The master's thesis (GEO4-1520)

What came first: the Chick or the Island

On the role of coastal birds in ecopote evolution of the Wadden Sea Islands

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Contents

Abstract

The Wadden Sea is a unique ecosystem and a very significant breeding, roosting, and migratory area for birds. Moreover, it protects the Netherlands from storms and the rising ocean. Due to the dynamic nature of local islands, it is important to find a key to natural preservation and sediment accumulation. Previous research showed that bird presence affects ecosystem productivity on hard-substrate islands via allochthonous nutrient transfer (guano, dead bodies) and physical disturbance (seed dispersal). At the same time, vegetation stimulates sediment accretion. However, how soft-substrate islands are shaped through bird-affected plant growth is not well studied, while the feedback between vegetation presence and sediment dynamics exists.

To reveal the influence on vegetation and sediment around, environmental characteristics are tracked within the timeline of 2017-2022 in the Dutch Wadden Sea within and outside of 61 avian colonies in a total of 9 different species. Based on normalized difference vegetation index (NDVI) and digital elevation maps (DEMs), four parameters are comprised: mean summer NDVI as a proxy for the amount of vegetation, a linear coefficient of spring greening (greening index) for noting the slope of vegetation increase, total elevation is taken as stated in DEMs, and an absolute maximum of space slope represents steepness. Eventually, all possible combinations of these characteristics are broken down into groups and 32 clusters are composed to reflect ecotopes. To demonstrate the evolution, a linear annual coefficient of continuous data and variability of categorical data are compared between groups and per island.

Overall, birds prefer highly vegetated places which green over spring with gently or not inclined low terrains and the clusters corresponding to these attributes. These distributions correspond with species' habitat preferences. Over the years, mean NDVI and greening index increase faster within avian colonies than outside while in general there is no significant common trend for elevation or slope changes. Random forest classification also stresses the importance of vegetation parameters for bird prediction. However, the tendency is clearer if considered per island.

The stage of island development defines the magnitude and direction of the bird effect. Islands in the bio-morphological stage are susceptible to the nutrient pump as both elevation and vegetation are increasing. Whereas, on islands in the ecological stage summer mean NDVI is growing even faster but without any effect on abiotic parameters. Cluster variability also reflects these stages, where on the first kind of islands birds dwell on more dynamic territories in comparison to the outside. While both groups transition from unvegetated areas to vegetated ones, birds boost this shift. Whereas, on islands undergoing succession birds are located in more stable places in comparison to the surrounding.

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Introduction

Theoretical background: global view

Birds as a source of vital nutrients

Because of its nature, there are not so many subsidies on the island as most of them constantly wash into the sea [1], [2]. Therefore, the allochthonous transfer is essential for life to thrive in these habitats [3]. Coastal or seabirds among other animals import these extra supplements from the outside world influencing the whole ecosystem [4], [3], [1], [5], [6].

Fertilisers such as guano [7], [8] or (parts of) bodies [9], [10] bring nutrients to the soil boosting vegetation around and further up the food chain. The number of nutrients deposited by birds (especially N and P [11], [1]) is bigger [12], [6] during the breeding season and at rookeries [13], [14] or around burrows [15]. However, sometimes guano does not stimulate plant growth due to its dissoluble state, over-concentration ("ammonia shadow") [14], [4] leads to soil alkalisation [16] or wash away offshore [7], [17]. Therefore, the density of colonies is significant too with highly populated areas containing fewer plant species [12], [18]. Yet visa versa intermediate amount stimulates this parameter [12]. The impact decreases with the distance from seabirds' colonies [19]. As for other effects, burrowing or tramping can create physical disturbances which could both aerate soils and damage roots [12]. Moreover, different species produce different guano based on their diet [20], [21] and affect different vegetation differently [22], [21]. Besides, birds can distribute seeds with their defections [23]. Nevertheless, sometimes there is no influence of nesting seabird colonies [24].

Thus, birds play an important role as keystone species for islands stimulating vegetation via allochthonous nutrients [12]. By this transfer the soil becomes more fertile and more plants start growing [8] supported by increased seed distribution and germination [25]. That activates the positive feedback by preventing the washout of this nourishment [26]. Subsequently, highly productive areas become less dependent on external subsidies and more self-sufficient [27].

Vegetation shapes habitats on islands

By changing and stabilising the environment [28] as an ecosystem engineer [29] vegetation defines the surroundings and creates a safe place for other species to anchor.

Vegetation provides food, shelter, and other resources for animals living on islands and plays a critical role in forming habitats there. Moreover, on islands the presence of certain species, species richness, and overall bird frequency could be significantly influenced by vegetation type [30]. Thus, vegetation is crucial for birds to settle. In turn soil composition could determine vegetation types [31] when the edaphic environment is chemically influenced by birds [11], [1], [12]. So, the landscape can be a function of bird presence; however, a landscape can also dictate bird colony establishment (fig.1).

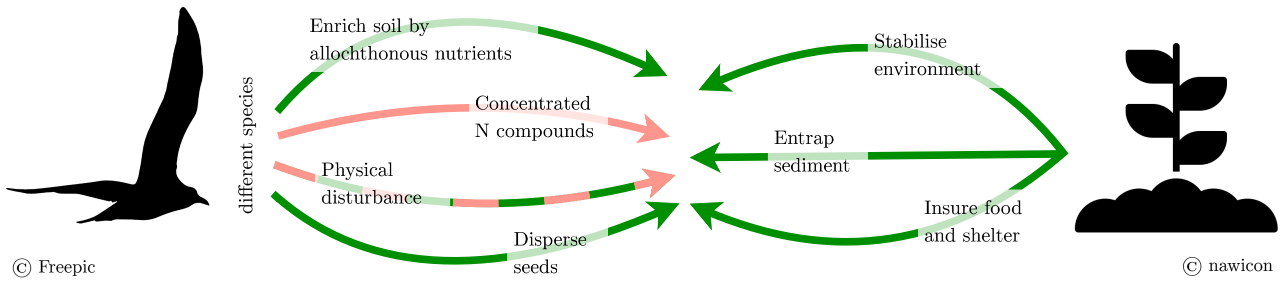


Figure 1: The chicken or the egg causality dilemma: birds contribute to vegetation thriving as well as vegetation facilitate the environment for birds' settlement

As for physical impact, vegetation (plants, algal/diatom/microbial mats) acts as a natural sediment trap and limits erosion [32], [33]. Also, plants accumulate nutrients and by that produce even more sediment [34]. Furthermore, they initialise positive feedback [35] when more plants start growing around [36], [37] and entrap sediment [38]. That leads to sediment accumulation by root entrapment which in general causes elevation [39]. So, vegetation could be potentially used as a coastal protection strategy [28], [40].

Such features as sediment entrapment and stabilisation could be essential to make the dynamic sandy islands of the Wadden Sea livable for birds and other animals.

Theoretical background: meanwhile in the Wadden Sea

Sandy islands could be unstable

The dune and geest/marsh barrier islands enclose the Wadden Sea as a belt from the North Sea along three countries: the Netherlands, Germany, and Denmark [32]. Moreover, there are also many (65) sandy islets in the inlets which share sediment as an enclosed system (fig.2) [41], [42].

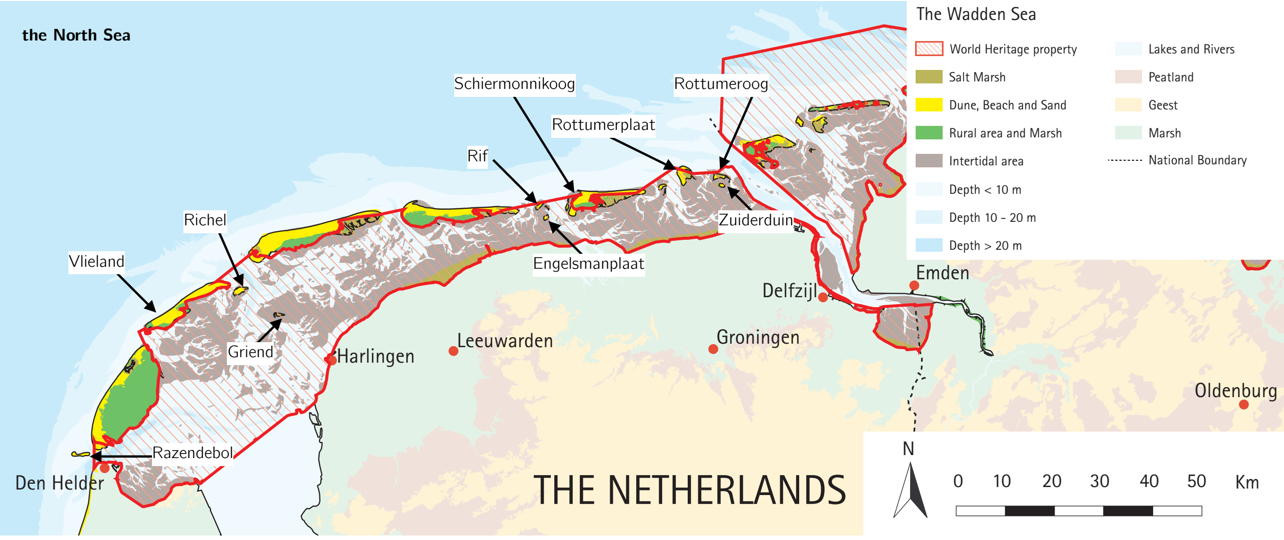


Figure 2: The Dutch part of the Wadden Sea: only islands used in this research are marked. Source: WHC UNESCO (modified)

The smaller islands are more dynamic and shifting; they could emerge or disappear under the water [43], [44]. Nowadays, the whole chain is migrating landwards at 1-2 m/year and eroding at some parts often by winter storms [32], [42]. Therefore, sometimes people are trying to control this and prevent islands from rebuilding by applying nourishment [45], for example on Griend and Vlieland [42], [46]. That causes a succession across vegetation [47] especially with no or moderate intervention [40]. Island fixation is generally not good for biodiversity and resilience, therefore this new hands-off policy [42] was chosen: for Rottumerplaat, Rottumeroog, and Zuiderduin to let them be dynamic [48], [43].

Some of those islands are full of plants and animals (Richel, Zuiderduin, Rottumerplaat, etc), while others are bare (Razendebol, Engelsmanplaat, Rif, etc). Despite having a physical place, some areas are not inhabited because of too strong geomorphological dynamics [49] with intense burial and erosion, frequent storms or other environmental disturbances. Periodic saline water flooding could affect too [50], [51]. Also, very small islands physically can not form long-lasting vegetation establishments because of an absence of suitable niches [52], [53]. Nonetheless, when a window of opportunities gets open [54] the environment goes from a geomorphologic stage with a dominance of abiotic factors to a bio-geomorphologic one with vegetation settlement [49]. Further, this establishment could ecologically transit into succession.

As all islands are similar in terms of geography and climate, they have analogous compositions of typical vegetation zones with a difference in a succession stage.

Vegetation on islands and its capacity

Apart from vegetation under the seawater level, salt marshes, sandy beaches with dunes and dune slacks, and fresh grasslands are the most common ecotopes in the Wadden Sea (fig.2) [55]. Woodlands can also appear on slacks and dunes [36].

Salt marshes contain enough nutrients and elevate fast

The salt marshes (including pioneer and low-marshes) appear in the flooded from time to time upper intertidal territory with brackish or saline water around [56], [57]. They are located in areas with low wave stress and therefore mud accumulation [58], [59], [60].

Nutrient-wise, in general, salt marshes are considered to be a nutrient-rich environment [56]. Where extra nitrogen causes an increase in the total above-ground biomass on the low salt marsh and no impact on the high marshes [61], [62]. While there is no effect of P and K addition [61] or low influence of P [62]. The effect also depends on the succession stage with late-successional one more susceptible [62].

Being at the edge, accretion rates of salt marshes are crucial for protection from sea level rise (SLR) [63], [64]. Here, foreland salt marshes elevate 3x times faster than SLR [40]. Whereas, the elevation is lower than SLR for halligs and almost at the same speed for barrier-connected island salt marshes which is caused by negative feedback [40]. Man-made salt marshes grow higher than natural ones due to differences in drainage [65]. With ages old salt marshes almost stop growing [66], [64].

Dunes are dynamic and poor in supplements

Just like islands, sandy shores also undergo geomorphological, bio-geomorphological, and ecological phases [67], [68]. This group could be divided into two ecosystems: 1) within the tidal zone with beaches, surfzones, and nearshores; 2) supratidal areas and uplands with the coastal dune systems [44]. Further only the latter habitat will be considered.

For dunes island age, grazing, and level of androgenic impacts define vegetation area and composition [44]. To secure its position, the sediment bed should be stable [69]. After that when the establishment is sufficient the bio-geomorphological stage starts. Later, with successful vegetation settlement succession goes into the ecological phase [68]. In return vegetation helps dunes to grow [32] and stabilise them [70], [71].

Coastal dunes are considered to be a nutrient-poor environment [72], [44]. Atmospheric nitrogen deposition as a significant nutrition input leads to acidification, eutrophication, grass invasion, and a rapid species-poor succession from pioneer to woodlands [73], [36]. The increasing temperature can bust vegetation yet droughts and aeolian mobility too [36].

All in all vegetation patterns are influenced by keystone species and starting conditions as these things define soil composition and condition [74]. Where seabirds could directly change these parameters [12].

Bird situation or ei voor eiland

Due to its richness of food in intertidal communities and space on islands, the Wadden Sea is a hotspot place for wintering, breeding, and migratory birds [75], [76].

Table 1: Population dynamic and species preferences for birds in the Wadden Sea

bird name	long-term*	short-term**	Flyway 2011-2020	population size***	habitat
Great cormorant	⬆ ⬆	➡	⬆ ⬆	4 873	saltmarshes [77]
Sandwich tern	➡ ⬆	➡ ⬆	➡	15 780	bare sand, dune ridge [78]
Black-headed gull	➡ ⬇	➡ ⬇	⬇	113 723	saltmarshes, polders [79]
Eurasian spoonbill	⬆ ⬆	⬆ ⬆	⬆ ⬆	1 945	saltmarsh[80], low dune[81]
Arctic tern	➡ ⬇	⬇	-	4 849	saltmarshes [79]
Common (mew) gull	➡	➡ ⬇	⬇	13 011	low saltmarsh[82], dune[83]
Common tern	➡ ⬇	⬇	➡	8 442	saltmarshes [79]
European herring gull	⬇ ➡	➡	⬇	62 278	dunes, saltmarshes [84]
Lesser black-backed gull	⬆	➡ ⬇	➡	94 496	dunes, saltmarshes [85]

* for 23-year period 1997/98-2019/20 [86], for 26 years 1991-2017 [87], from 1980s-90s by Sovon Stats
** for 10-year period 2010/11-2019/20 [86], for the past 12 years [87], for the past 12 years by Sovon Stats
*** number of breeding pairs in 2012 [87]

⬆ means *increase* in population size; ➡ means *stable*; ⬇ means *decrease*

However, the reproduction rate and amount of many beach-breeding (18/33 species) and migratory (13-16/34 species) birds are declining (tab.1) especially with those in dunes and in the western part [88], [76], [75], [86], [87]. Moreover, predators' pressure (plus hunting), lack of food leading to starvation, and flooding depress populations [89]. Yet some colonial breeders are stable or raising in numbers [75]. Furthermore, wind farms (as well as other human constructions and artificial light [90]) get in the flyways and cause collisions [91]. Also, sand nourishment affects birds and macrozoobenthos [76] since it literally buries such needed birds' food [92]. The intertidal flats area can also shrink because of SLR [93]. As for other human impacts, herbivorous birds compete with livestock and agriculture [75], shellfish-eating or piscivorous birds are versus fisheries [94], [76]. The level of contamination is considered to be not hazardous for eggs [95].

Ecotopes: finite clusters to simplify environment

Ecotope is an easily recognisable, homogeneous, and mappable part of the physical environment/ecosystem that combines both geological parameters and biological community features.

Previously a significant amount of ecotope classifications was made for the Wadden Sea and/or for its Dutch part: [96] (islands; vegetation and landscape), [97] (littoral and supralittoral; sediment composition, abiotic factors as for emersion, and benthic biocommunities), [98] (Dutch national waters; abiotic parameters: depth, exposure time, dynamics, sediment composition, salinity), [99] as known as the ZES.1 system (coastal and transitional waters; abiotic factors: salinity and its variation, type of substratum and its composition, type of littoral and its depth subtypes, hydrodynamics), [100] (the Dutch part; depth, silt), [101] (the Dutch littoral and supralittoral part; bathymetry (depth), sediment, exposure time, coastal vegetation, mussels and eelgrass presence), [102] (the sublittoral and the littoral zones of the Western Scheldt; abiotic parameters (flow velocity, median grain size and other sediment characteristics, depth, duration flow velocity > 65 cm/s, salinity), benthic organisms (species richness, log transformed density, log transformed biomass)), [103] (of the Eems-Dollard estuary; salt content, bathymetry (bottom height, depth classes, exposure time), hydrodynamics, salt marshes, eco-elements such as eelgrass beds, banks of mussels and oysters, shipwrecks, gullies), [104] (the Dutch Wadden Sea; salt content, bottom height and depth, hydrodynamics, salt marshes including supratidal dunes, sediment and substrate, eco-elements such as eelgrass or mussel/oyster beds), [105] (39 tidal basins of the entire Wadden Sea; bathymetry, salinity, flow velocity, exposure time, sediment composition, hard substrates and salt marshes). Yet most of them are dedicated to the most-of-the-time underwater inlet systems. Islands and their vegetated landscapes are reviewed only once and almost half of a century ago [96]. Moreover, most of them are based on the hierarchical idea of abiotic parameters determining biological ones [106].

Since birds can change the physical environment, ecotopes can help identify environmental change as a consequence of bird presence.

Identifying possibilities

Scientific gap

In the Wadden Sea, there is a lot of literature on how birds are affecting soil composition, and vegetation communities, but not the direct relation between bird-affected plants and morphology [42]. Nonetheless, avians are expected to have an influence [75]. Here the increase in numbers occurs for birds (tab.1) [76] that mostly live on the salt marshes as the fast-elevating habitats [40]. Also, due to the high nutrient input, rookeries are anticipated to speed up succession on the younger island [44]. So, potentially there are prerequisites for finding the correlation between surface elevation, amount of vegetation, and birds in the Wadden Sea.

Also, no multi-year ecotope map of the supratidal parts of islands in the Wadden Sea is available right now. Making one could simplify tracking and calculations.

Practical relevance

The Netherlands is sinking due to several naturally or anthropologically caused reasons such as subsidence, volume reduction of deltas leading to less sediment accumulation, sea level rise (SLR), etc [42], [33]. Yet there are some counterbalances of the coming doomsday such as glacial isostatic adjustment (ground goes up) [107] and Greenland melting ice mass self-gravitation (water goes down). Thus, a silver bullet against drowning would be to accumulate sediment faster and naturally [108], [28], [33].

Currently, the Wadden Sea receives natural sediment input and also from artificial nourishment that rate of accumulation is higher than SLR [109], but maybe not enough for future [41], [42]. As it is recognised as a UNESCO World Heritage Site [110], some saving strategies should be researched for its natural conservation.

As the sea level rise, there is less space for birds to breed and rest. Therefore, preserving islands is crucial for the survival of these keystone species and the whole unique ecosystem.

Aim

Find a correlation (or its lack) between island ecotope compilation, vegetation, elevation, and birds' composition and distribution in the Dutch Wadden Sea over 2017-2022. Figure out the evolution linkage between abiotic conditions, vegetation, and birds by analysing the trend.

Research questions

1. How does the presence of birds correlate with:
    1.1. amount summer vegetation and speed of its spring greening?
    1.2. elevation and space slope?
    1.3. certain types of vegetation zone codes?
2. To what extent does the birds' presence affects over time:
    2.1. amount summer vegetation and speed of its spring greening?
    2.2. elevation and space slope?
    2.3. certain types of vegetation zone codes?
3. Can clustered ecotopes be used as indicators to detect any avian colonies or even point to the exact species?
4. Could one of the environmental parameters be used as a proxy of avian colonies or species?
5. Do any characteristics of avian species such as density, diet, time of migration, etc have an effect on any environmental parameters?
6. How does the stage of island development affect the influence of birds' presence?

Hypotheses

1. 1.1. With more vegetation there should be a higher rate of elevation yet with regards to vegetation type.
    1.2. Birds are found more often at higher vegetated elevations.
2. With more birds there should be more vegetation and a higher rate of its intensity leading to an increase in sediment accumulation yet with regard to vegetation type.
3. All birds pilled up together could not be defined as they inhabit different environments. As some species are specialists and other are generalists regarding the ecological niche, some of them could be described by clusters while others do not.
4. Variables reflecting trend and magnitude of development could be used to detect birds' presence but with comparison to the local outside areas.
5. 5.1. The decline in breeding birds speeds down the elevation rate and vegetation.
    5.2. Diet could impact as different forages contain different amounts of nitrogen.
6. A stage of island development influences environmental parameters on a greater scale than the presence of birds.

Approach/methods

Normalized difference vegetation index (NDVI) and digital elevation models (DEMs) would be used as a proxy for vegetation and elevation respectively.

Data will be retrieved from AHN (DEMs), Planet (NDVI), Rijkswaterstaat (vegetation maps), and the field trip or local counters (birds) from the period of 2017-2022 for the Dutch Wadden Sea.

Ecotopes will be grouped by supervised clustering based on elevation, vegetation quantity, and their derivatives. The correlation with bird colonies will be assessed. The relationship will be researched via the evolution of the ecotopes and birds per island. The results will be explained by statistical analysis (such as logistic regression and random forest classification).

Theory of methods: how it works

DEMs

Digital elevation models (DEMs) reflect a relief map of a landscape as a point cloud (fig.3A). For the current research purposes, it could also be described as digital terrain models (DTMs) since they should represent exactly the bare ground surface i.e. the ground level.

Airborne LiDAR (LIght Detection And Ranging) is one of the methods used for mapping the Wadden Sea with high accuracy and resolution [111]. The laser (usually near-infrared light) is beamed by an emitter (satellite, plane, UAV) and backscatters from any surface. Response time and returning angle constitute height and elevation direction. However, part of it is absorbed differently by water and land. Therefore, it reflects also qualities of a pined point [112], [113]. Moreover, LiDAR can show canopy height and volume in addition to the ground level [114].

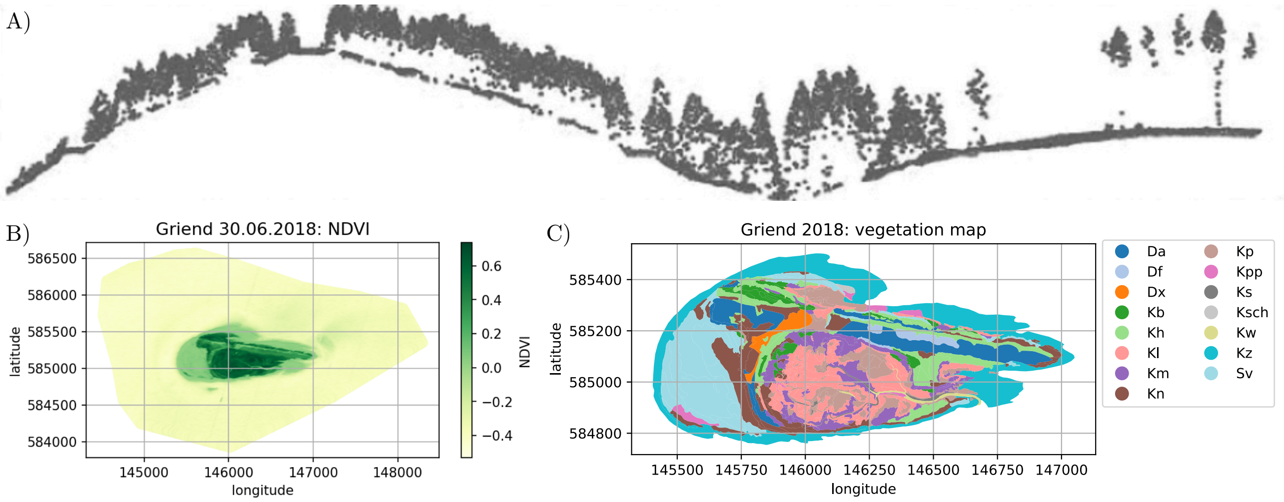


Figure 3: Data: how it looks like. A) a LIDAR map from [114], B) an NDVI map by Planet, C) a vegetation map from the database by Rijkswaterstaat

NDVI

Normalized difference vegetation index (NDVI) is used as a proxy for chlorophyll A and therefore for the amount of vegetation (fig.3B). During photosynthesis, chlA absorbs red and blue lights, yet re-emits near-infrared (NIR) ones. Thus, all vegetation shines bright in the NIR radiation spectrum and dark in the red one which can be easily detected by filters [115], [116]. In contrast, other materials like soil and water reflect way less at NIR wavelengths [117]. NDVI represents the ratio of NIR to red light as:

$$NDVI = (NIR - Red)/(NIR + Red) \tag{1}$$

Vegetation ecological groups distribution

Vegetation mapping databases by Rijkswaterstaat are built based on aerial photographs and fieldwork (fig.3C). Zonation is based on the Salt97 and Salt08 classifications, where typology has been harmonised for the whole data frame [55].

Methods

Data sources

The current research is based on two environmental parameters (vegetation index and elevation level) and the presence of birds on 10 islands in the Wadden Sea: Razendebol, Vlieland, Richel, Griend, Rif, Engelsmanplaat, Schiermonnikoog, Rottumerplaat, Rottumeroog, Zuiderduin. Vegetation maps are checked for co-dependence.

NDVI

The NDVI (normalised difference vegetation index) data is obtained via Planet which collects terrain images through its constellation of satellites (PlanetScope). The resolution of GeoTIFF files is 3 meters per pixel. To catch vegetation intensity, both red and near-infrared spectra are needed. Therefore, the orthorectified option is chosen with four bands (near-infrared, red, green, and blue channels). This analytic asset type compensates for terrain distortions and sensor artefacts and translation to Top of Atmosphere (at-sensor) radiance. Since the company started to launch only in 2016, the first space- and time-consistent images appeared in 2017. The data is reached with the university access and published with a Creative Commons 4.0 licence.

