffC)/100, sum(ShrubExpansionC)/100, sum(ShrubEstablishmentC));
else
    fprintf('final shrub size: %13.2f\n',ShrubTotalC(end)/100);
end

% save final to TIFF file
imwrite(Roses(:,:,end),sprintf('%sCA%d.tif',Output_F,Years(end)));

% return: comparison to measured values
if comp
    compValue = ( (1-(sum(ShrubDieOffC) / mShrubDieOff))^2 ) + ...
                ( (1-(sum(ShrubExpansionC) / mShrubExpansion))^2 ) + ...
                ( (1-(sum(ShrubEstablishmentC) / mShrubEstablishment))^2 );
    fprintf('comparison (configuration - measured): %f\n',compValue);
else
    compValue = 0;
end
```

**Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.**

Studentexamensarbete (seminarieuppsatser). Uppsatserna finns tillgängliga på institutionens geobibliotek, Sölvegatan 12, 223 62 LUND. Serien startade 1985. Hela listan och själva uppsatserna är även tillgängliga på LUP student papers (https://lup.lub.lu.se/student-papers/search/) och via Geobiblioteket (www.geobib.lu.se)

The student thesis reports are available at the Geo-Library, Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden. Report series started 1985. The complete list and electronic versions are also electronic available at the LUP student papers (https://lup.lub.lu.se/student-papers/search/) and through the Geo-library (www.geobib.lu.se)

400 Sofia Sjögren (2016) Effective methods for prediction and visualization of contaminated soil volumes in 3D with GIS
401 Jayan Wijesingha (2016) Geometric quality assessment of multi-rotor unmanned aerial vehicle-borne remote sensing products for precision agriculture
402 Jenny Ahlstrand (2016) Effects of altered precipitation regimes on bryophyte carbon dynamics in a Peruvian tropical montane cloud forest
403 Peter Markus (2016) Design and development of a prototype mobile geographical information system for real-time collection and storage of traffic accident data
404 Christos Bountzouklis (2016) Monitoring of Santorini (Greece) volcano during post-unrest period (2014-2016) with interferometric time series of Sentinel-1A
405 Gea Hallen (2016) Porous asphalt as a method for reducing urban storm water runoff in Lund, Sweden
406 Marcus Rudolf (2016) Spatiotemporal reconstructions of black carbon, organic matter and heavy metals in coastal records of south-west Sweden
407 Sophie Rudbäck (2016) The spatial growth pattern and directional properties of *Dryas octopetala* on Spitsbergen, Svalbard
408 Julia Schütt (2017) Assessment of forcing mechanisms on net community production and dissolved inorganic carbon dynamics in the Southern Ocean using glider data
409 Abdalla Eltayeb A. Mohamed (2016) Mapping tree canopy cover in the semi-arid Sahel using satellite remote sensing and Google Earth imagery
410 Ying Zhou (2016) The link between secondary organic aerosol and monoterpenes at a boreal forest site
411 Matthew Corney (2016) Preparation and analysis of crowdsourced GPS bicycling data: a study of Skåne, Sweden
412 Louise Hannon Bradshaw (2017) Sweden, forests & wind storms: Developing a model to predict storm damage to forests in Kronoberg county
413 Joel D. White (2017) Shifts within the carbon cycle in response to the absence of keystone herbivore *Ovibos moschatus* in a high arctic mire
414 Kristofer Karlsson (2017) Greenhouse gas flux at a temperate peatland: a comparison of the eddy covariance method and the flux-gradient method
415 Md. Monirul Islam (2017) Tracing mangrove forest dynamics of Bangladesh using historical Landsat data
416 Bos Brendan Bos (2017) The effects of tropical cyclones on the carbon cycle
417 Martynas Cerniauskas (2017) Estimating wildfire-attributed boreal forest burn in Central and Eastern Siberia during summer of 2016
418 Caroline Hall (2017)The mass balance and equilibrium line altitude trends of glaciers in northern Sweden
419 Clara Kjällman (2017) Changing landscapes: Wetlands in the Swedish municipality Helsingborg 1820-2016

420 Raluca Munteanu (2017) The effects of changing temperature and precipitation rates on free-living soil Nematoda in Norway.

421 Neija Maegaard Elvekjær (2017) Assessing Land degradation in global drylands and possible linkages to socio-economic inequality

422 Petra Oberhollenzer, (2017) Reforestation of Alpine Grasslands in South Tyrol: Assessing spatial changes based on LANDSAT data 1986-2016

423 Femke, Pijcke (2017) Change of water surface area in northern Sweden

424 Alexandra Pongracz (2017) Modelling global Gross Primary Production using the correlation between key leaf traits

425 Marie Skogseid (2017) Climate Change in Kenya - A review of literature and evaluation of temperature and precipitation data

426 Ida Pettersson (2017) Ekologisk kompensation och habitatbanker i kommunalt planarbete

427 Denice Adlerklint (2017) Climate Change Adaptation Strategies for Urban Stormwater Management – A comparative study of municipalities in Scania

428 Johanna Andersson (2017) Using geographically weighted regression (GWR) to explore spatial variations in the relationship between public transport accessibility and car use : a case study in Lund and Malmö, Sweden

429 Elisabeth Farrington (2017) Investigating the spatial patterns and climate dependency of Tick-Borne Encephalitis in Sweden

430 David Mårtensson (2017) Modeling habitats for vascular plants using climate factors and scenarios - Decreasing presence probability for red listed plants in Scania

431 Maja Jensen (2017) Hydrology and surface water chemistry in a small forested catchment : which factors influence surface water acidity?

432 Iris Behrens (2017) Watershed delineation for runoff estimations to culverts in the Swedish road network : a comparison between two GIS based hydrological modelling methods and a manually delineated watershed

433 Jenny Hansson (2017) Identifying large-scale land acquisitions and their agro-ecological consequences : a remote sensing based study in Ghana

434 Linn Gardell (2017) Skyddande, bevarande och skapande av urbana ekosystemtjänster i svenska kommuner

435 Johanna Andersson (2017) Utvärdering av modellerad solinstrålning i södra Sverige med Points Solar Radiation i ArcGIS

436 Huiting Huang (2017) Estimating area of vector polygons on spherical and ellipsoidal earth models with application in estimating regional carbon flows

437 Leif Holmquist (2017) Spatial runner: environmental and musical exposure effects on runners through an idealized routing network

438 Adriana Bota (2017) Methodology for creating historical land use databases – a case study for ICOS-station Hyltemossa, Sweden

439 Michael Araya Ghebremariam (2017) Urban flood modelling: a GIS based approach in Lomma, Skåne region

440 Stina Sandgren (2017) Climate change impact on water balance and export of dissolved organic carbon - a sub-catchment modelling approach

441 Karla Münzner (2017) Variability and regulation of the planktonic respiratory quotient in a eutrophic lake (Lake Vombsjön) in summer 2016

442 Bastian Berlin (2017) Modeling the Weibull shape parameter to improve estimates of the annual wind energy potential in Sweden

443 Christine Walder (2018) Humpback whale (*Megaptera novaeangliae*) location in Southeast Alaska: modeling the influence of mesoscale krill (*Euphausiacea*) patch depth and size

444 Astrid Zimmermann (2018) Projecting invasive species using remote sensing and spatial explicit models