DEM

The DEM (digital elevation model) data sets are provided by AHN (Actueel Hoogtebestand Nederland). The cloud points (*.laz files) and georeferenced images (*.geotiff files) are retrieved from Rijkswaterstaat via GeoTiles, Deltares, or directly. Only the AHN3 and AHN4 projects are explored since they cover timelines of 2014-2019 and 2020-present years respectively. This survey of topography measurements is operated annually for highly dynamic areas such as the Wadden Sea. It is licensed for free usage for research purposes with acknowledgements to Rijkswaterstaat. For 2021 data is kindly provided by K.J. (Kasper) Meijer, MSc, University of Groningen. It also originates from coastal LiDAR by Rijkswaterstaat.

Birds

Polygons with the presence/absence of specific avian species are comprised based on point data by Floris van Rees, MSc or personal observations of local rangers. Polygons of Griend, Rottumerplaat, and Texel are based on delineating a convex hull around individual nest locations as 0.03 nests/m^2 in 2022 that were localized by a survey of the local ranger. The Schiermonnikoog shapefile is a convex hull on nest locations identified by a drone in 2020. The polygons of Richel, Zuiderduin, Vlieland, and Rottumeroog are formed by experienced local rangers who draw polygons built upon their grounded expertise in the field. Besides, areas within a radius of 300 metres are considered as outside of avian colonies. It is all shared with freedom of use.

Vegetation maps

The VEGWAD dataset contains information about vegetation's ecological groups in polygons. It is released by Rijkswaterstaat approximately every 6 years and includes data from 01.01.1978 with the last update on June 2020. It is distributed under the Creative Commons 1.0 licence with no usage limits.

Data availability

As proper NDVI data is accessible only from 2017, the timeline of this thesis is from 2017 to 2022 inclusively. Overall, 10 islands are chosen with control including. In the beginning, Texel was considered to be one of the most interesting locations. However, it was eliminated because of the almost complete absence of DEM data (fig.A.1). Also, sometimes a lack of full-time or space coverage for one of the parameters occurs within other islands (tab.2, NDVI per island per year in the Supplementary materials fig.B.1-B.10).

Table 2: NDVI and DEM data availability for 2017-2022

	Razendebol	Vlieland	Richel	Griend	Rif	Engelsmanplaat	Schiermonnikoog	Rottumerplaat	Rottumeroog	Zuiderduin
2017		🟩		🟥	🟥	🟥	🟩			
2018	🟩	🟩								
2019										
2020		🟩								
2021										
2022							🟩			
tiles*	09cz2	04gn2 04ez2 04fz1	04fz2	05cn2	02dn2 02gn1	02dn2 02gn1	02fz1, 02fz2, 02hn1, 02hn2	03an2 03az2 03bz1	03bz1 03bz2	03bz1 03bz2

🟩 represents the lack of NDVI data to perform the analysis

🟥 represents the lack of DEM data to perform the analysis

* researched areas of interest are indicated as geotiles encoded by AHN

Data for bird colonies is available only in 2020 for Schiermonnikoog and only in 2022 for the rest of the islands. Yet, a colony location does not change much over the years [118] (especially of the Herring gull [119]).

Vegetation maps within the chosen timeline are possible to compose only for Griend and Richel in 2018.

Raw data processing

The processing and also further analysis are executed by Python v3.7 if the opposite is not stated. A significant number of processes are accelerated by `numba`. The versions of packages could be found in Supplementary materials (tab.C.1).

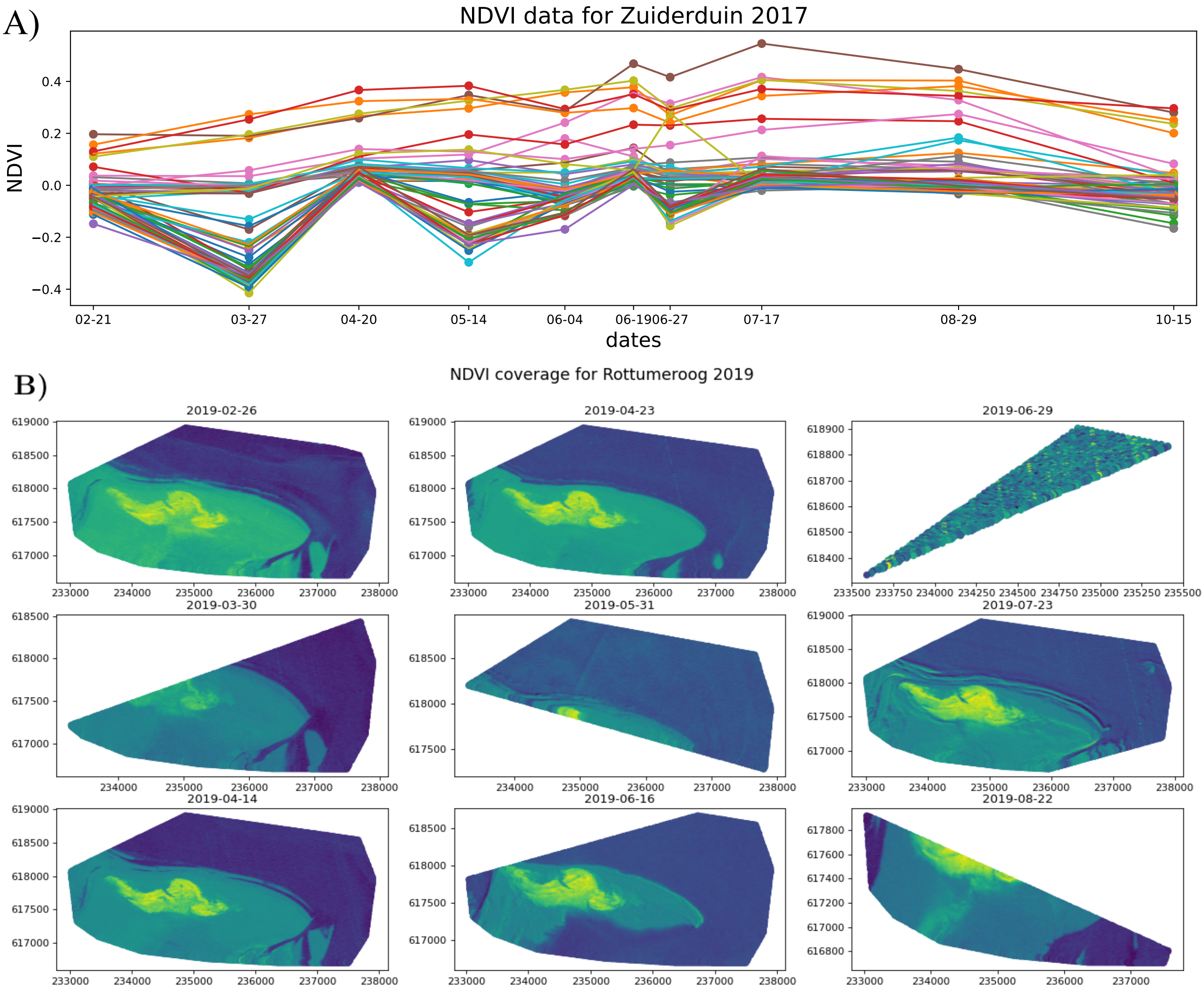


Figure 4: Coverage of NDVI: A) time coverage, B) space coverage

NDVI

Data is retrieved from the Planet servers via its standard API protocols with the `requests` library [120]. Ideally a space point is requested every two weeks from mid-February til the end of June when only one point is ordered in July and August (fig.B.1-B.10). The cloud coverage is set to be less than 10%. All geometry settings are consistent within a settled polygon shape for each island by using `geopandas` and `shapely` libraries. An obtained GeoTIFF file is translated from geographical coordinates in World Geodetic System (WGS84, EPSG:4326) into the Rijks-Driehoek System (RD, EPSG:28992) by `osgeo.gdal` and henceforth by `pyproj`. Furthermore, the `rasterio` package extracts red and near-infrared bands from this GeoTIFF file and transfers them into `numpy` arrays to calculate NDVI (eq.1). The result is stored in a `pandas` data frame as tidy data for each pair of geographical coordinates with time NDVI points as characteristics. In the end, ideally (tab.4) there are around six tables (one per year) for each island with ideally 10 data points per year (one in February + 2x month in March-June + one in July + one in August) stored as *.csv files.

As often data is scarce (fig.4A, only one point per spring month; fig.4B, partial space availability), it has to be transformed into combining illustrative features. Thus, a mean of all NDVI points during the summer months (hereinafter referred to as **mean NDVI**) is chosen for a description of total vegetation because it is stable and at its maximum amplitude throughout that time (fig.4A). Whereas, the springtime slope defines the intensity of greening. For that a linear coefficient (hereinafter referred to as **greening index** or **GI**) is calculated starting at the mid-end of February and during the following spring months. Different time gaps between data points are taken into account by the `datetime` library.

DEM

All elevation models are acquired from AHN but in three different ways. Most DEMs are obtained via the OPeNDAP servers linked to the Deltares database using `pydap`. The output is in the DatasetType format from which among other characteristics a system of coordinated (CRS), latitude and longitude, time (yearly), and height (Z) could be retrieved. Geographical coordinates are in the Rijks-Driehoek System (RD, EPSG:28992). The time is counted as the number of days from 01.01.1970. For 2021 DEMs by K.J. (Kasper) Meijer are attained in form of one large GeoTIFF file for the whole Wadden Sea. The data is transferred into a `pandas` data frame by `rasterio`. Only the islands of interest are filtered and stored. As it does not contain Razendebol, Vlieland, and Schiermonnikoog, those islands and all ones in 2022 are extracted from the original point clouds (*.laz files). CloudCompare v2.13.alpha [macOS 64-bit] or `lastools` transform from the LAZ format to the LAS one. The `arcpy.conversion.LasDatasetToRaster` function from ArcGIS Pro converts LAS lidar point cloud data to a GeoTIFF raster. The rest of the processing is the same as for 2021 data from K.J. Meijer using `rasterio`. Everything has a resolution of 5 meters except K.J. Meijer's data which is 2 meters per pixel.

In contrast to NDVI, the space coverage for DEMs is complete almost all the time (the exception is tidal channels). Therefore, raw data (hereinafter referred to as **elevation**) could be used for the analysis straight away. Rare small gaps in the order of a few pixels are patched by exact Euclidean distance transform using the `ndimage.distance_transform_edt` function from `scipy`. Moreover, the absolute value of the first derivative in space is calculated to estimate a maximal slope around a point (hereinafter referred to as **slope**). If there is only one of two neighbours presented, the backward/forward difference is computed (eq.2). Otherwise, the central difference (eq.3) is applied as a more precise Tailor's approximation. The absolute maximum is chosen among all four directions (north-south, west-east, NE-SW, NW-SE). In the end, all data are stored as a *.csv file with tidy data containing height and slope values as attributes. Since the scanning is launched once per year, ideally (tab.4) there are overall six tables per island.

the backward/forward approach

$$|h'| = \left|\frac{\delta h}{\delta x}\right| \approx \left|\frac{h_{i\pm1} - h_i}{\Delta x}\right| \quad (2)$$

the central approach (combining forward and backward)

$$as \quad 2\frac{\delta h}{\delta x} \approx \frac{h_{i+1} - h_i}{\Delta x} + \frac{h_i - h_{i-1}}{\Delta x} \rightarrow \left|\frac{\delta h}{\delta x}\right| \approx \left|\frac{h_{i+1} - h_{i-1}}{2\Delta x}\right| \quad (3)$$

Integration

As NDVI and DEM data have different resolutions (3 and 5 (or 2) meters per pixel respectively), interpolation is needed to link each attribute to one geo point. For effective rapid nearest-neighbour search the KD-tree method [121] from the `scipy` package is implemented to approximate DEM points to coordinates of NDVI characteristics.

So, a final table contains for each space point two geographic coordinates (latitude and longitude), two NDVI features (a mean NDVI of summertime and greening index during spring), and two DEM characteristics (an elevation and an absolute value of a maximum slope).

Clustering

To group environmental variables into more discrete categories supervised clustering is performed based on the data distribution. Yet first of all the too-low parameter values have to be eliminated (fig.5, 6) to sort sea areas out. All elevation values below 0.3 meters are not interesting for this research since it is located in the intertidal zone or below. Moreover, since terrestrial areas have NDVI at least low positive and free-standing waters are slightly negative [117] the cut of summer mean NDVI is executed at -0.05. The filtered data is grouped into several clusters using lifelike break-lines (fig.6, 7).

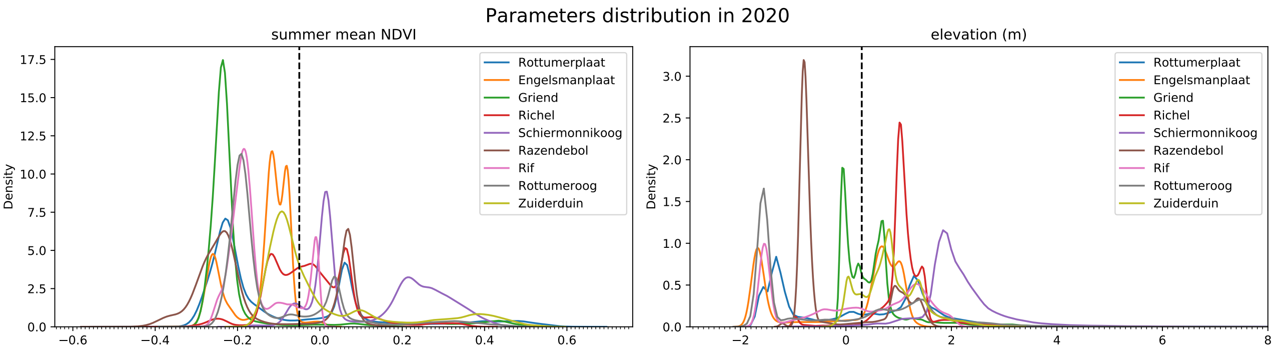


Figure 5: Raw parameters: mean NDVI value of summer months and elevation. The black dotted line represents the cut of separate terrain values from the marine ones. The X-axis for height is cut at 8 m

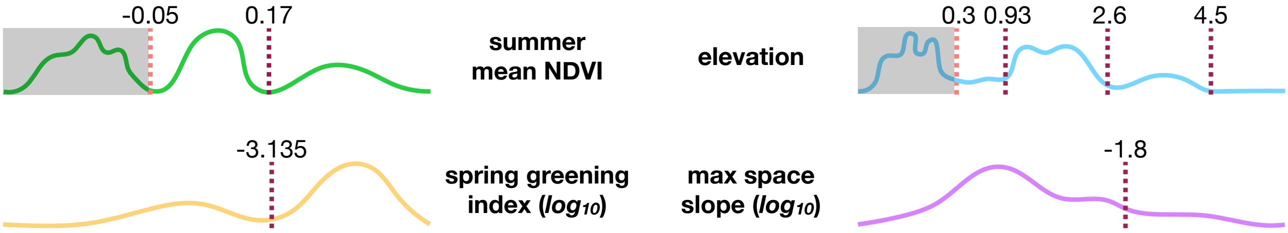


Figure 6: Breaks over the variables. The shady boxes represent the cut-off of irrelevant areas

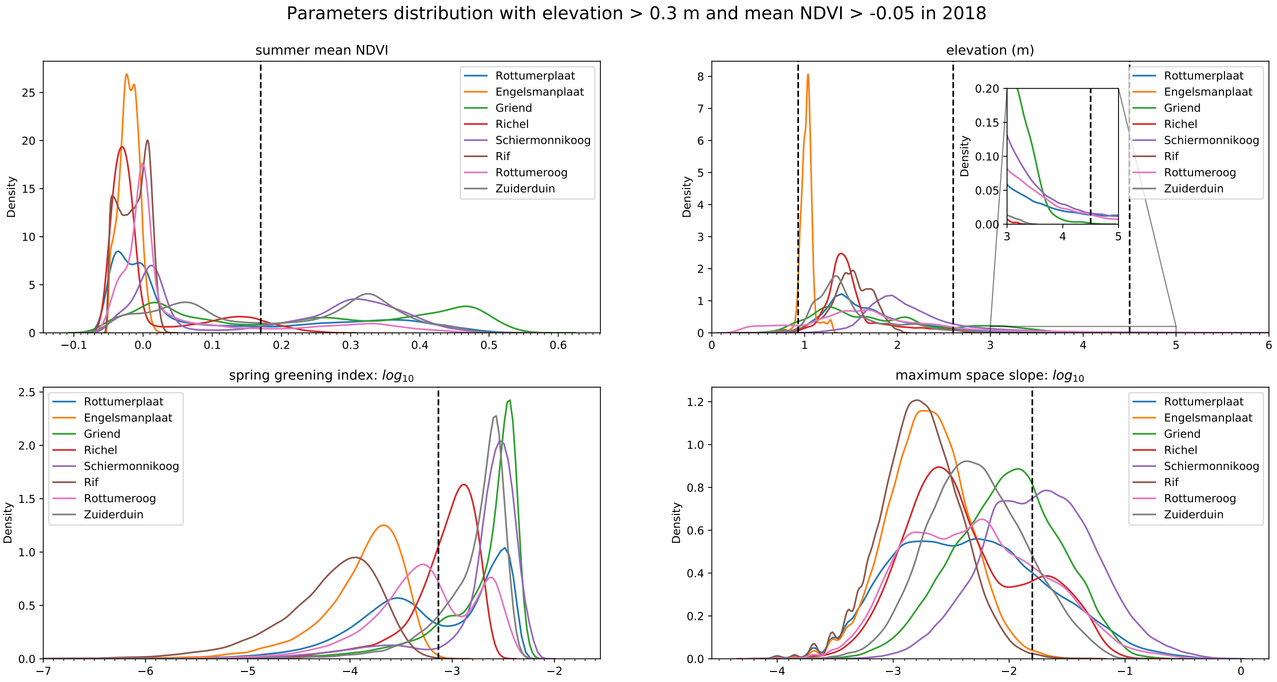


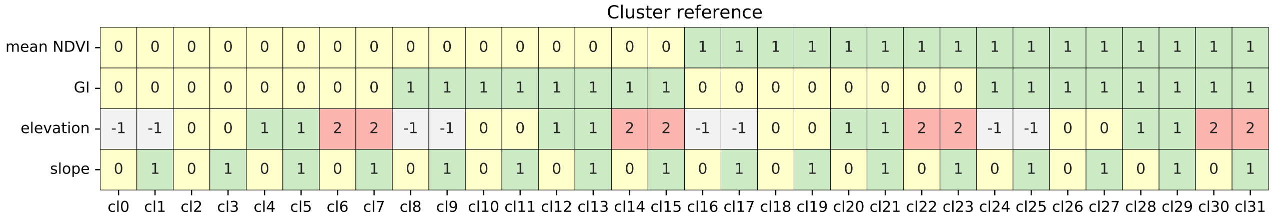
Figure 7: Separation into groups: NDVI and DEM parameters. The dotted line represents breaks. Distributions of elevation and spring GI (log_{10}) are cut at 6 m and -7 respectfully

For vegetation parameters, a filtered mean NDVI value is separated into two groups by 0.17 NDVI as highly vegetated and sparsely vegetated areas. A greening intensity (log_{10}) is cut at -3.135 of its decimal logarithm getting intense greening and bare greening classes. This transformation is performed to highlight the difference between values.

Table 3: Mean High Waters (MHW), m for the Wadden Sea in 2011 [122]

	Razendebol	Vlieland	Richel	Griend	Rif	Engelsmanplaat
MHW	0.61	0.85	0.85	0.85	0.93	0.93
	Schiermonnikoog	Rottumerplaat	Rottumeroog	Zuiderduin	**mean**	**median**
MHW	0.93	0.98	0.98	0.98	**0.889**	**0.93**

As for elevation variables, the division of filtered elevation into four groups is carried out by height: 1) at a border of supratidal zone of 0.93 (the median of mean high waters is chosen as a middle value non-sensitive to outliers, tab.3); 2) at 2.6 m sea water enters only during strong storms; 3) at 4.5 m for rare high areas (for example, dikes). The elevation slope as well as for greening intensity is transformed into a decimal logarithm for better scale representation. This parameter is broken at -1.8 (log_{10}) creating classes with plain and steep surroundings.


Cluster reference

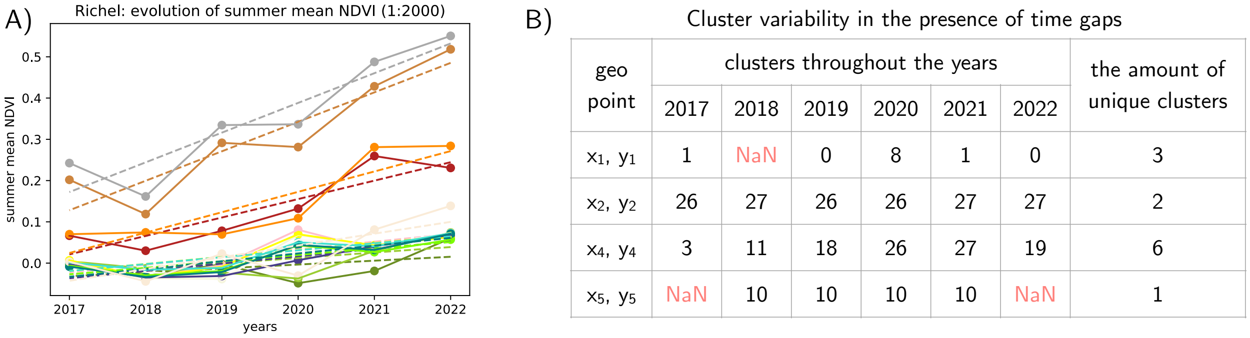
	cl0	cl1	cl2	cl3	cl4	cl5	cl6	cl7	cl8	cl9	cl10	cl11	cl12	cl13	cl14	cl15	cl16	cl17	cl18	cl19	cl20	cl21	cl22	cl23	cl24	cl25	cl26	cl27	cl28	cl29	cl30	cl31
mean NDVI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
GI	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
elevation	-1	-1	0	0	1	1	2	2	-1	-1	0	0	1	1	2	2	-1	-1	0	0	1	1	2	2	-1	-1	0	0	1	1	2	2
slope	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

Figure 8: The deciphering table for clusters: digits from -1 to 2 represent a group of a variable (ascending order)

Overall, 32 clusters are comprised (fig.8). The clusters are enumerated from 0 to 31 which does not make the meaning obvious. Therefore, the deciphering table should be used. As a rule of thumb, low-numbered clusters mean sparsely vegetated areas and the opposite is true for high-numbered clusters.

Evolution over the years

To describe a dynamic environment and downsize the data, a linear coefficient for continuous data and the number of unique clusters per geographical point are counted (fig.9).



Cluster variability in the presence of time gaps

geo point	clusters throughout the years						the amount of unique clusters
	2017	2018	2019	2020	2021	2022	
x_1, y_1	1	NaN	0	8	1	0	3
x_2, y_2	26	27	26	26	27	27	2
x_4, y_4	3	11	18	26	27	19	6
x_5, y_5	NaN	10	10	10	10	NaN	1

Figure 9: Methods to calculate the way of evolution: A) for continuous variables, B) for clusters

For four continuous variables (mean NDVI, GI, elevation, slope), a linear coefficient of a parameter's yearly development is calculated (fig.9A). It allows all the islands or additional avian subgroups to be compared with each other showing evolution within these classes.

The number of unique clusters can show the variability of the environment but only points with full-time coverage should be taken into account. Otherwise, this parameter may be unintentionally undervalued (fig.9B). Yet this technique could not be unified among all islands since they have different years covered (tab.2).

Cross-linking with birds

To each geographical point a boolean value is added indicating a presence/absence of an avian species. Also, areas outside of colonies are marked by a boolean value too as well as a variable for the presence of any bird (a sum for all species).

Overall, 8 groups of birds are used including 9 species (*Larus argentatus* and *Larus fuscus* are combined, tab.4). Primarily they are carnivores (tab.4) or omnivores [83]. From now on a genus name of species could be abbreviated to its first letter.

Table 4: Names of avian species used in this thesis

Dutch common name	English common name	Latin name	diet
Aalscholver	Great cormorant	*Phalacrocorax carbo*	fish [77]
Grote Stern	Sandwich tern	*Thalasseus sandvicensis*	fish [123]
Kokmeeuw	Black-headed gull	*Chroicocephalus ridibundus*	bivalves, crustaceans [83]
Lepelaar	Eurasian spoonbill	*Platalea leucorodia*	fish [80]
Noordse stern	Arctic tern	*Sterna paradisaea*	crustaceans, fish [124]
Stormmeeuw	Common (mew) gull	*Larus canus*	bivalves, polychaetes [83]
Visdief	Common tern	*Sterna hirundo*	fish [124]
Zilvermeeuw en Kleine mantelmeeuw	European herring gull	*Larus argentatus*	bivalves, crustaceans [83], earthworms, insects [125]
	Lesser black-backed gull	*Larus fuscus*	fish, crustaceans[83], earthworms, insects, grass [85]

Statistics

Several statistical methods are implemented to prove a correlation between birds and the environment. For comparing distributions of continuous variables, first, the Shapiro–Wilk test is managed by `scipy` to check normality. Based on its result, the two-sided Mann–Whitney U test from `scipy` is applied for non-normally distributed parameters. A p-value below 0.05 is considered to be sufficient to highlight the difference.

By building a contingency table with clusters, avian species, or vegetation zone codes, the correlation between two parameters is computed by the Chi-square test of independence using the `scipy` library.

Logistic regression by `sklearn` is used to estimate the impact of continuous characteristics to construct categorical ones. Mean NDVI, greening index, elevation, and space slope all over the available years as well as their linear yearly time coefficients plus the different amount of unique clusters within the timeline are comprised to predict avian species and outside of bird colonies. Standardised variables are transformed to eradicate scale differences. Class weights are balanced to eliminate size difference. Data is split into a test group (30%) and train one (70%). The portion increasing up to 80-90% for tests was not productive. The coefficients of predictions are compared.

To evaluate the variable importance, Random Forest Classification by the `sklearn` library is implemented for standardised data. A test group makes up 20% of the total data with random state of 42 and numbers of estimators as 100.

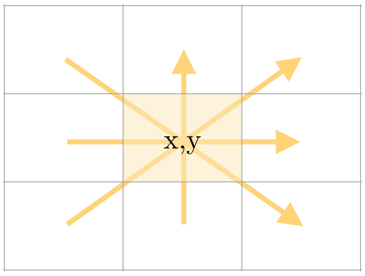
The whole pipeline is summarised in fig.10.

Obtaining raw data

years

	NDVI	DEM
resolution	3 m 4 spectral bands	2017-2022: 5 m Some in 2021: 2 m
source	Planet (PlanetScope satellites)	Actueel Hoogtebestand Nederland Rijkswaterstaat by KJ Meijer, RUG

	the mid of February	the end of May	the start of June	the end of August
A	NDVI_A1	NDVI_A2	NDVI_A3	NDVI_A4
B	NDVI_B1	NDVI_B2	NDVI_B3	NDVI_B4
C	NDVI_C1	NDVI_C2	NDVI_C3	NDVI_C4



greening index

mean NDVI

elevation

slope (abs)

Interpolation by KD-Tree for Nearest Neighbor lookup

Supervised clustering

- greening over spring
- not so intense

- bare

cut

- sparsely vegetated
- vegetated

breaks

- intertidal

cut

- supratidal (MHW)
- average height
- uplands

- plain
- steep

Evolution over the years

- Continuous variables → a linear coefficient as a first time derivative calculated annually
- Categorical variable (clusters) → an amount of different clusters (not universally applicable)

Cross-linking with birds

categories

inside birds colonies

outside colonies

per species

per island

- Mann-Whitney tests with quantitative data to compare distributions
- Chi-squared tests between categorical data to check co-dependence
- Logistic regression and Random Forest to predict a categorical variable

Figure 10: Methods: graphic summary

Vegetation maps

The correlation between clusters and zone codes is computed by the Chi-square test from a contingency table. Zonation is based on the Salt97 and Salt08 classifications, where typology has been harmonised for the whole data frame (tab.5, [55]). Also, a basic frequency of clusters per one zone code is compared as well as vice versa.

Table 5: Describtion of zone codes [55]

zone code	description	zone code	description	zone code	description
Da	Young shifting dunes	Kl	Low salt marsh	Ks	Bare (drying) mud
Df	Young stable dunes	Km	Medium salt marsh	Ksch	Bare shells
Dx	Disturbed dunes	Kn	Nitrophilic zone	Kw	Bare water
Kb	Brackish salt marsh	Kp	Pioneer salt marsh	Kz	Bare sand
Kh	High salt marsh	Kpp	Pre-pioneer salt marsh	Sv	Beach plain

Results

Raw data

Overall, 51 island-years are composed based on data availability for 10 chosen areas (tab.2). Among them four islands (Richel, Rottumerplaat, Rottumeroog, Zuiderduin) have full six-year coverage; four ones lost one year (Griend, Rif, Engelsmanplaat in 2017 and Razendebol in 2018); Schiermonnikoog does not contain data for 2017 and 2022. Whereas, data for Vlieland is available only for 2019, 2021, and 2022. Thus, henceforth data analysis for some sections divides the data into these four groups to avoid bias.

In the Supplementary Materials, DEMs for Texel (fig.A.1) show a lack of coverage for the analysis. Herewith NDVI coverage per year per island (tab.B.1-B.10) illustrates the necessity to eliminate some time points.

Processed data is displayed ibid to portray the magnitude of parameters as well as their coverage (fig.D.2-D.10). Furthermore, the distributions of these variables over the settled polygons are there too (fig.E.1).

Clustering

There are one break for NDVI means (vegetated / sparsely vegetated), greening index (greening much/not so intense), and steepness (plain/steep) along with three breaks for elevation (below mean high waters, below max high water, uplands) (fig.6). So, 32 clusters of all possible combinations are comprised after removing water-level values for mean NDVI and elevation (fig.8). The location of breaks per characteristic is shown in the Supplementary materials per year (fig.E.2) as well as the distribution of clusters per island (fig.D.11-D.20).

The numbering of clusters does not reflect direct sense albeit clusters 16 and up are highly vegetated (reference fig.8). As for cluster frequency, altogether clusters 26, 27, and 29 are more common among all islands than others (fig.11). Whereas, clusters 2 and 10 are not rare too but follow up into the sea or shoreline zones (fig.E.3). However, some clusters are not so ordinary such as clusters 6, 14, and 16. Some clusters (for example, 18, 31) are trending to increase their frequency over the years. To understand, see the reference fig.8.

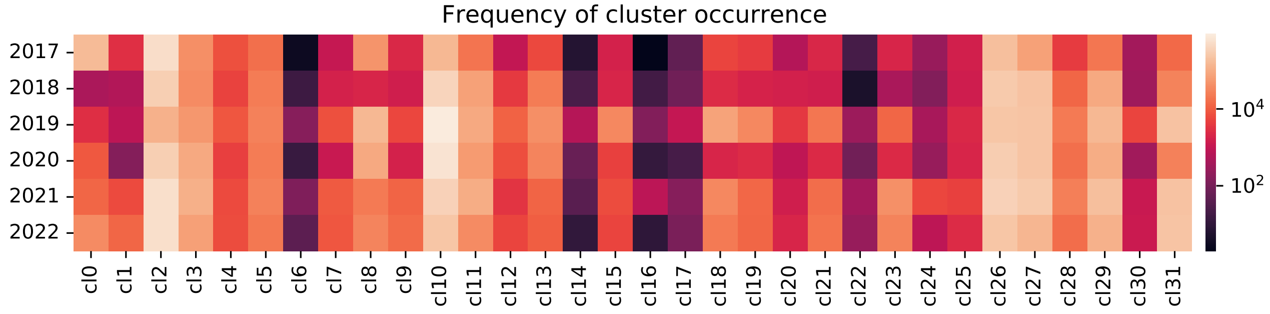


Figure 11: Amount of pixels per cluster within all six years and all islands combined

Birds

As for birds, seven of ten islands (fig.12) turned out to contain overall 61 bird colonies. Respectfully Razendebol, Rif, and Engelsmanplaat are empty. The amount of space occupied varies from species to species with obvious dominance of *L. argentatus* (Zilvermeeuw) and *L. fuscus* (Kleine mantelmeeuw) (tab.6). The most diverse island is Griend with 6 groups of birds including uniquely Noordse stern (*S. paradisaea*), Lepelaar (*P. leucorodia*), and Grote Stern (*T. sandvicensis*). While others have only seagulls.

To assess the correlation between birds and the surrounding area, first, the distribution of parameters in 2022 (or 2020 on Schiermonnikoog) is characterised since the colonies were observed only once. Further, by assuming that these areas are constant due to birds' habits, the evolution of these regions is illustrated.

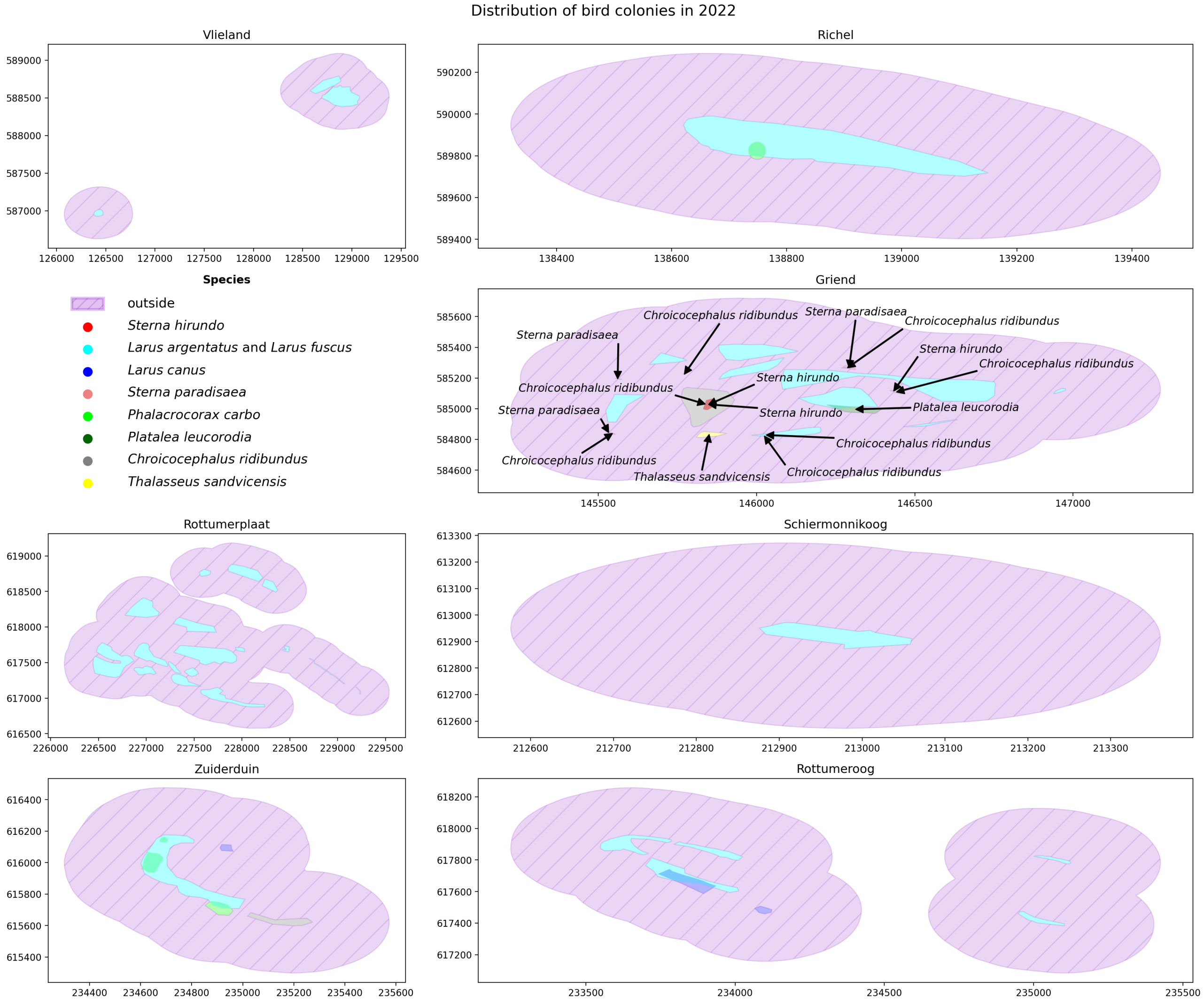


Figure 12: Eight groups of bird colonies among seven islands in 2022 (and 2020 for Schiermonnikoog)

Table 6: Area* occupied or not by birds per island

	Aal	GrSt	Kokm	Lep	NooSt	Storm	Visd	Zil&Kl	**all birds**	**outside**
Vlieland	0	0	0	0	0	0	0	8301	8301	73042
Richel	218	0	0	0	0	0	0	7275	7300	17156
Griend	0	232	3173	540	62	0	190	13158	16980	50335
Schiermonnikoog	0	0	0	0	0	0	0	1008	1008	47151
Rottumerplaat	0	0	0	0	0	0	0	61369	61369	431173
Rottumeroog	0	0	0	0	0	1341	0	4650	5247	75186
Zuiderduin	1594	0	923	0	0	189	0	5660	7214	57659
overall	1812	232	4096	540	62	1530	190	101421	109883	751702
Razendebol**	-	-	-	-	-	-	-	-	-	461983
Rif	-	-	-	-	-	-	-	-	-	63466
Engelsmanplaat	-	-	-	-	-	-	-	-	-	2426

* in pixels: each pixel represents the 3x3 m^2 square

** for uninhabited islands outside means the whole area of a polygon

Aal is for Aalscholver (*P. carbo*), GrSt is for Grote Stern (*T. sandvicensis*), Kokm is for Kokmeeuw (*C. ridibundus*), Lep is for Lepelaar (*P. leucorodia*), NooSt is for Noordse stern (*S. paradisaea*), Storm is for Stormmeeuw (*L. canus*), Visd is for Visdief (*S. hirundo*), Zil&Kl is for Zilvermeeuw en Kleine mantelmeeuw

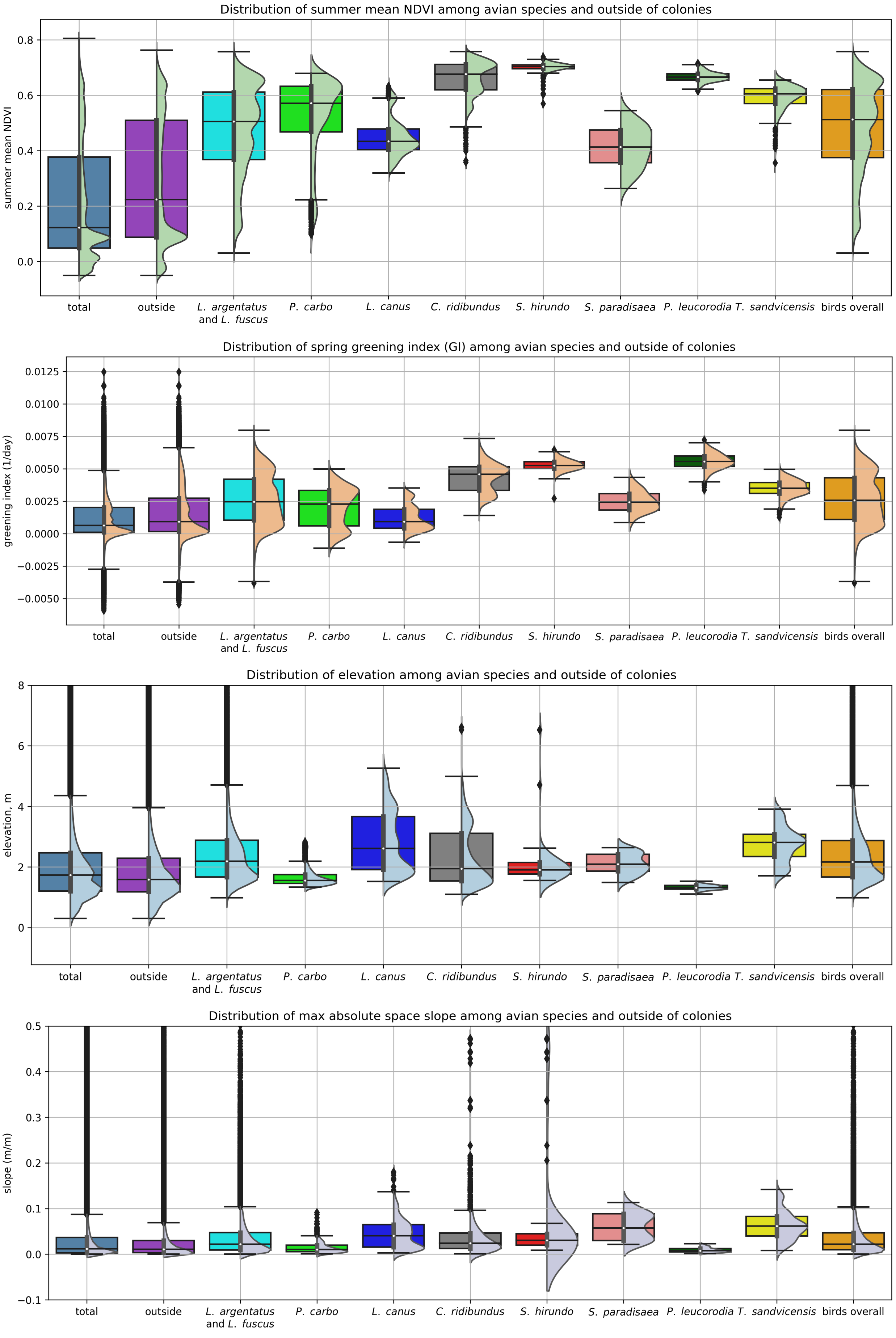


Figure 13: Distribution of four environmental parameters on all bird-containing islands in 2022 (or 2020 for Schiermonnikoog). Elevation trimmed at 8 m and space slope at 0.5. Total is for the whole area of islands

Environmental parameters within and outside of colonies in the year of observation

For all four parameters almost always there is a significant difference between areas with bird presence and outside across all islands with birds in the year of observation (fig.13, 14). In general, avian colonies contain a greater amount of vegetation during the summertime and consequently these places are greening more intensely. Also, birds predominantly prefer areas above storm peak waters with a slope less than 3° (fig.13). Mainly the difference between groups is clear and supported by the Mann-Whitney U test (fig.14) since almost none of the distributions are proven to be normal by the Shapiro-Wilk test. However, there is some overlapping.

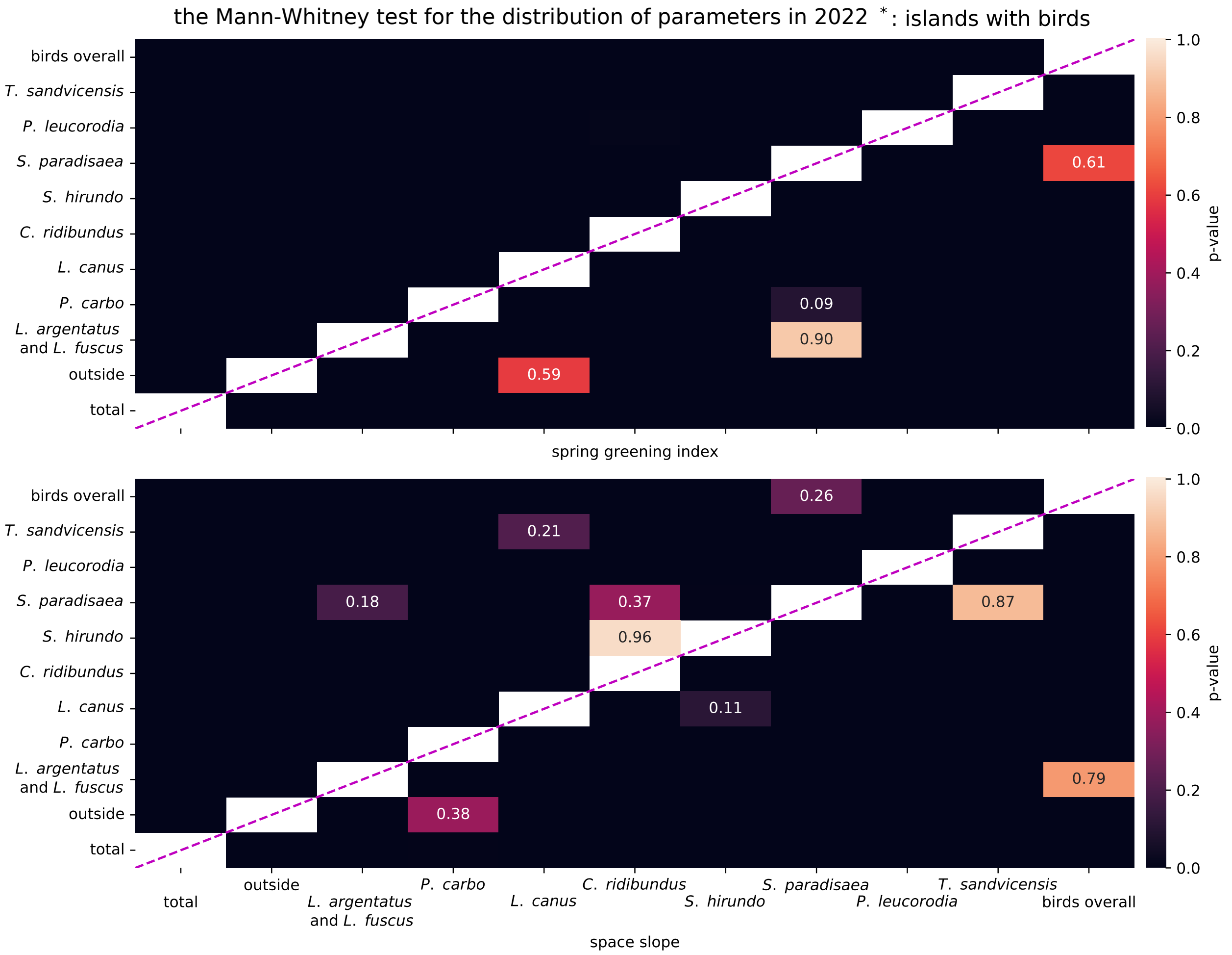
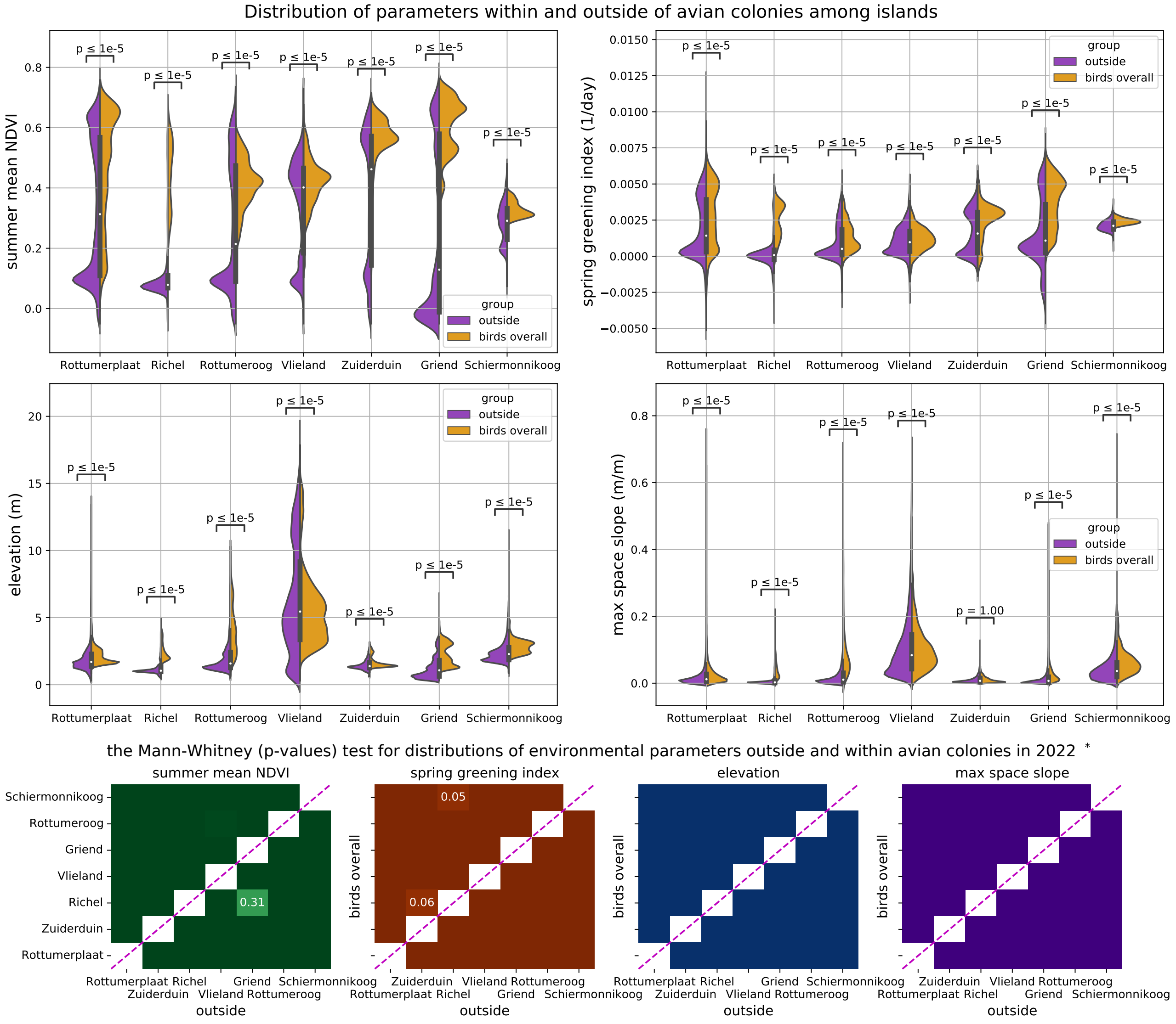


Figure 14: The Mann-Whitney U test for environmental variables within and outside of bird colonies in the year of observation (in 2022 except * Schiermonnikoog in 2020). Each table is split into two parts that represent the p-values of marked parameters. The intensity of a colourmap represents a value of p-values. All p-values are marked if they are higher than 0.05. The p-value maps per each feature are in the Supplementary materials (fig.F.1)

Among environmental variables, some parameters vary a lot whereas others fluctuate over a small range (fig.13). Thus, a mean NDVI presents across its possible borders for terrestrial areas as in the 0-0.8 range. All birds have an increase of around x2.5 times at this parameter in comparison to the outside terrains. Some species as Visdief (*S. hirundo*), Kokmeeuw (*C. ridibundus*), or Lepelaar (*P. leucorodia*) are used to having even trice higher mean summer NDVI while Stormmeeuw (*L. canus*) and Noordse stern (*S. paradisaea*) prefer less vegetated places. Spring greening index shows a similar trend precisely correlating with the amount of vegetation. Assuming that the greening period takes ~90 days, the increase in NDVI could vary from Δ0.11 (Stormmeuuw, *L. canus*) til ~Δ0.5 with an average of Δ0.24 NDVI for all birds and Δ0.137 for outside. Similarly, birds opt for relatively higher lands yet the difference is typically a half meter. Noticeably Aalscholver (*P. carbo*) and Lepelaar (*P. leucorodia*) reside down in the lowlands but gulls are less preferable. In general, the values of space slope are up to 0.1. As a slope is a difference in height within an interval (eq.**??**) then it is a tangent. Therefore, the range for slope is within 0-6° for the most of groups. Comparing slope means, birds (2.20°) dwell in slightly steeper places than outside (1.67°) with a Δ0.53° difference. However, all these estimations are done for all islands with birds combined. Often these distributions do not have a clear unimodal distribution varying alongside all environmental parameters.

This multimodality occurs due to the summing of different islands altogether even though they are structured statistically differently (fig.15). Nonetheless, the trend is still the same: per island avian colonies are located usually in places with more vegetation, more intense greening, higher, and a little steeper in comparison to outside. Although, these parameters vary between islands significantly with few exceptions. Outside areas usually have bimodal distribution with one peak at lower values and the other one around bird numbers. Sometimes birds overall could be multimodal too. Once again it could be linked to summing all species together. Per species variations along all islands and parameters are in the Supplementary materials (fig.G.2-G.6). Different islands have different distributions per species almost always. Only for *L. argentatus* and *L. fuscus* elevation is the same on Rottumerplaat and Griend (fig.15). Furthermore, for this pair of species distributions could be widely dispersed and still multimodal. This phenomenon could correlate per individual colony or just reflect a generalistic trend of no specific preference. To accept or reject the hypothesis, each colony should be plotted separately.



* for Schiermonnikoog data is from 2020

Figure 15: Distributions of environmental parameters per island for outside areas and places with birds in the year of observation. Square brackets represent p-values of the Mann-Whitney test between 'outside' and 'birds overall' groups. Moreover, below the difference is proven or not between islands by the Mann-Whitney U test with tables split into two parts per each group. All p-values are marked if they are higher than 0.05. The full p-value maps could be found in the Supplementary materials (fig.G.1)

The majority of birds are located within a few distinct clusters (fig.16). As an exception most gulls could be considered generalists as they can live in a number of habitats. Whereas, some species fit into a particular niche (mostly minorities, for example, Noordse stern (*S. paradisaea*)). Altogether birds opt for places with high vegetation and greening rate as well as not too high enough in terms of height (clusters 26, 27, and 29; the deciphering map for clusters fig.8). While outside territories are not into a certain pattern even having the same

Figure 16: The interconnection between birds and clusters in 2022: proportion of clusters per avian species and dependency between those two categorical variables. For the Chi-squared test of independence only matches with 5 or more observations are used. All p-values are marked if they are higher than 0.05. Total means the territory of the whole island

hit on cluster 26 as well as 2 and 10. As for co-dependence, there are statistically proven relationships between bird groups and clusters with few exceptions (fig.16). All proportionally dominated clusters indeed co-depend with avian species and outside of colonies. The distribution of clusters within each colony is illustrated in the Supplementary materials (fig.E.4-E.10) within all years to track the evolution.

Environmental parameters within and outside of colonies: evolution

In order to detect the development of parameters, several variables are comprised. Thus for quantitative data (summer mean NDVI, spring greening index, elevation, and space slope), a linear time coefficient could reveal the direction and the magnitude of changes (fig.9A). While counting unique clusters per geo point reflects the environmental variability (fig.9B). The assumption is that birds are constantly present within polygons.

The same as for the static distribution, some changes within continuous variables are more distinct and vary with greater amplitude among groups than others (fig.17, 18). Detailed intensity maps are in the Supplementary materials (fig.H.1). For NDVI parameters (mean NDVI and GI) the outside has a similar bimodal trend as it is for the static distribution with one part matching birds and the other one lower in values. In general, within colonies of all avian species the level of vegetation is growing faster than the outside and islands without birds year after year. Some birds have a similar distribution of this parameter (fig.18). On average mean NDVI is increasing by 0.05 per annum in the presence of birds. Considering NDVI varies roughly between 0 and 1 that is 5% per year. For bare islands without any avian species, this parameter is only 1.3-2.2% per annum. While the growth in spring greening has a resembling tendency. It is already not so distinct yet statistically significant that birds accelerate greening a little bit than bare areas. The gap in GI between areas is at least ∼0.0002 per annum which means that every year on inhabitant islands mean NDVI is growing 0.018 more if considering a 90-day growth period. Typically bare islands have stable GI without many changes. Noticeably some species (as Aalscholver or *P. carbo*) partly dwell in the environment with decreasing vegetation and GI.

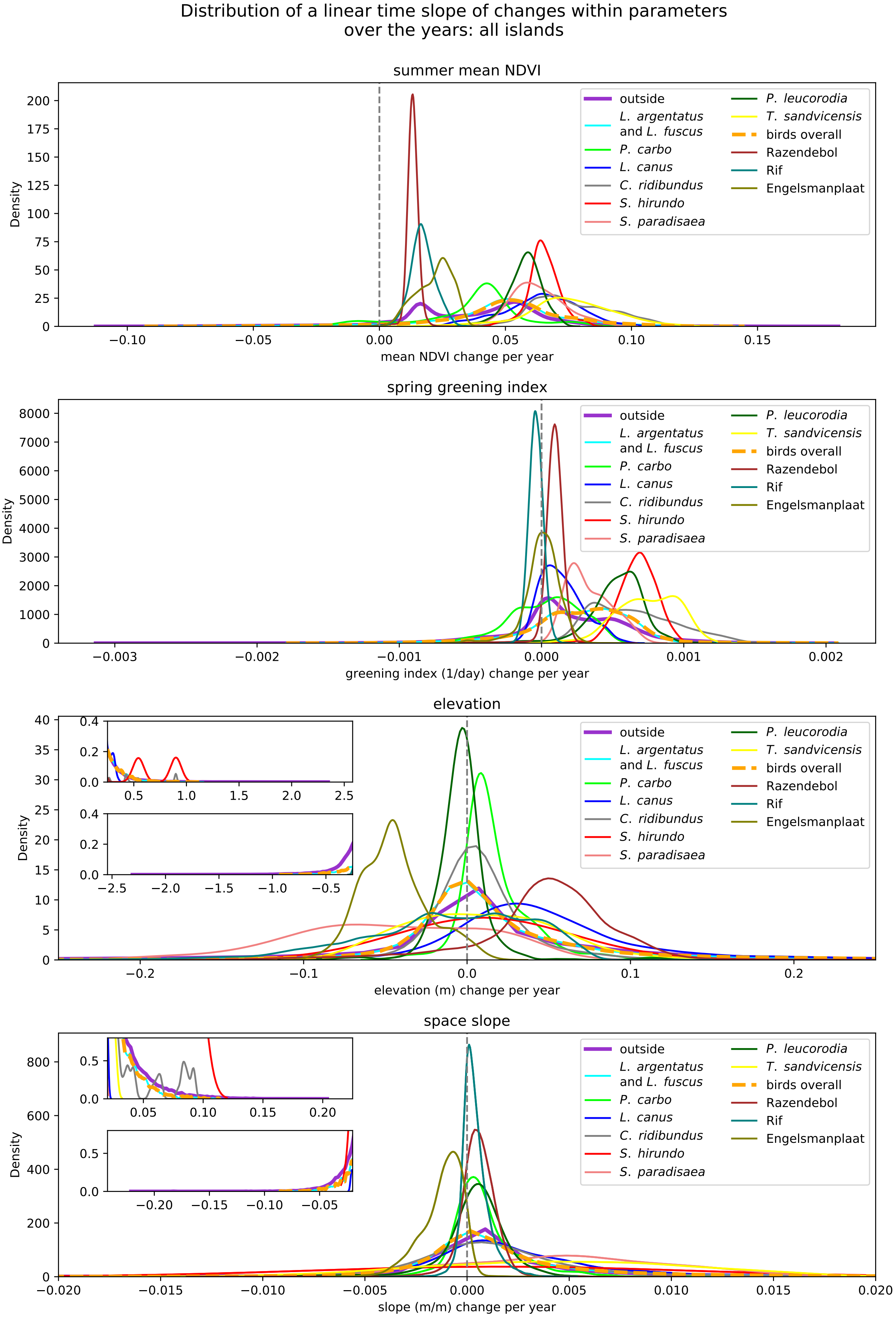


Figure 17: Distribution of a linear time coefficient for the period of 2017-2022: all islands included

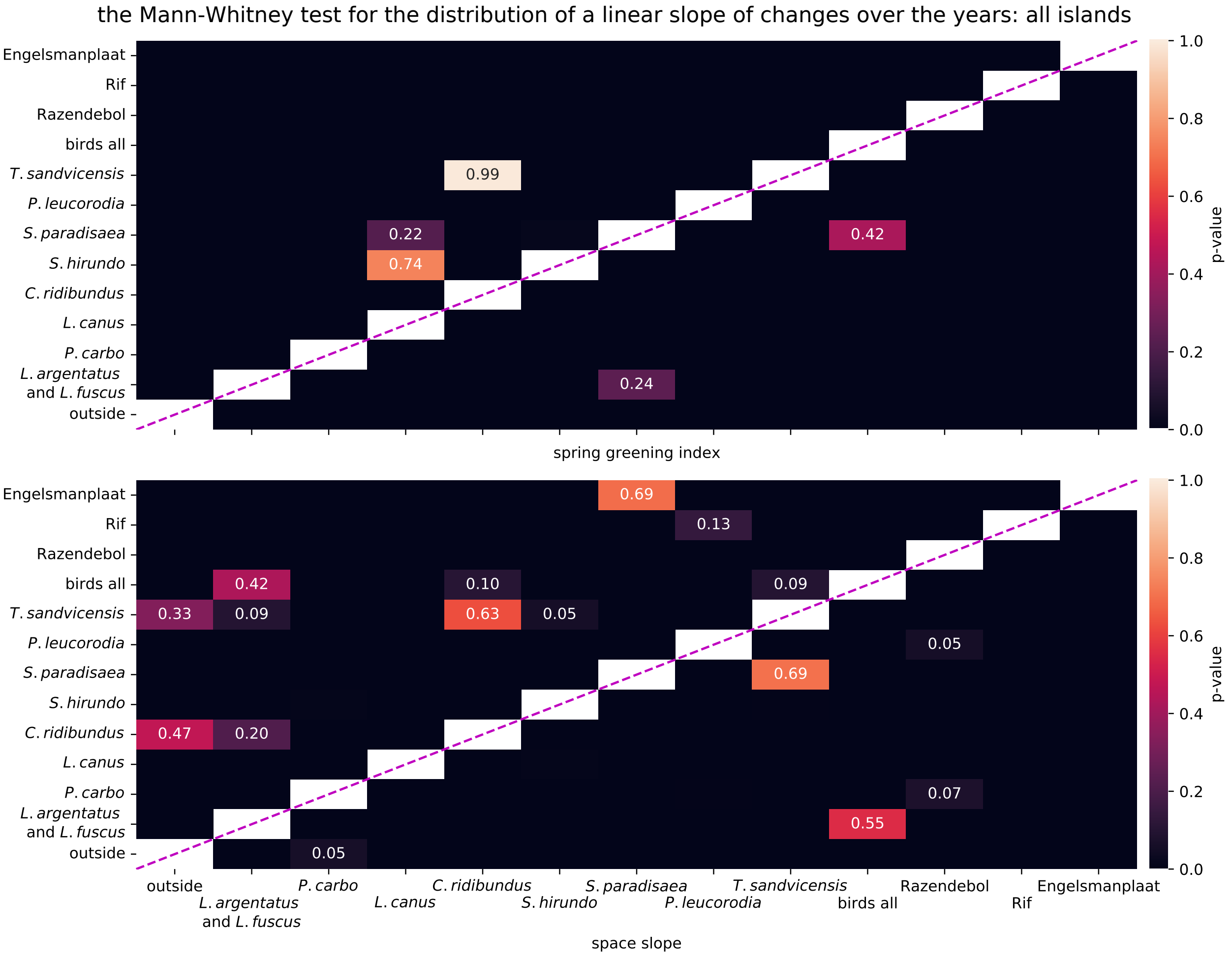


Figure 18: The Mann-Whitney U test for a linear annual time coefficient within and outside of bird colonies as well as uninhabited islands in 2017-2022 (per feature see in the Supplementary materials (fig.F.2)). Each table is split into two parts that represent the p-values of marked parameters. All p-values are marked if they are higher than 0.05

Contrary, with the speed of elevation and space slope growth bird-containing and not containing spots could overlap more often (fig.17, 18). While on average avian species still stimulate elevation build-up more (as birds have a mean of 0.019 m/year versus outside 0.009 m/year) with the exception of Razendebol (a mean of 0.048 m/year). Opposite, Noordse stern (*S. paradisaea*) correlates with decreasing of mean -0.05 m/annum in elevation as well as partly other avian groups (for example, -0.004 m/year for Lepelaar or *P. leucorodia*). So, this parameter especially depends on the type of avian species and varies widely. At the same time areas with birds and outside spread in both directions and do not have such a radically different change of slope as the first one on average increases steepness by $2.25 \cdot 10^{-3}$ m/year^2 and the second one by $2.3 \cdot 10^{-3}$ m/year^2. Most avian species can influence slope evolution in both ways making the surroundings steeper or plainer. Thus, Lepelaar (*P. leucorodia*) and Aalscholver (*P. carbo*) inhabit an environment that resembles Razendebol in terms of slope changes (fig.18). Nevertheless, Noordse stern (*S. paradisaea*), Grote Stern (*T. sandvicensis*), and Visdief (*S. hirundo*) often alter terrains to steeper ones yet could drastically affect in the other direction too (fig.17).

Nonetheless, observed distributions are most of the time bi-/multimodal and distributed widely (fig.17). That could cause either by the pilling up of all different islands together or that means a lack of correlation. To accept or reject the hypothesis, each island should be plotted separately to see if 'island' affects the trends more than colony type. Indeed distribution for all environmental parameters more depends on an island for both birds and outside areas (fig19). Statistically, birds match by mean NDVI only on Rottumerplaat and Zuiderduin and outside has the same distribution only for elevation. Outside places are all different for vegetation markers. Yet the tendency is the same as increasing summer vegetation places trend to rise GI too. While for elevation avian colonies could rise slowly (Rottumerplaat) or even decrease (Schiermonnikoog) in height in comparison to outside. The same situation for these islands is for slope distributions with birds on Schiermonnikoog making the surrounding plainer. On Vlieland avian colonies have the same distribution of mean NDVI, GI, and slope as outside terrains. Similarly, on Zuiderduin greening index, elevation, and space slope are identical within these two groups too.

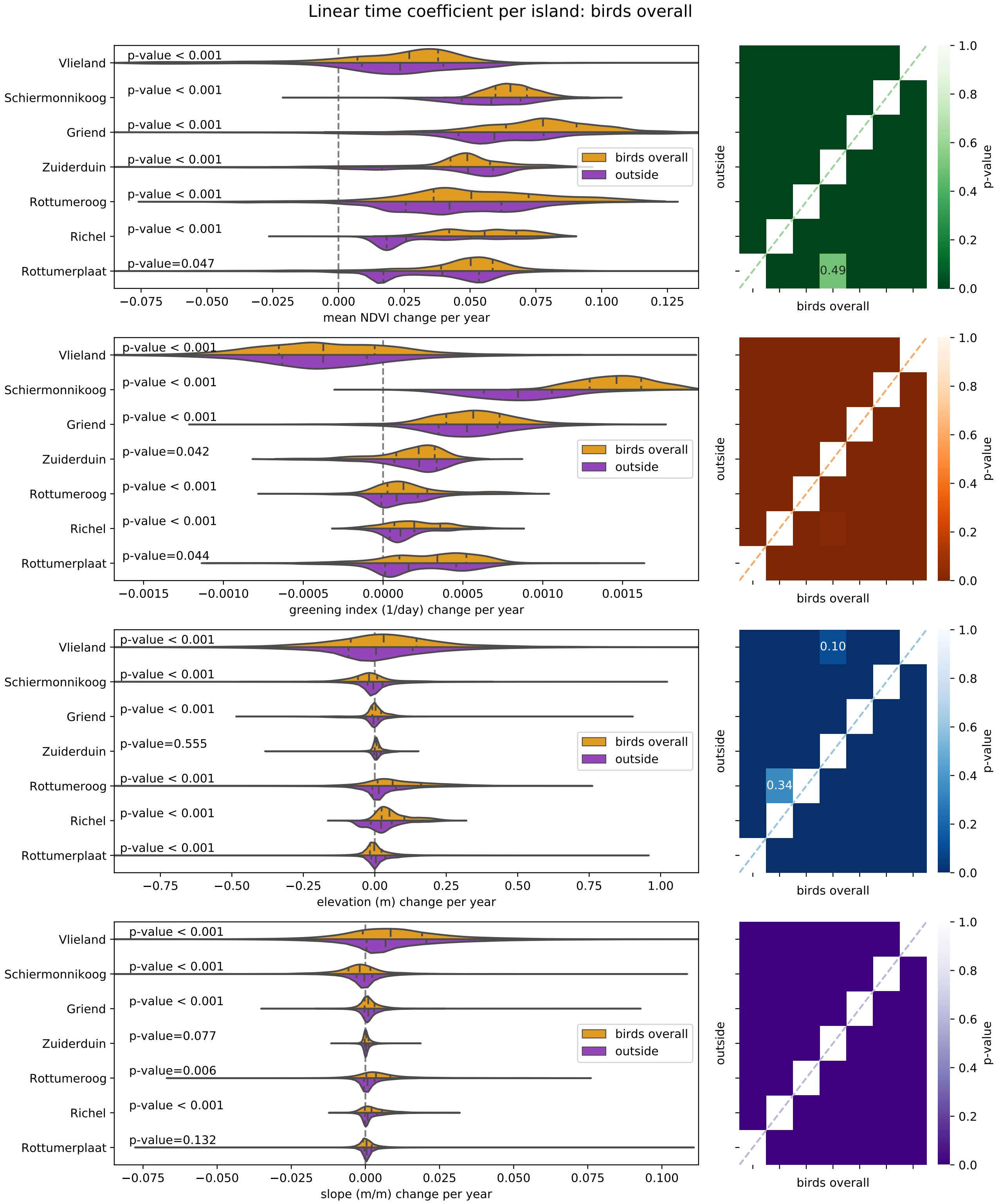
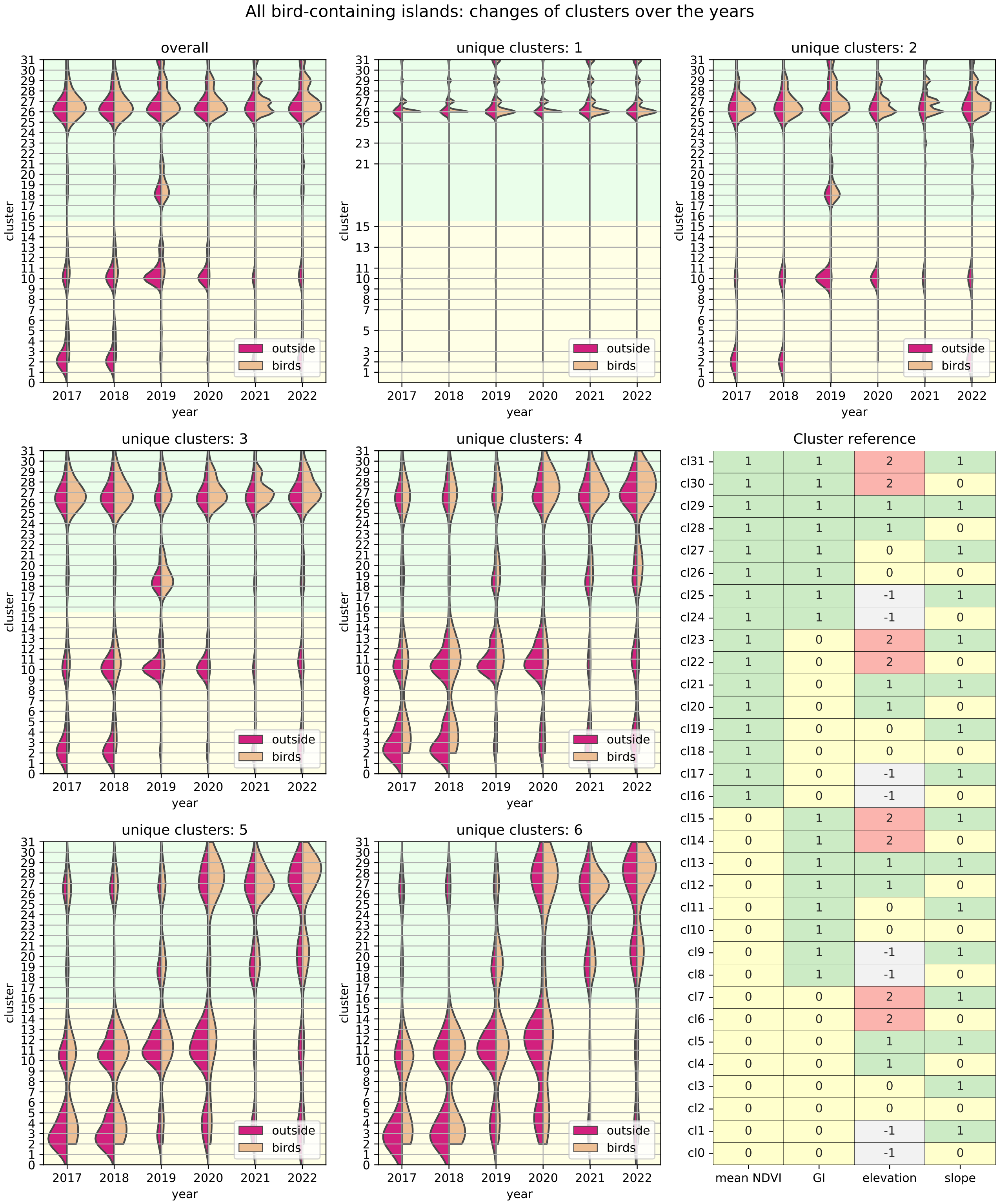


Figure 19: Distribution of a linear time coefficient per island for within and outside of avian colonies in 2017-2022 for bird-containing islands only (see per species in the Supplementary materials fig.H.2-H.6). On the left p-values describe the difference between outside and birds with dotted lines as quartiles. Whereas on the right side p-values reflect similarity within these groups on different islands. Ibid each table is split into two parts that represent the p-values of marked parameters and all p-values are marked if they are higher than 0.05

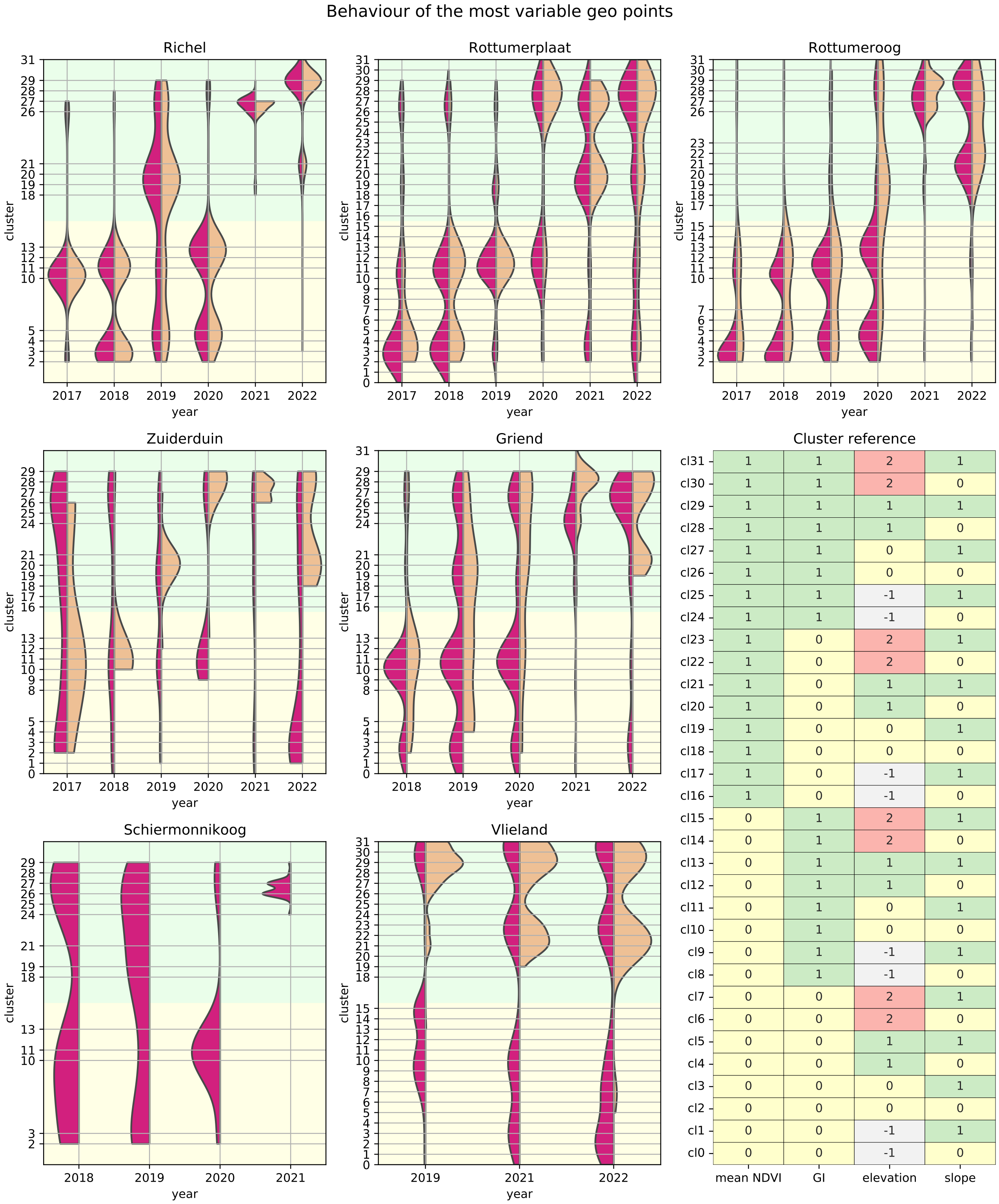
To visualise how stable or dynamic the environment is, the number of unique cluster types is calculated (fig.20, 21, 22, full description per island in the Supplementary materials fig.I.1, I.2-I.9). Due to imperfect time coverage, this procedure could be implemented for groups with the same amount of years (fig.9B).

Places with only one cluster type within all years are stable or varying within boundaries. For islands with avian colonies, both outside and inside avian colonies those areas are usually in the 26th cluster with high vegetation and GI while just above the mean high water line with the plain surrounding (fig.20). Other popular places are higher and steeper at the same time (clusters 27, 29, and 31). For bare islands (fig.22), those areas are in the 2nd and 10th clusters with the same elevation and slope preference but with way less vegetation.



	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure 20: Distribution of the number of total unique clusters regards the variably of the environment for all islands with avian colonies. Only present clusters are marked at the y-axis. The number of unique clusters reflects the amount of different clusters at this geo point within years of observation (fig.9B). This amount is calculated separately for each island to avoid underestimation of low variable clusters. Background colour represents the amount of vegetation. Here all islands are summed together therefore, for example, violins for the unique clusters: 1 are different each year



	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure 21: Distribution of clusters for geo points with a unique cluster type every year per island. Therefore, this graph illustrates the behaviour of the most dynamic territories. The colour representation is the same with magenta reflecting outside areas and orange as birds' colonies. As different islands have different time coverage, the number of years and max cluster variability change from island to island

The most dynamic areas could have some direction of development or just be chaotically unstable (fig.21, 22). In general, for islands with bird colonies, the evolution is going from low vegetated clusters to higher ones with the interim steps in clusters 8-15 with already intense spring greening but still less vegetation (fig.21). This transition is faster for birds' colonies (for example, Rottumeroog). Outside areas sometimes do not follow the trend (Zuiderduin, Vlieland, Schiermonnikoog). Whereas, for bare areas the fluctuation remains at low vegetation levels (fig.22, per bare island in the Supplementary materials fig.I.2).

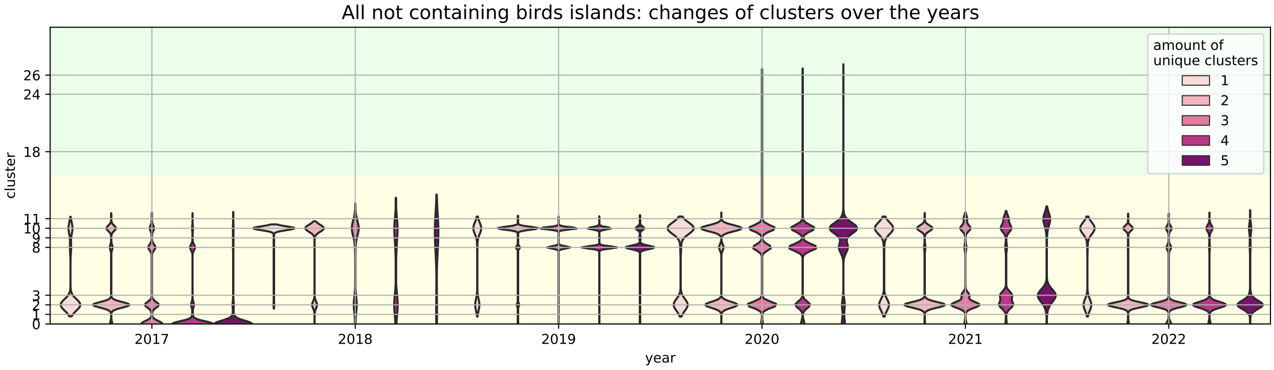


Figure 22: Distribution of total unique clusters regards the variably of the environment for all uninhabited islands summed up. Only present clusters are marked at the y-axis. All bare islands are summed together

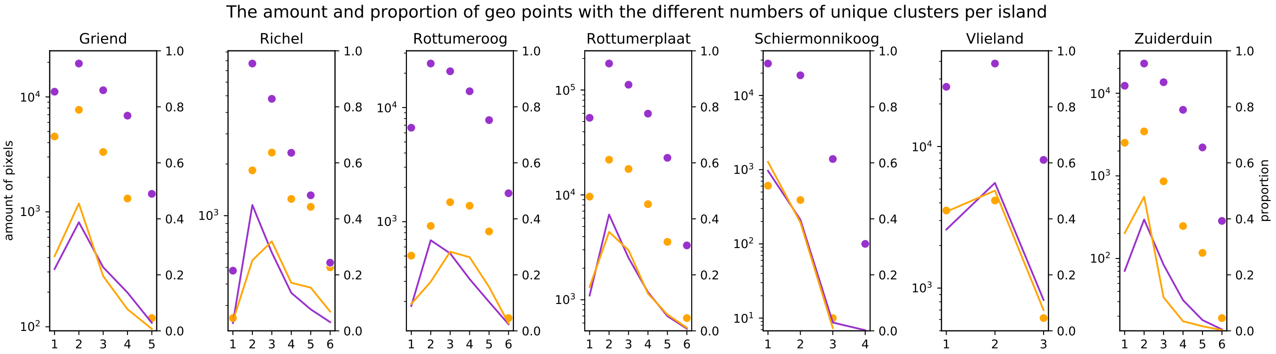


Figure 23: Pixels for different unique cluster totals (x-axis) regards outside (purple) and inside of avian colonies (orange). Dots represents the amount of geo points, lines are for their proportion per group

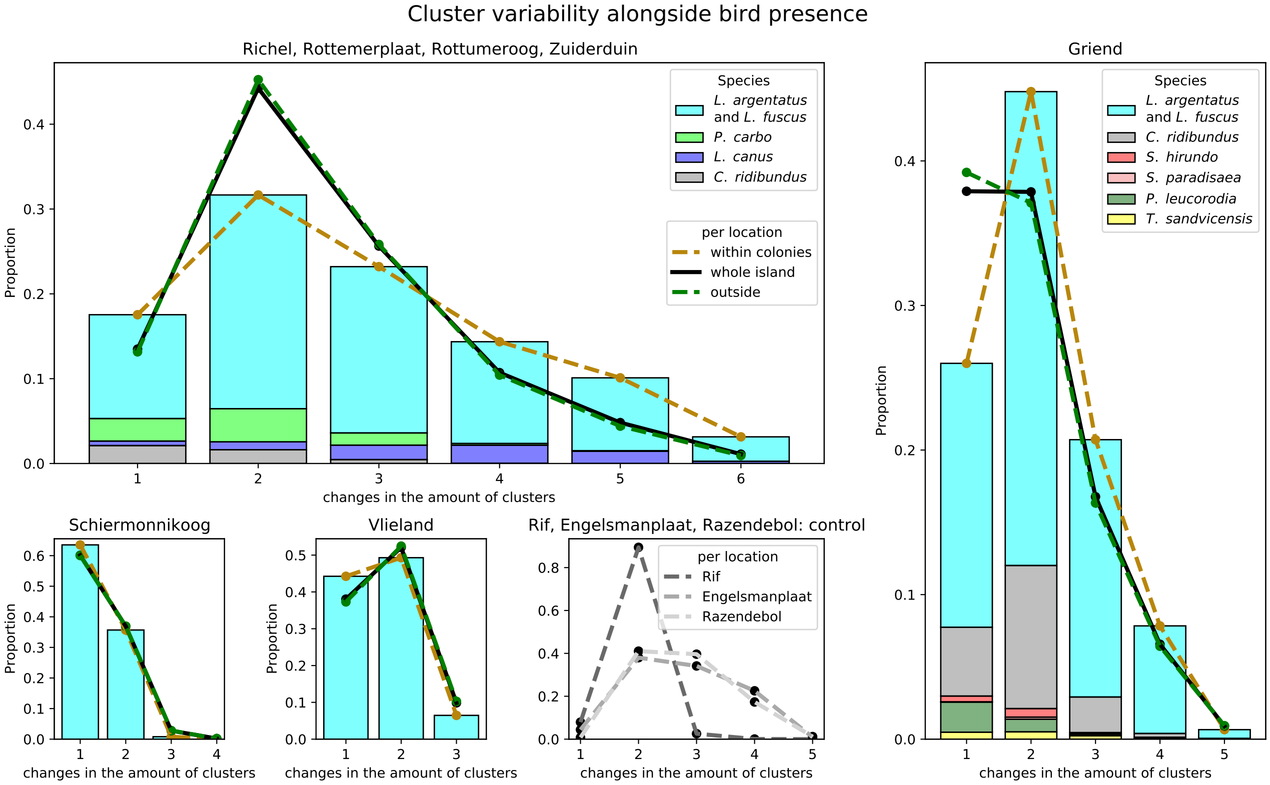


Figure 24: The number of unique clusters per avian group and overall per bird presence. Designations are the same among all subplots. The whole island means the territory of the whole polygon of an island

Birds could contribute to more variability as well as the environment could be more dynamic outside (fig.23, 24). That varies from island to island (fig.21). For example for Schiermonnikoog there are no geo points with birds among the most variable pixels (fig.23, 24). While on Richel and Rottumeroog birds inhabit more dynamic places (fig.23). Some avian species are associated with a more stable environment (Kokmeeuw (*C. ridibundus*), Aalscholver (*P. carbo*)) (fig.24). Alternatively, Stormmeeuw (*L.canus*) resides at relatively (3-5 unique clusters per 6 years) changing territories. Whereas others are generalists (Zilvermeeuw and Kleine mantelmeeuw (*L. argentatus* and *L. fuscus*)). Nonetheless, most areas among all islands pick at two unique clusters in the period of observation; the pattern is duplicated in the bare islands too (fig.24, 23). Detailed cluster transition could be observed per colony in the Supplementary materials (fig.E.4-E.10).

What is the most influential environmental parameter?

Some environmental parameters show a noteworthy correlation with one another during the presence or absence of bird colonies (fig.25). Height parameters (elevation and space slope) demonstrate a positive correlation with one another and a negative one with NDVI characteristics. This last trend is more represented within avian colonies. While space slope in outside areas correlates with vegetation parameters more often positively. The variables closest in time show more correspondence to each other. As for linear time coefficients, on the territories of avian colonies there is less connection between changes in the amount of vegetation and the level of summer mean NDVI as well as spring GI for back in times in comparison to the outside. Also, almost a lack of correlation is between changing amount of vegetation and height parameters. The opposite tendency is for changes in elevation and space slope. The variability of the environment (amount of unique clusters) correlates negatively with vegetation factors and positively with elevation ones. Again this trend is more vivid within the birds' presence.

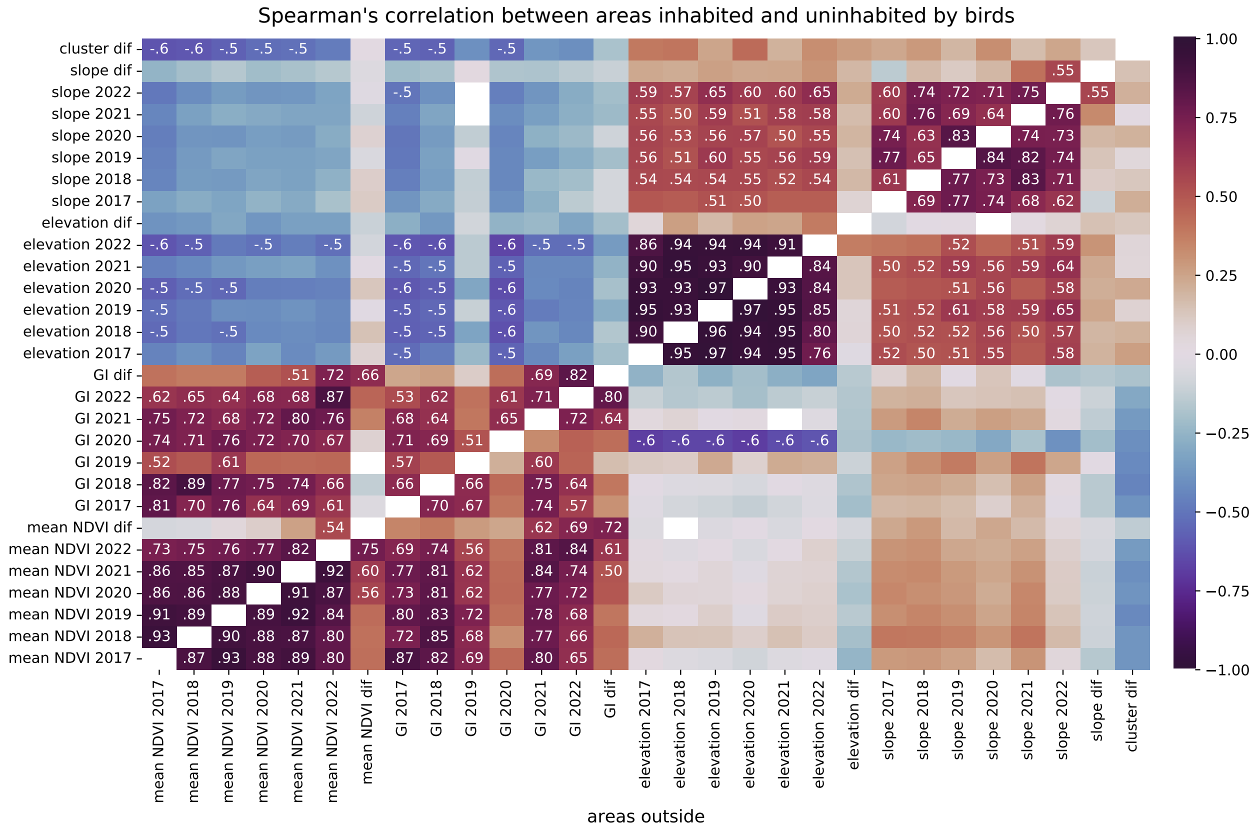


Figure 25: Correlation between environmental parameters over six years for areas outside and inside colonies. Significant values are annotated. 'Dif' is for difference and means a linear time coefficient. Blanked not on the diagonal cells reflect coefficients with p-value > 0.05

To reveal the most impacting parameters that determine or narrow down the possibility to recognise one group or another, logistic regression and random forest classification are performed using all variables (summer mean NDVI, spring greening index, elevation, space slope) within all years available together with dynamic characteristics describing evolution to predict the presence or absence of avian colonies. The full analysis excluding year after year since 2017 was found per island and did not reveal any significant difference with the same pattern repeated.

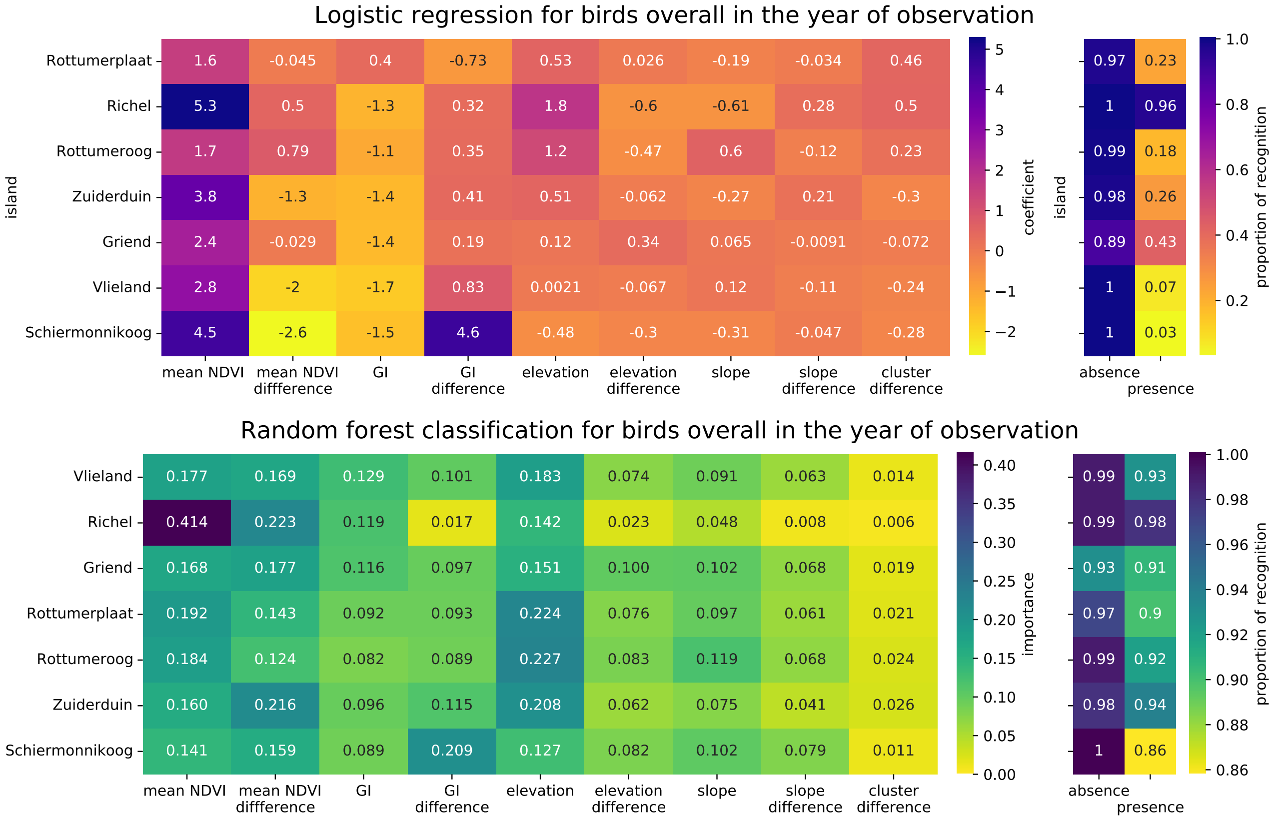


Figure 26: Environmental proxies to predict the birds' absence or presence in the year of observation per island. Logistic regression is used to comprise coefficients of influence and random forest classification is implemented to assess the importance of the parameters. Difference stands for a linear time coefficient. All variables were standardized

Results of logistic regression (fig.26) have an extremely low percentage of recognition for the presence of birds almost for all islands. The exception is Richel. Yet there the whole area nearly completely is occupied by the colony of *L. argentatus* and *L. fuscus* (fig.H.1). For others the increase in the proportion of test data from 33% to 99% to train a model was not productive since the performance improvement was around 1-3%. The absence of avian colonies is predicted with high preciseness with an error of a maximum of 2% (with exception of Griend with an error of 13%).

In contrast, random forest classification calculates variable importance with a high probability for both inside and outside of birds' colonies (fig.26). The error for presence could be a maximum of 14% and for absence is up to 7%. The rate of success correlates with the proportion of the area regarding the whole polygon (tab.6). Thus, for Richel birds occupy almost half of the polygon and for Schiermonnikoog the outside is slightly more than 97% of the polygon. Vegetation parameters (mean NDVI and its linear time coefficients) impact significantly as well as elevation. The number of unique clusters makes relatively a modest contribution. Overall, there is no particular parameter that describes the presence and absence of birds across all islands.

Per species regression results are the same with high variability per island: no obvious patterns or consistency are marked (in the Supplementary materials fig.J.1-J.5). Likewise, the absence of birds is predicted way more reliable than their presence. Throughout the species mean NDVI and elevation are the most important variables in the year of observation with an average bootstrap of more than 90%.

Vegetation maps

Vegetation zone codes logically co-depend with environmental clusters and show preferences of birds (fig.27, 28). This survey was performed only for Griend and Richel in 2018 due to the lack of any other data.

With clusters correlation is mostly due to the elevation and periodically to vegetation (fig.27, abbreviation tab.5, cluster reference 8). Young shifting dunes (Da) are located roughly at an elevation of 0.93-4.5 m with no connection to other parameters. Yet noticeably all clusters marked as 26 belong to this zone. Young stable dunes (Df) and disturbed dunes (Dx) also stick to elevation but mostly at the 1.125-4.5 m range with obligatory high summer mean NDVI for the first group. They both fall mostly into clusters 21 and 24. Brackish salt marshes (Kb) are at greening sites with 0.93-1.125 m of elevation or slightly above it. On the other hand, high salt marsh (Kh) and nitrophilic zone (Kn) are characterised again only by elevation with a range of 0.93-4.5 m. Furthermore, low salt marshes (Kl) and medium salt marshes (Km) are also described by elevation. Pioneer salt marsh (Kp) follows the same trend for low elevations along with pre-pioneer salt marsh (Kpp) where the last one prefers plain lowlands more. Most commonly marshes occur in clusters 19 and 20. Bare (drying) mud (Ks) are again at low elevations and similar to bare water (Kw) which is even lower. Remarkably it could have high mean NDVI level. Bare shells (Ksch) are located above mean high waters but with no vegetation preferably in clusters 2 and 3. Bare sand (Kz) is encountered mostly at low elevations with no regard to other attributes. It appears predominantly in clusters 2 and 3. Beach plain (Sv) is mostly represented by cluser 2 (and vice versa) with the lack of intense mean NDVI, GI, and elevation; also these plains are also primarily plain.

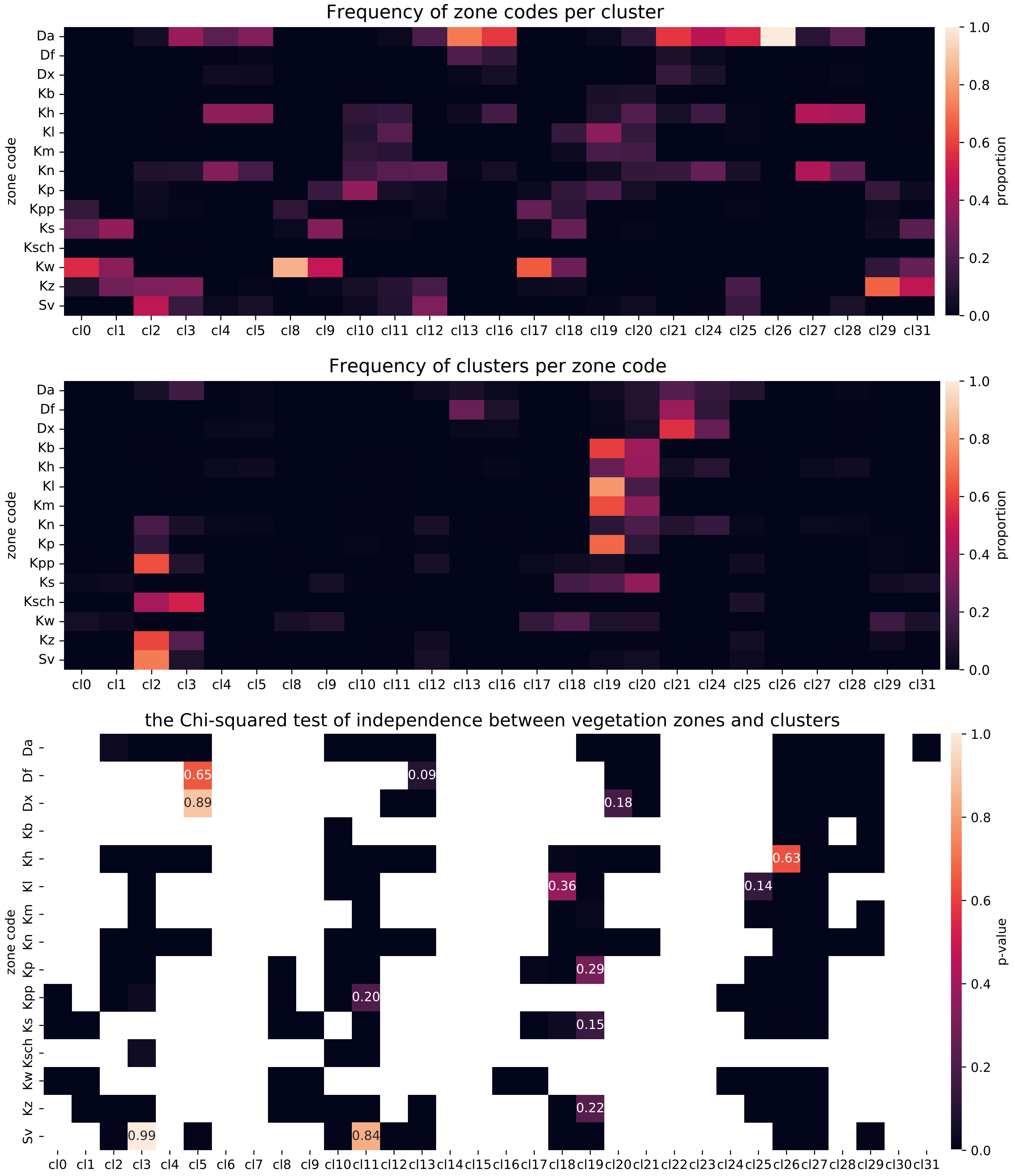


Figure 27: The Chi-squared test between zone codes and clusters. P-values are marked if they are higher than 0.05. For the Chi-squared test only matches with 5 or more observations are used

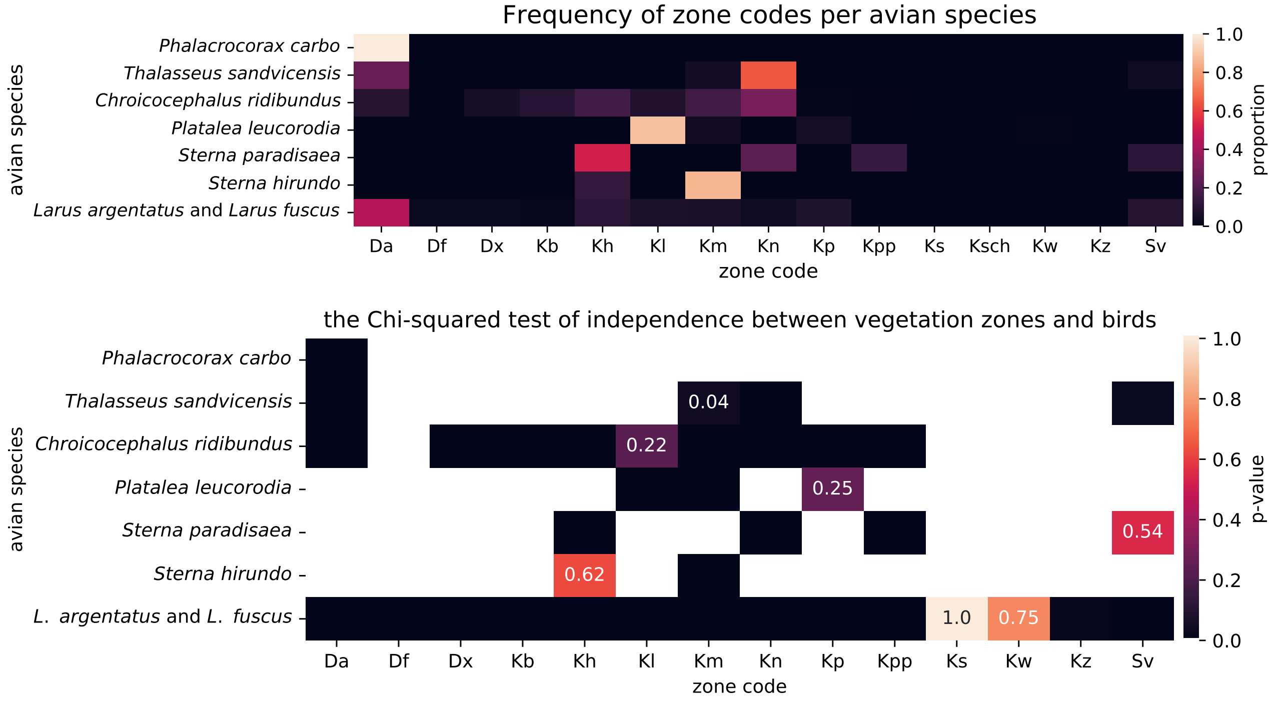


Figure 28: The Chi-squared test between zone codes and birds. P-values are marked if they are higher than 0.05. For the Chi-squared test only matches with 5 or more observations are used

As for birds, distribution reflects not only species preferences (fig.28) but also the number of occupied pixels (tab.6). Thus, *L. argentatus* and *L. fuscus* (Zilvermeeuw and Kleine mantelmeeuw) are ubiquitous and occur almost everywhere except mud and water but preferably on young shifting dunes. Whereas, *C. ridibundus* (Kokmeeuw) is a generalist too but avoids the bare and low areas as well as stable young dunes preferring salt marshes. Being the second most prevalent species *P. carbo* (Aalscholver) is found only on young shifting dunes. *P. leucorodia* (Lepelaar) favours low salt marshes while *S. hirundo* (Visdief) sticks only to medium ones. The other two species *T. sandvicensis* (Grote Stern) and *S. paradisaea* (Noordse stern) choose salt marshes.

Discussion

Method disadvantages and how to overcome it

For the NDVI technique, two problems are the most substantial: space and time coverage (tab.??-??). First, the time coverage is not consistent. As a result, some features are computed based on one (summer mean NDVI) or two (spring greening index) data points which at the end is not the exact true value. Furthermore, time coverage could vary too. For example, while some geo points could have data only at the end of spring, others could be available just once in February and once in June. This could be fixed by launching any time points available instead of sticking to the distance of two weeks. Second, sometimes space coverage is partial for an area of interest. Then the entire time point should be eliminated since it would affect only a part of an area leading to patches with uneven coverage. Last but not least, each month NDVI points are given with different coordinates. Therefore, by linking them all to one point the error of max ±2 meters is occurring. To reduce its impact the resolution of a data set should be downsized. Hence this problem is unavoidable in the absence of more precise techniques. The same issue arises when DEM data should be coupled with the NDVI one.

For DEMs occasional space gaps happen also from time to time. To avoid scarcity of it the exact Euclidean distance transform is implemented. Since the landscape is usually consistent, the gap fusion based on neighbours is relatively effective [126]. Yet it is not the exact true value which could be resolved by more research and more data.

As for clustering, breaks for supervised clustering could be optimised by unsupervised 1D array clustering, for example using `ckmeans` by `ckwrap` which is relatively fast for big data as written on Cython. However, then it could lead to a loss of a clear natural explanation of the obtained boundaries. Moreover, the whole clustering could be done as unsupervised machine learning. For example, by Gaussian Mixtures performed by `sklearn`. As again this option gives both the most realistic output and optimal time performance.

Also, some modifications could be implemented to optimise the design of the research. For example, if possible a set of avian species with diverse diets could reveal the impact of different guano compositions [20]. Besides, the outside area could be 1) tailored to be completely inside an island, 2) separated into several subzones based on a radius to distinguish the level of avian impact. Furthermore, a balanced proportion of areas inside and outside of avian colonies could help with logistic regression.

Cluster distribution

As the chosen environmental parameters correlate with one another (fig.25), some combinations of them are more common than others (fig.11). Therefore, some clusters are more frequent. For instance, the researched islands in the Wadden Sea are mostly plain (up to 5° fig.??-??) and existing sand dunes are not so high (up to 4m fig.??-??), therefore elevated steep areas are quite rare (clusters 6, 14, 22, 30, fig.11).

Moreover, certain combinations of features could describe particular habitats or ecological niches (fig.27). For example, salt marshes are high chlorophyll levels with not-so-intensive greening over spring [127] on the grounds above average tidal water level [56] and lays in clusters 19 and 20 (fig.27). However, most vegetation co-depends with clusters 26 and 27 (fig.11, 27) because these spaces are associated with greening and high vegetation level and are located above saline waters (fig.8). These areas are probably linked to dunes (fig.27). Also, clusters 2 and 10 are frequent too (fig.11) since the first one probably represents sandy beaches (fig.27) and the second one is for some spots at the supratidal areas with are greening but do not have much vegetation during summer, for example, pioneer salt marshes (fig.27).

If an area of some clusters is increasing that could mark it as a local steady state. For some clusters their occurrence is rising over the years (fig.11, clusters 18 and 31, fig.20). Also, some geo points are reflected by the same cluster type over the whole period of observation (fig.20, unique clusters:1). Usually that is cluster 26 (less 27, 29, 31). That could indicate that vegetated dunes are in a steady state condition.

Some unstable frequencies of clusters with low heights could be partly explained by the imperfection of the LiDAR or NDVI methods. For example, some low areas could appear and disappear in the analysis (fig.E.3, Engelsmanplaat). Due to mesotidal nature of the Wadden Sea, it is complicated sometimes to distinguish terrain level since it could be underwater since the LIDAR technique cannot penetrate water level [128]. As there is no indication of the time for DEM data collection [129], it could have occurred during high tides. Therefore, some parts of the coastal area could be not included as the high water would cover those terrains. Besides, at very flat surfaces stripes occur from laser traces (for example, areas around Razendebol fig.D.2). Furthermore, some borderline areas could be cut or not by the minimum of summer mean NDVI or cloud presence [130]. Thereby the frequency of clusters 0, 1, and 8 are varying in orders of magnitude with the timeline of this research (fig.11). Likewise, almost the whole area of Engelsmanplaat is out due to inconsistency of the coverage (fig.E.3). Yet the fact should be considered that low-lying areas are in general naturally more dynamic [131].

Birds

Because of the limitations discussed above, the areas of bird colonies could be not complete and thus not fully correspond to reality. For instance, the part of the *Larus argentatus* and *Larus fuscus* (Zilvermeeuw and Kleine mantelmeeuw) colony and one of *Sterna paradisaea* (Noordse stern) colonies on Griend (fig.H.1, also partly *L. argentatus* and *L. fuscus* on Vlieland) are excluded from the analysis due to the lack of coverage. On Griend this happens because of the gap in 2021 from the K.J. (Kasper) Meijer's dataset (fig.E.3). On Vlieland this area was not included in the polygon all along. As for *L. argentatus* and *L. fuscus* the loss of these areas is probably not essential since other colonies occupy the vast areas. Whereas for *S. paradisaea* it could be meaningful since the only two other colony consists of a few tens of pixels (tab.6).

Bird correlation with environment

Environment in the year of observation

In general, avian colonies are located in places with high vegetation (summer mean NDVI) levels and intense greening (GI) as well as at elevations with very light steepness (fig.13, 16). However, even with statistically significant differences slope is varying between 0° and 6° meaning between plain and gently inclined [132]. Usually, the researched avian species have distinct distributions of environmental parameters but sometimes these variables are similar (fig.14). Based on literature (tab.1), these similarities occur for species sharing the same environment. However, the general resemblance between GI for *L. argentatus* and *L. fuscus* and colonies of *S. paradisaea* is hard to explain as Arctic tern inhabits predominantly cluster 27 (fig.16) and Common (mew) gull is omnipresent. Birds who inhabit salt marshes (tab.1) are located at lower elevations and vary in vegetation parameters probably due to the variation of these characteristics between low, medium and high salt marshes [56]. Low mean NDVI for *L. canus* and *S. paradisaea* could be explained by the fact that these birds prefer low salt marshes [82] where is less vegetation [56].

The distributions of parameters in the year of observation (fig.13) do not always have a normal shape. For rare species such as *S. hirundo* (Visdief), *P. leucorodia* (Lepelaar), and *T. sandvicensis* (Grote Stern) (tab.6) these are almost normal probably because for last two species have only one colony in the limited space. As for Visdief its amount is relatively small but it could be a sign of space preferences. Whereas, two colonies of *S. paradisaea* (Noordse stern) from a bimodal or broad distribution of all four environmental parameters (fig.13) even within small areas occupied (tab.6). The other species mostly have multimodal distributions of variables with several preferable pikes. This could mean that 1) bird preferences vary depending on the islands, 2) colonies act as small populations, and 3) islands themselves offer different conditions. The other hypothesis could be that birds do not have favoured specifics but modify the area around them. Thus this detected multimodality reflects stages of development.

Evolution within and outside avian colonies

Linear coefficients calculated within 6 years reveal the possible changes of environmental parameters within avian colonies in comparison to stagnation outside (fig.17, 18). Overall, over the years vegetation and greening are increasing with the presence of birds whereas for outside areas these parameters are close to the absence of changes (for greening) or show a minor rise (for vegetation). The effect of the presence of some species is more intense than that of others. For example, *P. leucorodia* (Lepelaar), *S. hirundo* (Visdief), and *T. sandvicensis* (Grote Stern) boost greening more than others. All of them are purely piscivorous (tab.4) and arrive in the spring (late March, according to Sovon Stats). While other piscivorous species *P. carbo* (Aalscholver) is constantly present on the islands (according to Sovon Stats). Therefore, the exposure amplitude could so increase for visiting birds. As other spring-comer *S. paradisaea* but a crustacean eater do not influence so much, probably guano of fish eaters are more fertile. Nevertheless, these three species and *S. paradisaea* (Noordse stern) have a wide variation between influence on elevation and steepness growth than the others. Yet changes in space slope are so small in the environmental scale (units are $\Delta 0.005$ that corresponds to a change in 0.3° per year) that could be insufficient in the year timescale but the trend is here. Surprisingly the elevation does not grow fast within birds' presence or even stays the same (yet that varies per species) despite the increase in vegetation. That could be explained by deficient sediment accumulation by vegetation as opposed to weathering or other sediment depletion reasons.

The stimulus-response variance could be due to the different sensitivities of the environment to guano nourishment. As salt marshes are full of nutrients [56] and their addition does not bust vegetation much [61], [62]. Whereas, sandy dunes lack nutrients [72], [44] and extra supplements cause rapid succession of vegetation [73], [36]. However, species from salt marshes are associated with more changes than the ones from dunes (tab.1, fig.17). Yet dune species are mostly represented by *L. argentatus* and *L. fuscus* as being more than 84% based on the population size for the whole Wadden Sea (tab.1). Also, this group occupies more than 92% of all geo points with birds (tab.6). Therefore its population-to-area ratio is less than for other species even considering that these calculations are not reflecting reality as the population used is for the whole Wadden Sea and not specific for the area of the research. This very rough assumption could explain the less effect of birds on dunes by the low density of dune key species. The precise data for population density per island per species is needed to accept or reject this hypothesis.

Most bird-populated islands evolved into stable clusters 26 or 27 (fig.20, unique clusters: 1) representing areas with high vegetation, GI, and above MHW level even outside of colonies. Those are the succession state. While the bare islands do not have any specific direction preferably wandering between unvegetated clusters 2 and 10 (fig.22). Those are the most common combination for abiotic environments. Overall, birds stimulate space to change more but not radically or too fast (fig.24) but step by step. The most unstable areas show the general trend of the evolution both for outside and inside colonies from clusters without vegetation and greening to clusters with high mean NDVI (fig.20 unique clusters: 6, 21) thus illustrating succession. However, the tendency is varying from island to island (fig.21). That fact and the multimodality of distributions per species (fig.17) could indicate that islands influence to the development of characteristics more than birds.

At the end: chick or island?

Both outside and inside avian colonies a type of an island could impact the distribution of both stationary parameters in the year or observation (fig.15, per species fig.G.2-G.6) and dynamic variables more than species preferences (fig.19, per species fig.H.2-H.6). Almost always distributions per island are statistically different for birds overall and outside areas as well as per species too. Nonetheless, stationary and dynamic parameters are significantly distinctive between the inside and outside of avian colonies with a few exceptions. This trend is the same per species versus outside.

As islands or their parts could go through four different development stages [49], those macro processes override the effect of bird presence. Bare islands (Engelsmanplaat, Rif, Razendebol) are probably in geomorphologic phase 1 with the dominance of abiotic factors and the absence of vegetation (fig.22). During the 2nd phase pioneer plants are taking place [49] which is not the case for any island as a whole system in this research.

The third phase includes the facilitation of vegetation, soil formation, sand deposit, dune and salt marsh formation. Throughout the timeline, there is a clear transition from unvegetated clusters to vegetated ones for outside and inside of birds' colonies on Richel, Rottumerplaat, and Rottumeroog (fig.21). Also, these areas got elevated and slightly steeper (fig.19). Therefore, these islands presumably fall into the 3rd bio-geomorphologic stage. There are not so many stable geo points (less than 20%) and often birds significantly increase environmental variability (fig.23). Considering that avians regardless of species boost vegetation, **birds statistically accelerate vegetation build-up and succession**.

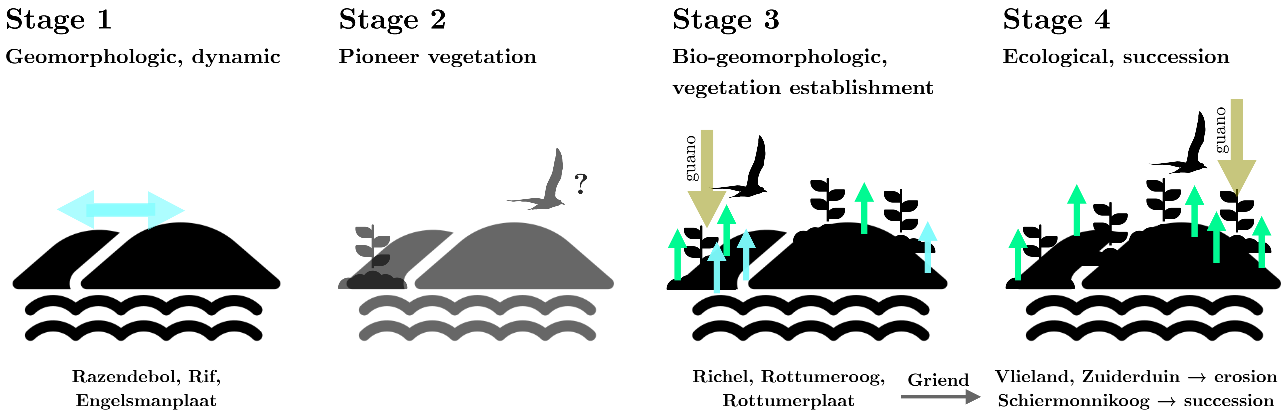


Figure 29: Different stages of an island (or its parts) development [49]. Green arrow represent a growth of vegetation parameters, blue ones stand for an increase in elevation. Credits: Vector Stall, Freepic, nawicon

Whereas, the fourth stage could lead to either ecological growth to succession or erosion. The other three islands (Schiermonnikoog, Vlieland, and Zuiderduin) are in this stage because there is already no massive vector of development for the environment towards gaining more vegetation (fig.21). On Zuiderduin the territories of birds' colonies still show the transition from clusters with no so intense vegetation towards high summer mean NDVI. Meanwhile, the outside drastically degrades in the opposite direction. So one part of the island is stable and goes into the ecological steady state, while without nutrient pump areas quickly lose any signs of vegetation. This may be because of too strong abiotic stresses (storms, erosion). On Vlieland even spaces with birds deteriorate, yet it still goes slower than for the outside. Even with positive mean NDVI growth, there is less greening over spring every year (fig.19). The elevation rate is the same as on Zuiderduin for outside territories. On these islands, birds dwell proportionally on more stable positions (fig.23) with in general 30-40% of all geo points being completely stable. As for Schiermonnikoog, all birds inhabit stable places with no geo points of colonies that occur to contain different clusters every year (fig.21). The outside area transits but within a limited amount of clusters with a trend to the vegetated state. Mean NDVI and greening index increase even faster than for islands from the third stage with a slight decrease in elevation and steepness (fig.19). Proportion distributions of cluster variability for outside and inside of avian colonies are virtually identical with a high dominance (up to 60%) of absolutely stable geo points (fig.23). Thus, presumably, Schiermonnikoog is in the ecological stability of succession.

As many of the described characteristics overlap, Griend could be on the transition from stage 3 to the fourth one. The trend of the transition from unvegetated clusters to vegetated ones for both areas is still readable yet already is not so clear (fig.21). However, the summer mean NDVI and spring GI are growing quicker than on Richel, Rottumerplaat, and Rottumeroog and closer to the level of Schiermonnikoog or even faster (fig.19). As for the proportion of cluster variability, birds are already in the more stable areas, whereas the last ones account for 30 % of all geo points (fig.23).

Birds with growing and shrinking populations

Not intense effects on environmental parameters could be explained not only by species characteristics but its populational dynamic. For instance, if one colony of birds occupies the same territory but over the year the amount of birds within this colony is decreasing. Then the effect is becoming less and less visible. The opposite is applicable to growing populations. In the Wadden Sea from 1991 til 2020 *S. hirundo* (Common tern), *L. argentatus* (European herring gull), *S. paradisaea* (Arctic tern), and *C. ridibundus* (Black-headed gull) are declining (arranged in descending order with the most affected first) [88], [86], [87] (tab.1). While *P. carbo* (Great cormorant), *P. leucorodia* (Eurasian spoonbill), *L. fuscus* (Lesser black-backed gull), *L. canus* (Common (mew) gull), and *T. sandvicensis* (Sandwich tern) are thriving or stable (arranged in descending order with the most flourishing first) [88], [86], [87] (tab.1). The tendency is quite opposite since the flourishing birds such as *P. carbo* increase vegetation way less than declining ones such as *S. hirundo* or *S. paradisaea* (fig.17). The same is observed for greening too. That could be due to guano concentration which in high dosages is more toxic than nourishing [16]. More up-to-date data about bird populations is needed for more clear discussion within the timeline of this research.

Bird diversity

On small islands there are more birds than on big ones. For example, on Griend there are 7 different species which is the most diverse island despite its size (fig.12). Moreover, birds occupy more than a third of its territory (tab.6). Also, on Richel as on the smallest island in the set the extensive colony of Zilvermeeuw en Kleine mantelmeeuw takes up space of almost the whole island (fig.H.1). Whereas on the big islands such as Vlieland or Schiermonnikoog birds do not fill much space. This paradox was observed previously and explained as on small islands seabirds have more territory for resources around [133].

Recommended research for the future

First of all, method disadvantages should be minimized as much as possible. Otherwise, a different approach should be chosen. Environmental parameters should have a balanced minimum of coverage which would be proven to be sufficient.

Second of all, the location of the colonies should be known for each year and based more on the field data rather than on oral descriptions. To explore the impact of different diets, more species should be spotted in total with more diverse food sources. Also, the density of colonies is better to be included in calculations too.

Third, a comparison should be focused on habitats too rather than only per island. As dunes and salt marshes could develop differently at each stage of island development, analysis per colony could be more precise. Here, unsupervised classification could be implemented as areas would be already divided into ecological groups.

Conclusion

1. The presence of birds correlates with high summer vegetation and intense greening over spring. Usually, avian colonies are located not too high but not too low: above the mean high waters level. Some species are associated with particular vegetation habitats, whereas others (most of the seagulls) are generalists. Species inhabited on salt marshes have a more pronounced preference for a certain level of elevation in comparison to those on dunes.

2. Birds have a significant impact on the amount of summer vegetation increasing it as well as the slightly rising speed of spring greening. While there is no certain direction of height development but some species make surroundings steeper. Therefore, it is not proven that sediment is not accumulated more within the presence of a high amount of vegetation. Due to the lack of enough time coverage of vegetation maps, no deduction could be comprised about birds' influence on types of vegetation.

3. Clustered ecotopes can be used to narrow down the range of possible habitats as some species dwell in particular clusters. However, generalists such as gulls could be found almost ubiquitous. That does not make clustered ecotopes applicable for use as indicators of birds or at least certain species as clusters only describe the static environment.

4. Variables reflecting dynamic (such as a linear annual coefficient for summer mean NDVI and spring greening index) could be used for bird detection while assuming that birds were staying at the same place within the timeline of the research. In comparison to the surrounding on almost all islands, vegetation within avian colonies grows faster and more intensely.

5. Within the researched avian species, all of them are carnivorous or omnivorous. Therefore, the dietary difference is not so pronounced. However, fish-eaters that arrive during spring have more influence on the spring greening index probably due to the contrast of their winter absence. As there are no data about density for the researched colonies, the assessment was made based on population trend. Where declining species have a more stimulating effect on the vegetation, probably because of the less concentrated per m^2 guano.

6. Islands that go through the bio-morphological stage of development (Richel, Rottumeroog, Rottumerplaat) and the ones that are already in the ecological phase (Vlieland and Zuiderduin are eroding, while Schiermonnikoog in the succession; Griend moves into this stage) are indeed differently affected by the presence of birds. Allochthonous nourishment is more boosting for vegetation (summer mean NDVI) on islands in the ecological stage, where the environment is already more stable (even in the eroding areas). The increase in elevation is only visible in the bio-morphological stage.

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Appendix A

Texel: a lack of DEM coverage

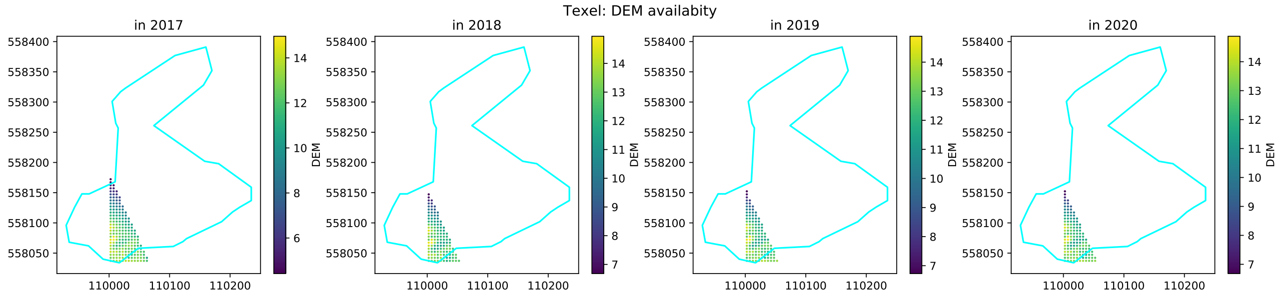


Figure A.1: Coverage by DEM for Texel within 2017-2020. The same area is available for 2021 and 2022. The cyan line represents a colony of *Larus argentalis* and *Larus fuscus*

Appendix B

NDVI coverage

Table B.1: Data with full or enough NDVI space coverage on Razendebol

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017			26.03					11.06	21.06	26.07			
2018				11.04									
2019			19.03				29.05	14.06			31.08		
2020		11.03		12.04			31.05				04.08		
2021	27.02		31.03				30.05			02.07		29.10	
2022		09.03	25.03				22.05	09.06	28.06	30.07		26.10	

Table B.2: Data with full or enough NDVI space coverage on Vlieland

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017					30.04								
2018					24.04								
2019	27.02					14.05							
2020						12.05						31.10	
2021			31.03				20.05	08.06					26.12
2022		11.03	24.03	12.04			21.05	09.06			25.08		

Table B.3: Data with full or enough NDVI space coverage on Richel

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017	13.02		24.03	11.04	30.04	11.05	25.05	11.06	21.06	22.07	28.08	15.10	29.12
2018		14.03	29.03	17.04		14.05	31.05	15.06	30.06	27.07	21.08	19.10	
2019	27.02		30.03		24.04	14.05	31.05	09.06	30.06	21.07	31.08	31.10	
2020		13.03	31.03		30.04	09.05	30.05			24.07	20.08	31.10	28.11
2021			31.03	13.04	28.04	13.05	30.05		24.06	22.07		24.10	07.12
2022		11.03	24.03	12.04			22.05	15.06	22.06	30.07	25.08	30.10	

Table B.4: Data with full or enough NDVI space coverage on Griend

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017			24.03		30.04	11.05							29.12
2018			29.03					15.06	30.06		21.08		24.12
2019		19.03	30.03	14.04	24.04	14.05	31.05	09.06	30.06		31.08		
2020			31.03	12.04	30.04	09.05	31.05	08.06	25.06		21.08		28.12
2021		19.03	31.03	13.04	28.04	13.05	30.05	08.06	28.06	20.07			26.12
2022			24.03	12.04			22.05	12.06	30.06		25.08	30.10	

Table B.5: Data with full or enough NDVI space coverage on Rif

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017				16.04			25.05	11.06	21.06	22.07	29.08	20.10	
2018	25.02	14.03			21.04			15.06	30.06	29.07	22.08	31.10	04.12
2019			30.03		22.04	14.05				23.07		31.10	
2020					30.04	09.05	31.05	08.06		24.07	21.08	29.10	
2021	13.02	05.03	31.03	13.04	28.04		20.05	13.06	28.06	05.08	24.08	28.10	27.12
2022		09.03	23.03	14.04		12.05		12.06		20.07	31.08	30.10	

Table B.6: Data with full or enough NDVI space coverage on Engelsmanplaat

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017			22.03		30.04			11.06		22.07	29.08	20.10	29.12
2018	25.02	14.03	29.03		21.04	14.05	31.05	15.06	30.06	29.07	22.08		04.12
2019			30.03	14.04		14.05	24.05		29.06	23.07	31.08	31.10	
2020		14.03	31.03	11.04		09.05		08.06			21.08	29.10	25.12
2021	13.02	05.03	31.03		28.04	18.05	20.05	30.05	28.06	18.07	24.08	28.10	
2022	18.02			14.04	21.04	12.05	03.06	12.06	23.06	20.07	31.08	30.10	

Table B.7: Data with full or enough NDVI space coverage on Schiermonnikoog

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017					30.04						29.08		
2018				11.04		14.05		15.06			29.08		
2019	27.02					14.05	31.05		23.06				
2020	14.02						31.05						
2021		08.03	31.03	13.04		18.05			28.06				
2022			25.03	14.04				12.06			31.08	30.10	

Table B.8: Data with full or enough NDVI space coverage on Rottumerplaat

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017	21.02		27.03			14.05			27.06				29.12
2018	25.02	14.03					31.05	15.06		29.07			
2019	26.02			14.04	23.04	14.05		01.06			22.08		
2020		11.03						08.06	26.06	24.07		28.10	
2021		16.03	31.03		28.04	18.05		14.06		24.07	30.08		27.12
2022				03.04	14.04		23.05	12.06	30.06		25.08	31.10	

Table B.9: Data with full or enough NDVI space coverage on Rottumeroog

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017	21.02		27.03			14.05		14.06				15.10	29.12
2018	25.02		29.03		23.04			15.06				31.10	
2019	26.02			14.04	23.04			16.06		23.07			30.11
2020	22.01	11.03	31.03	11.04	27.04		31.05		24.06	24.07			
2021		16.03	31.03	17.04	26.04		04.06	14.06	28.06	24.07	30.08		26.12
2022		13.03	03.04	14.04	23.04	12.05	23.05		30.06	30.07		31.10	

Table B.10: Data with full or enough NDVI space coverage on Zuiderduin

year	til end of Feb	start of Mar	end of Mar	start of Apr	end of Apr	start of May	end of May	start of Jun	end of Jun	Jul	Aug	Oct	Dec
2017			27.03		20.04	14.05	04.06	19.06	27.06	17.07	29.08	15.10	29.12
2018	25.02		19.03	11.04	23.04	14.05	29.05		28.06		11.08	04.09	
2019	26.02		30.03	14.04	23.04	14.05		01.06	29.06		22.08	30.10	
2020		11.03		11.04	27.04		30.05		19.06	24.07			19.12
2021	26.02	16.03	30.03		28.04	06.05	19.05	14.06	28.06	24.07	30.08	26.10	26.12
2022		13.03		03.04	23.04	12.05	23.05		30.06	30.07		31.10	

Appendix C

Versions of Python packages

Table C.1: Versions of Python packages*

package	**version**	**package**	**version**	**package**	**version**	**package**	**version**
`GDAL`	2.2.2	`numba`	0.56.4	`Pydap`	3.2.2	`scipy`	1.7.3
`geopandas`	0.12.2	`numpy`	1.21.6	`pyproj`	3.4.1	`seaborn`	0.11.2
`json`	2.0.9	`osgeo`	2.2.3	`rasterio`	1.3.4	`shapely`	2.0.0
`matplotlib`	3.2.2	`pandas`	1.3.5	`requests`	2.23.0	`sklearn`	1.0.2

* If anything is not stated here hence it is a built-in package

Appendix D

Raw variables distributions among islands

D.1 Map with characteristics

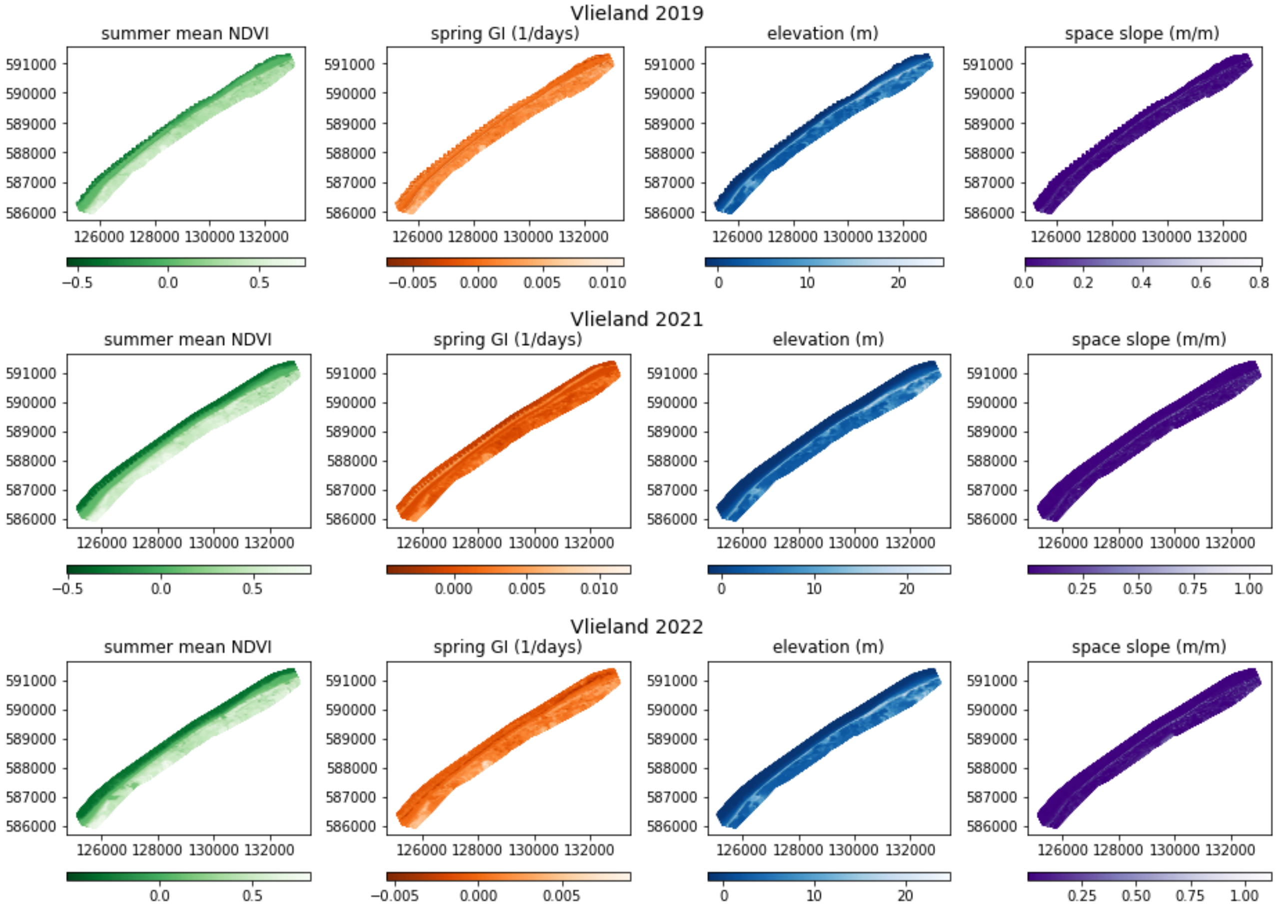


Figure D.1: Coverage and amplitude for four environmental parameters: Vlieland

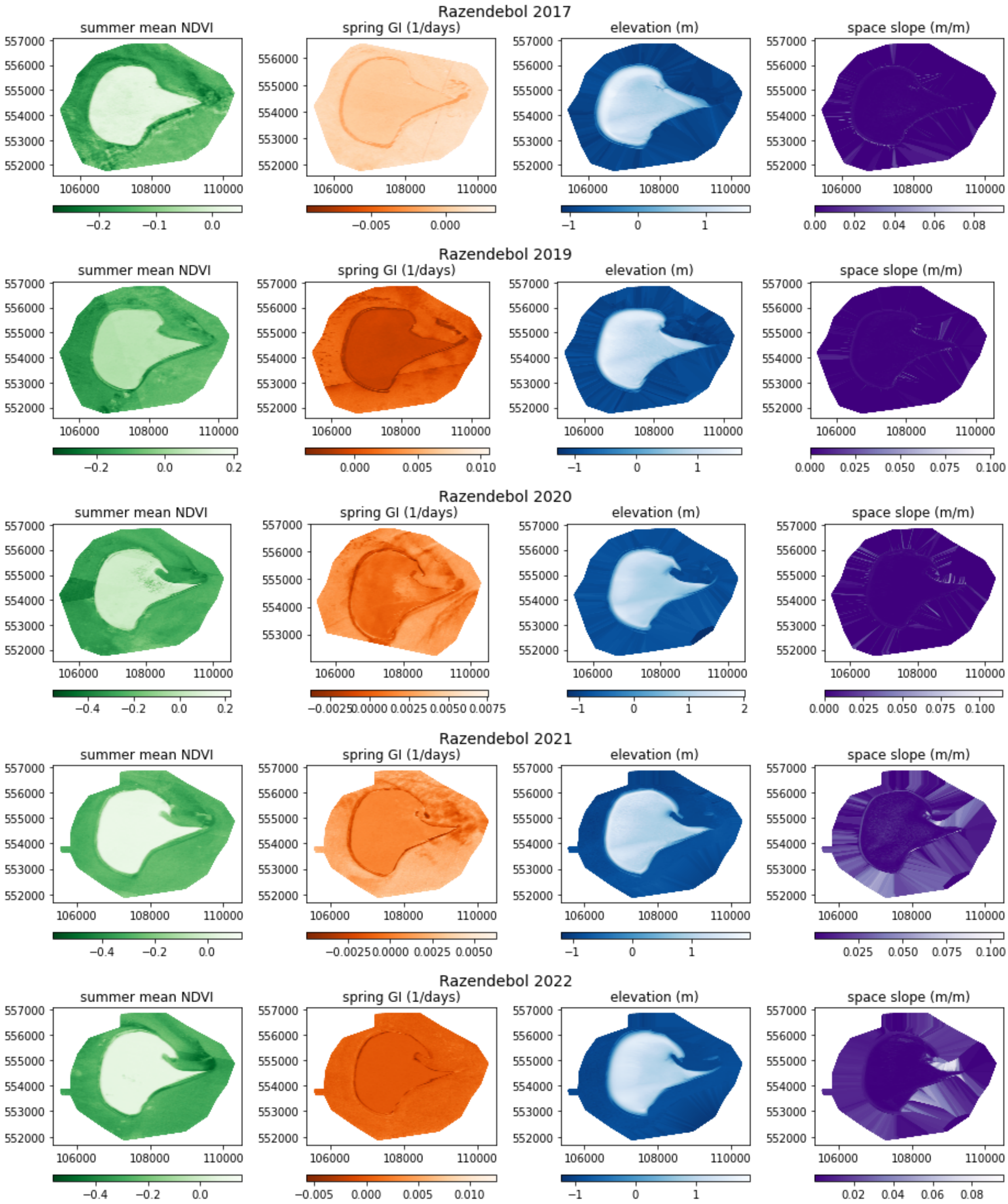


Figure D.2: Coverage and amplitude for four environmental parameters: Razendebol

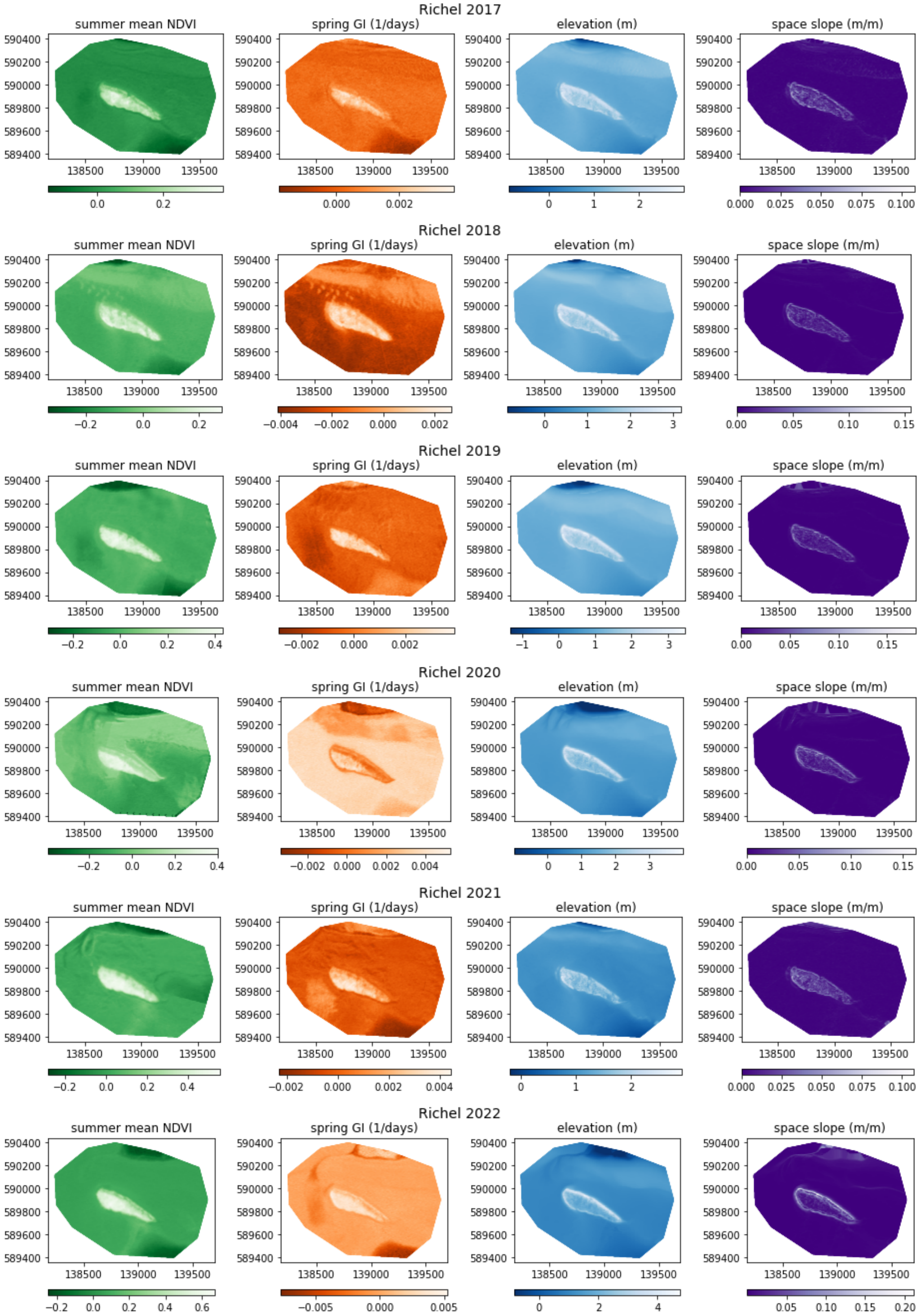


Figure D.3: Coverage and amplitude for four environmental parameters: Richel

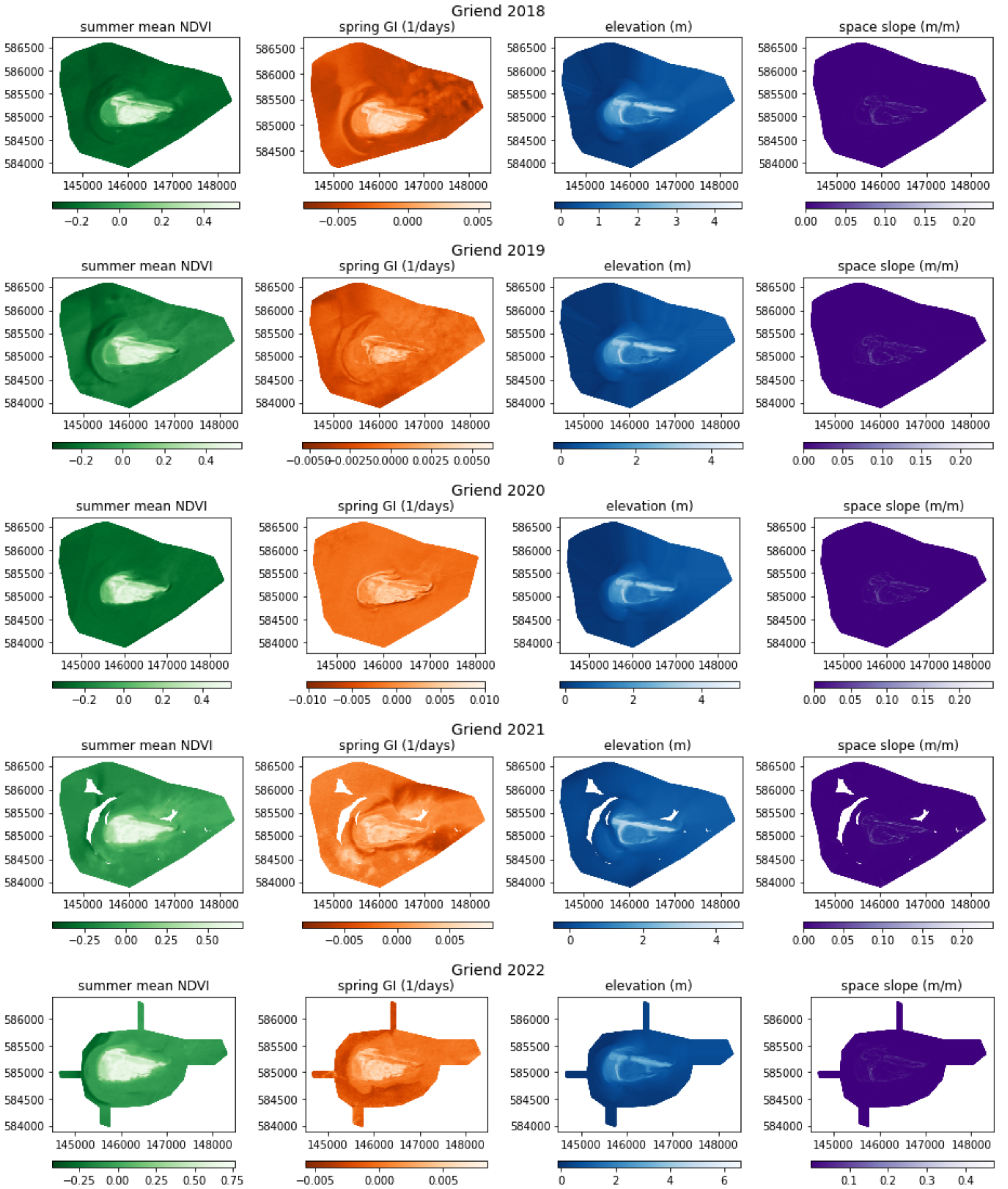


Figure D.4: Coverage and amplitude for four environmental parameters: Griend

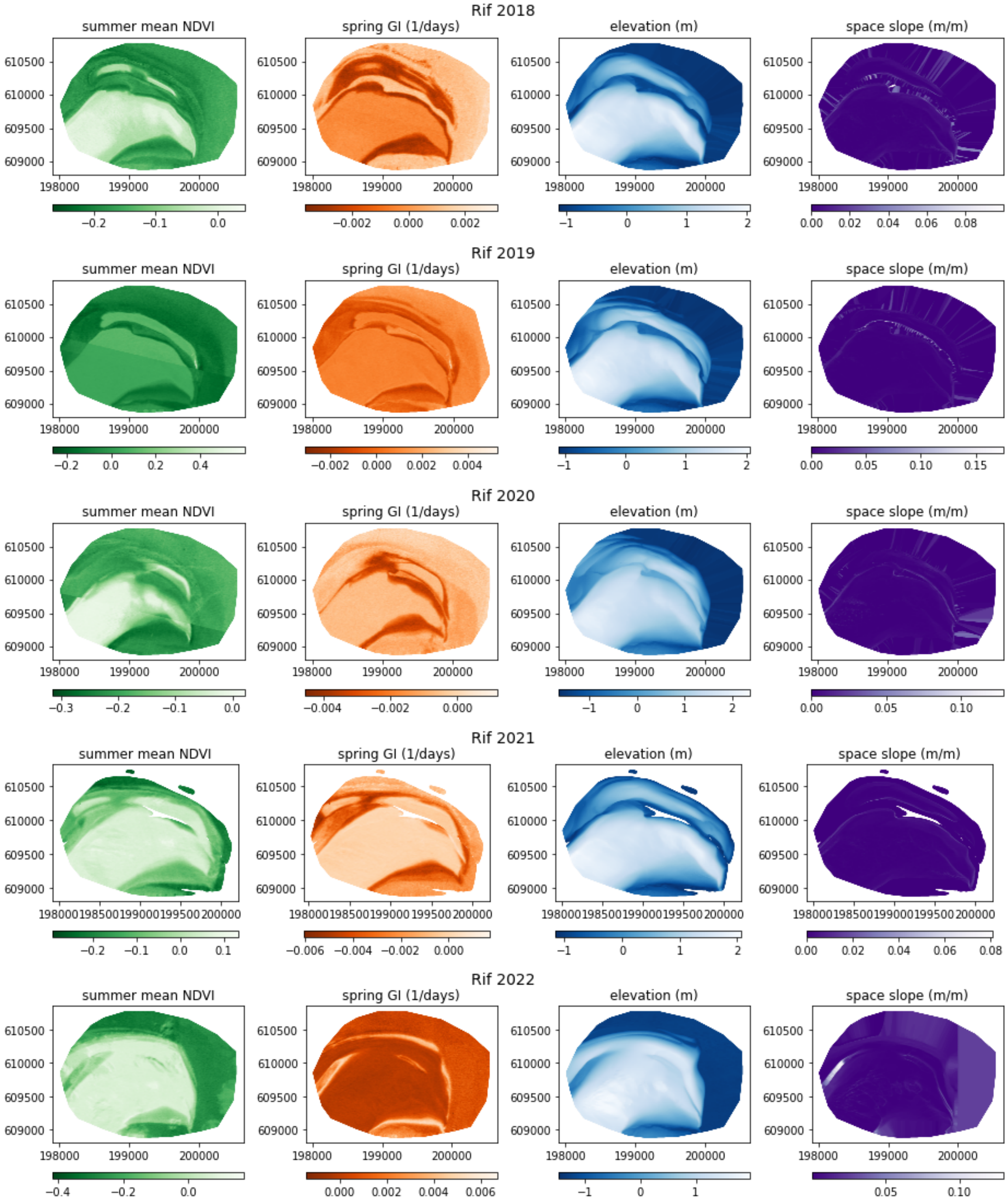


Figure D.5: Coverage and amplitude for four environmental parameters: Rif

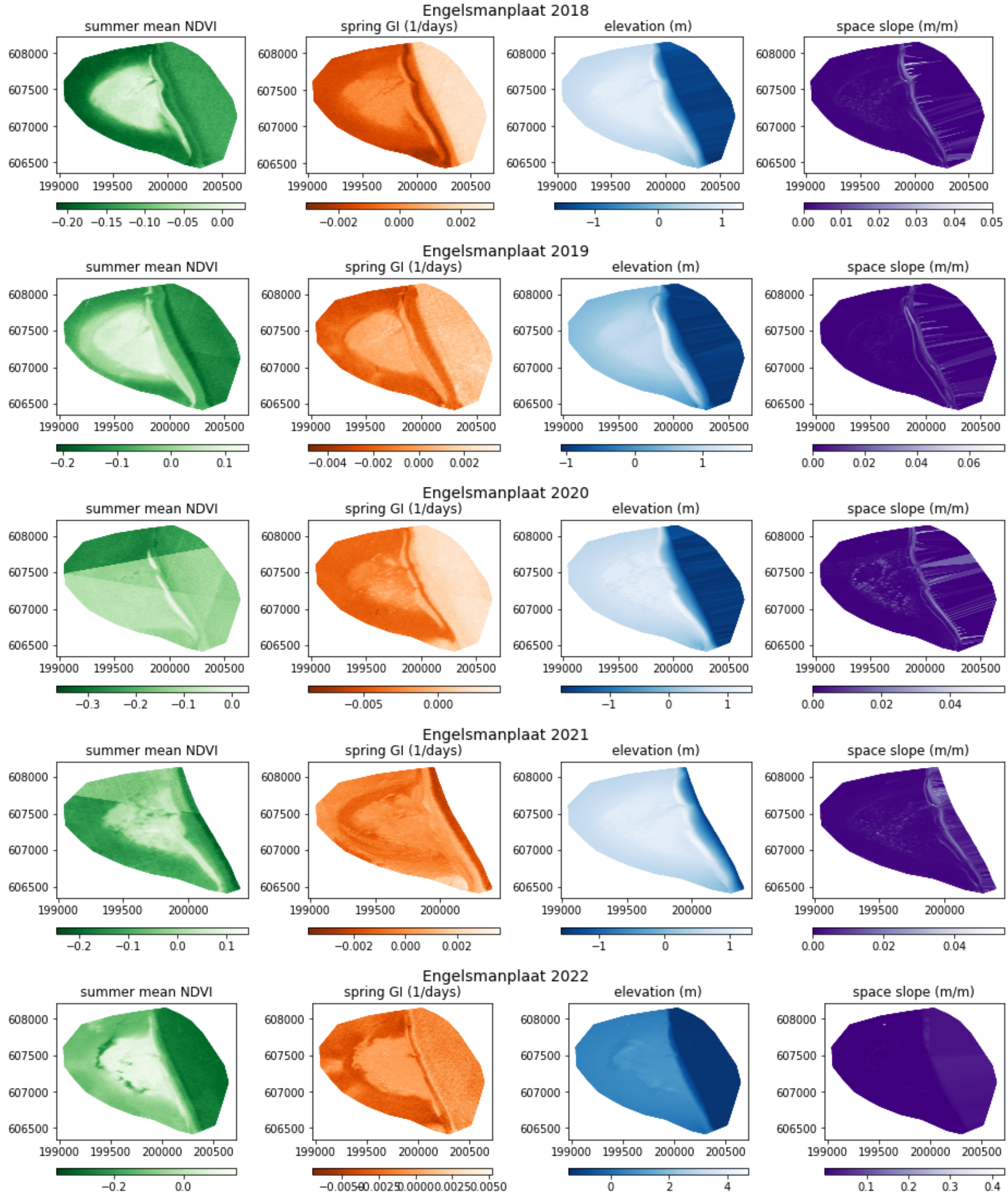


Figure D.6: Coverage and amplitude for four environmental parameters: Engelsmanplaat

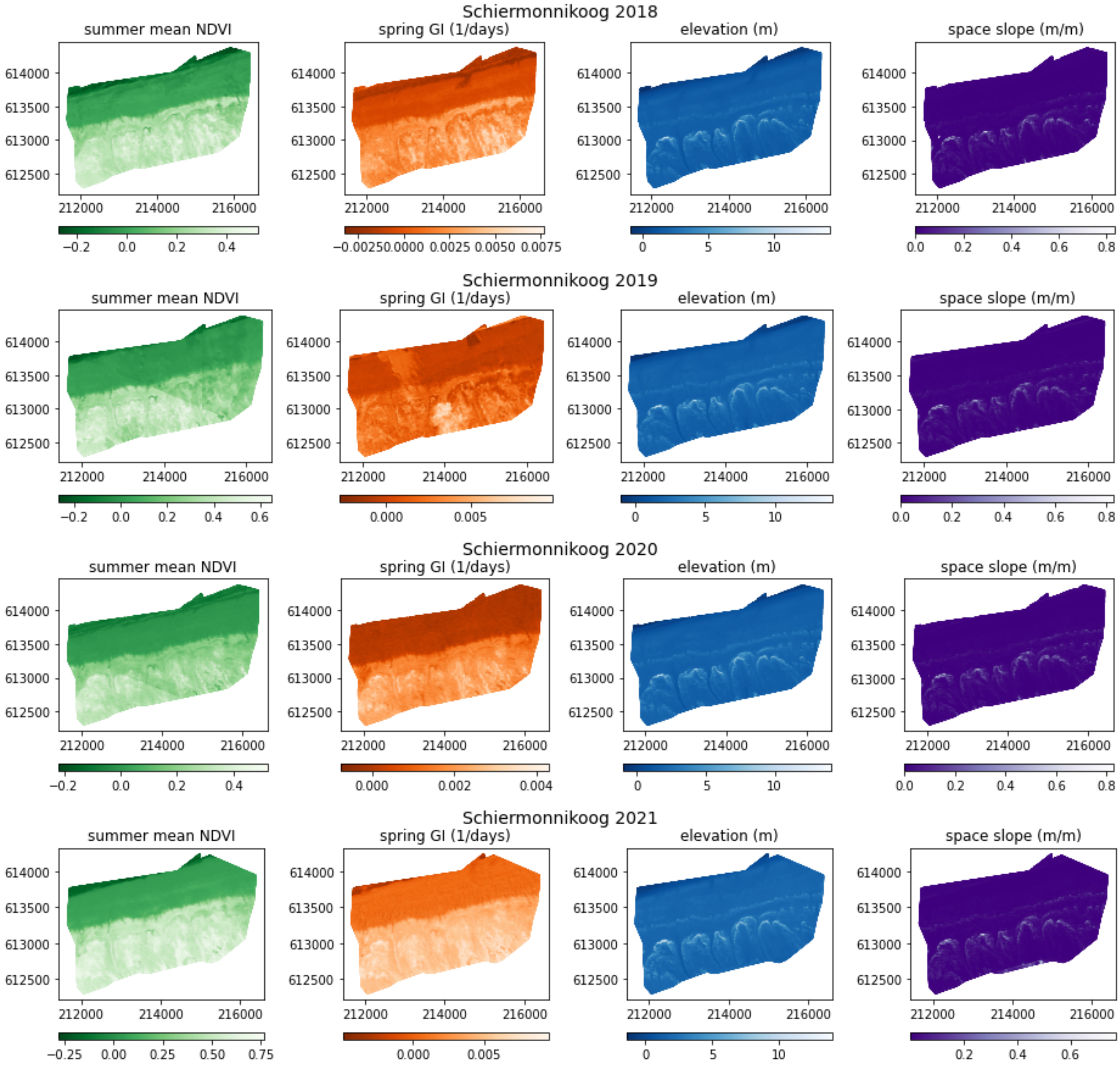


Figure D.7: Coverage and amplitude for four environmental parameters: Schiermonnikoog

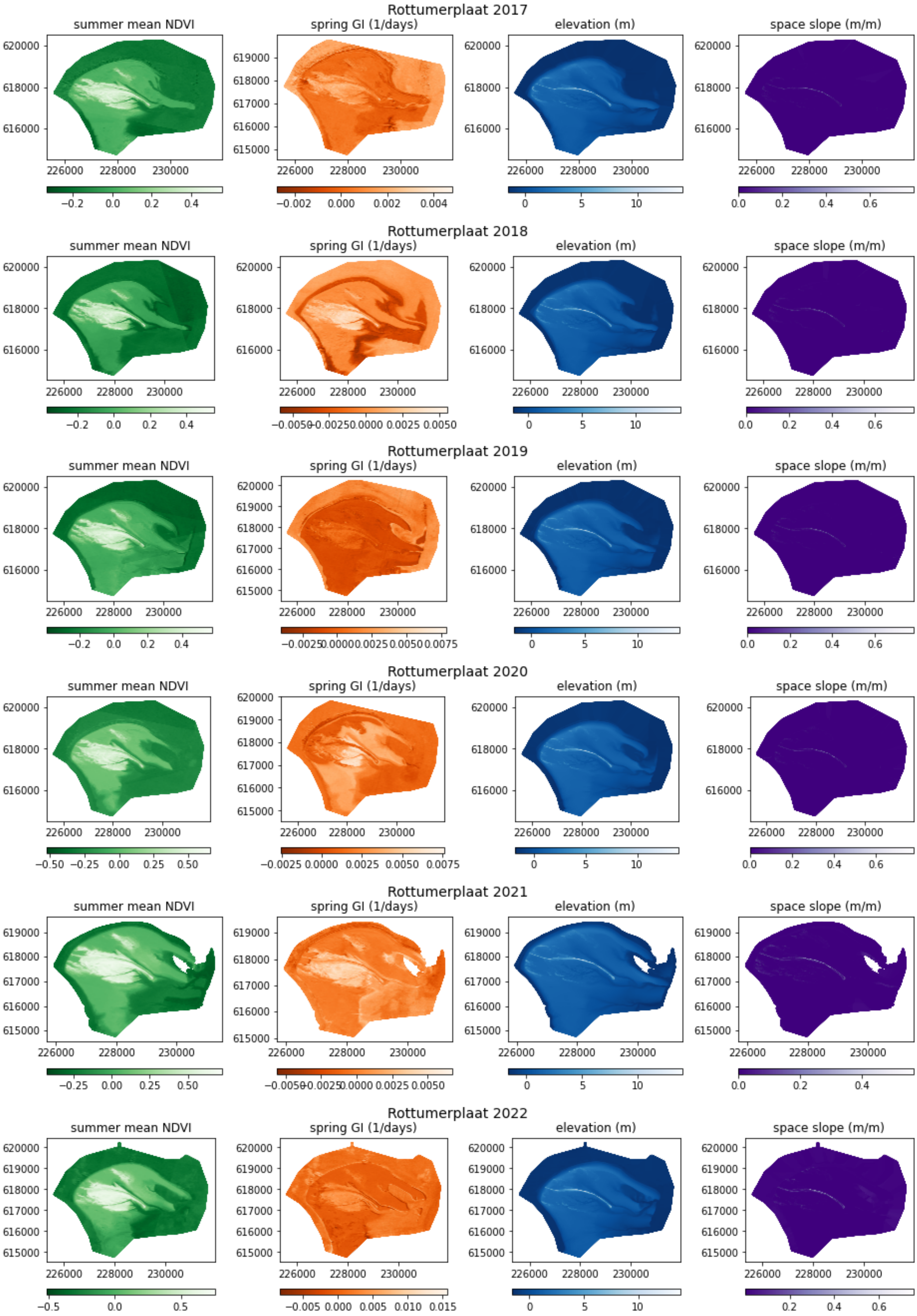


Figure D.8: Coverage and amplitude for four environmental parameters: Rottumerplaat

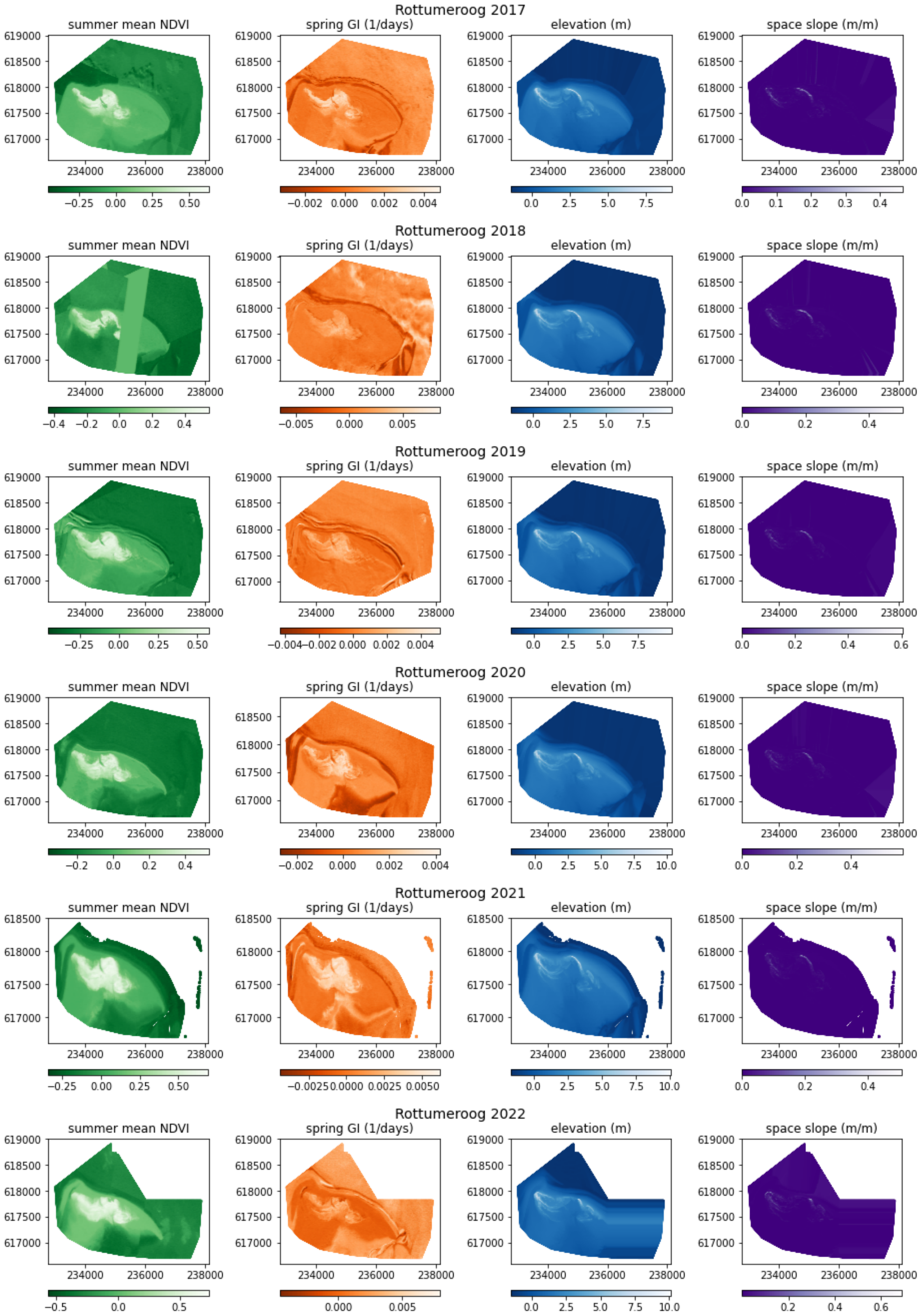


Figure D.9: Coverage and amplitude for four environmental parameters: Rottumeroog

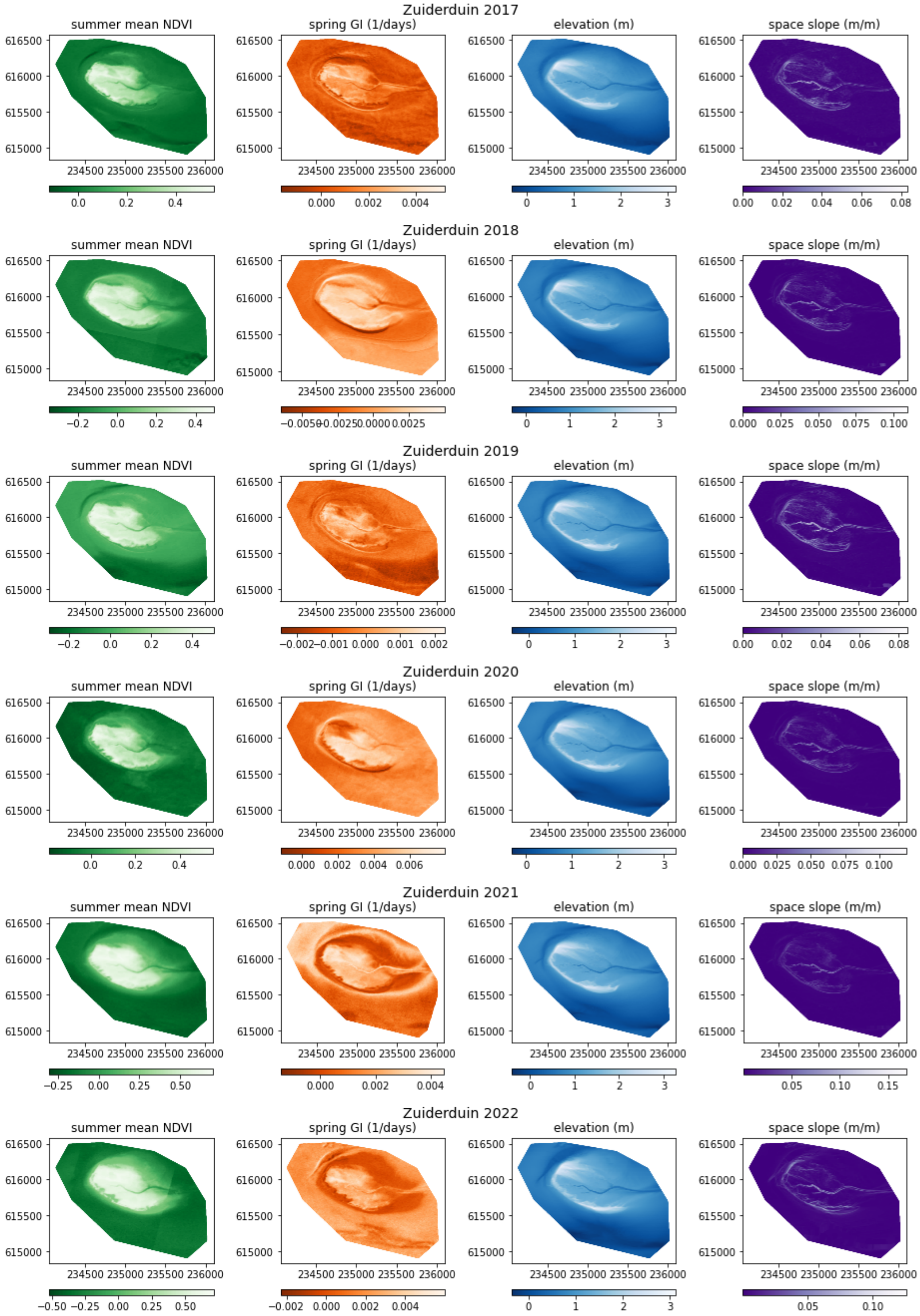


Figure D.10: Coverage and amplitude for four environmental parameters: Zuiderduin

D.2 Distribution of parameters per island

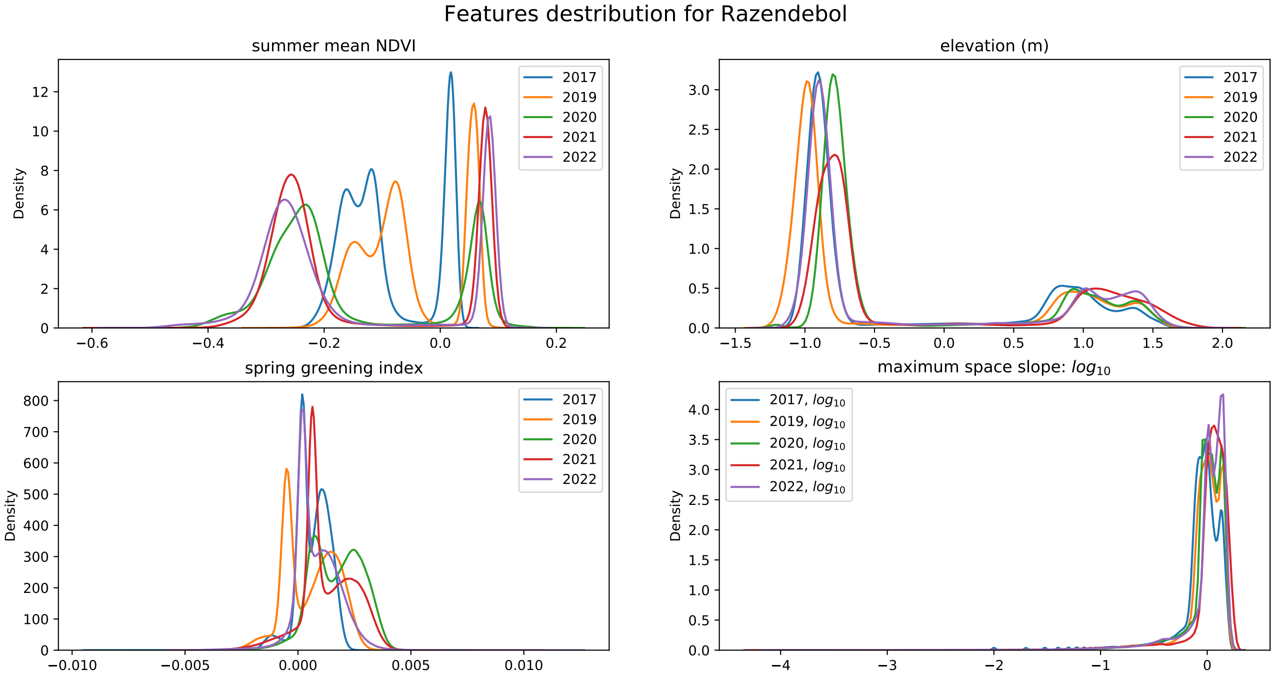


Figure D.11: Distribution of raw parameters per year on Razendebol within the settled polygons

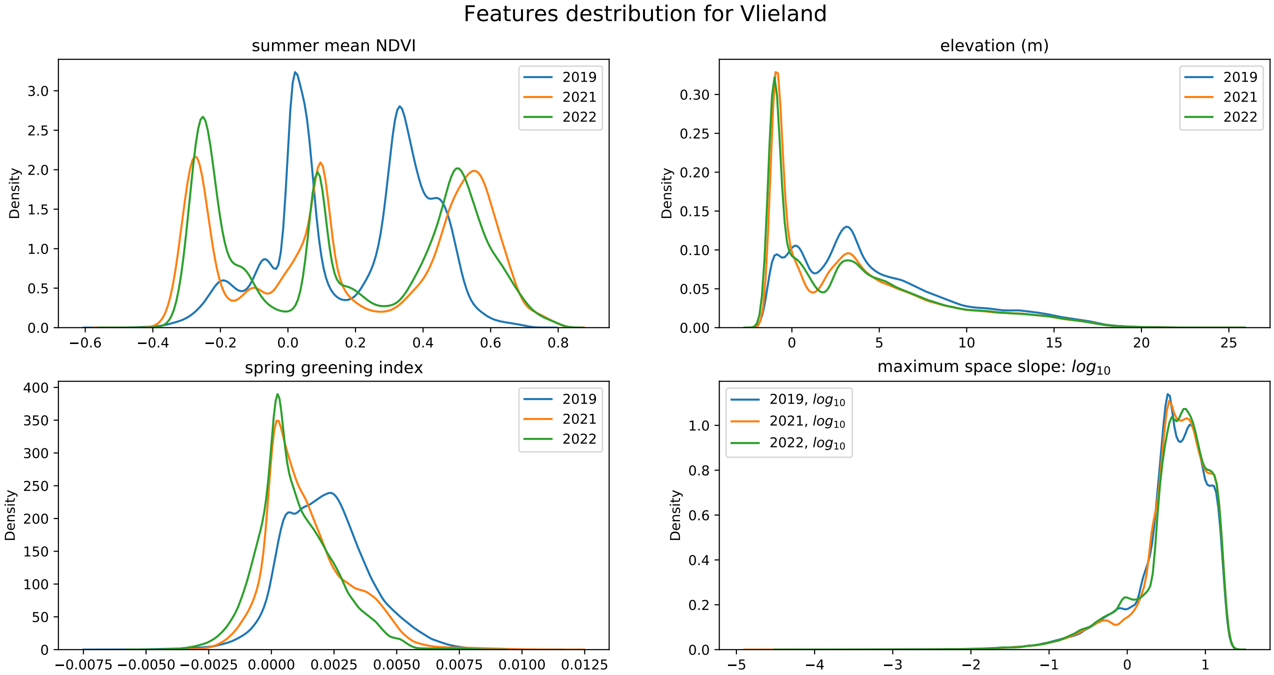


Figure D.12: Distribution of raw parameters per year on Vlieland within the settled polygons

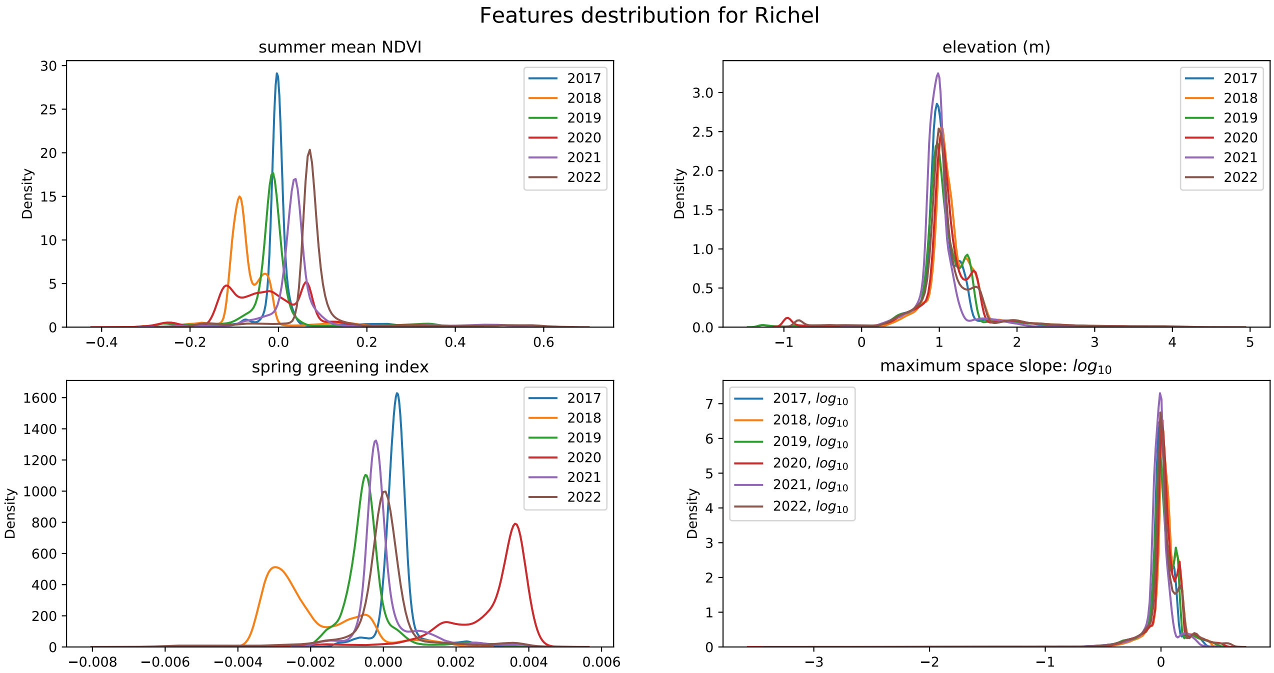


Figure D.13: Distribution of raw parameters per year on Richel within the settled polygons

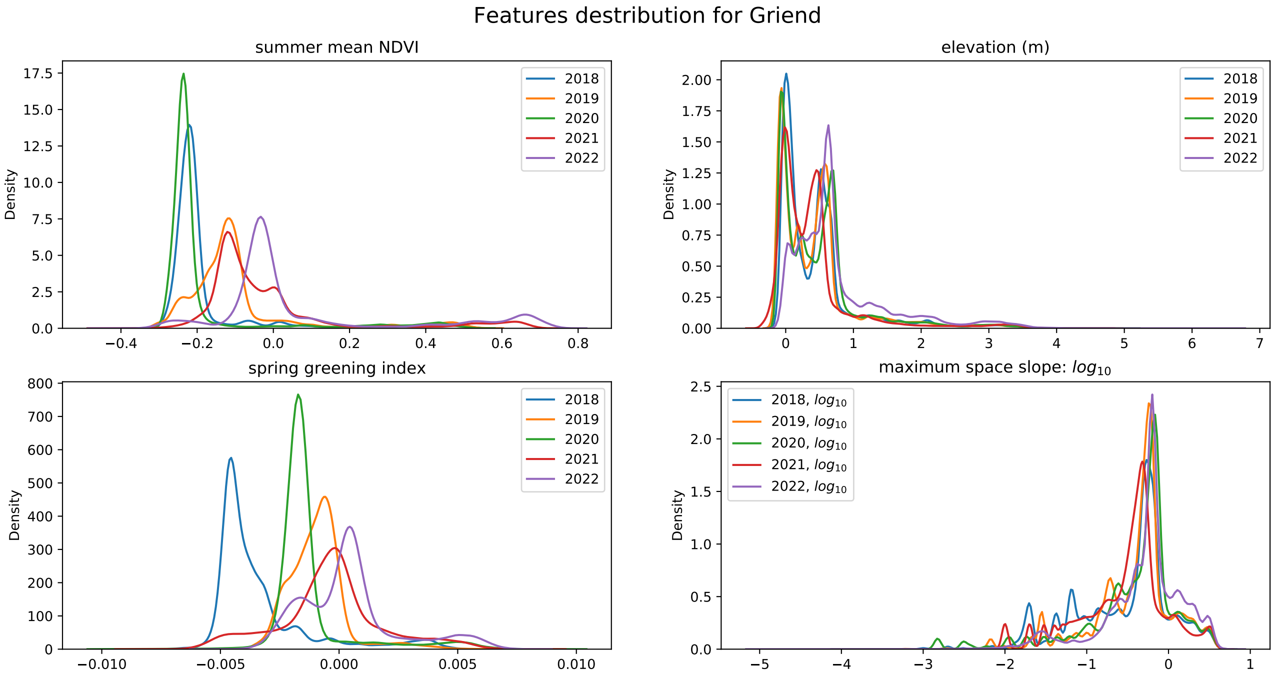


Figure D.14: Distribution of raw parameters per year on Griend within the settled polygons

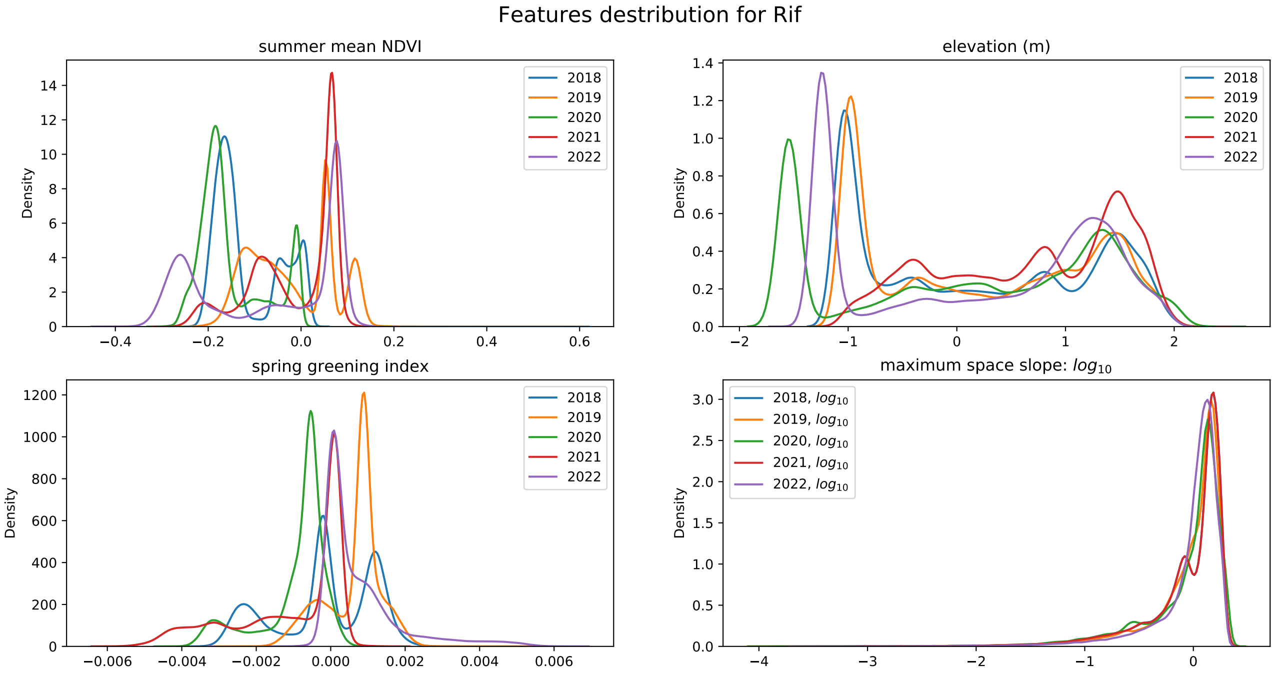


Figure D.15: Distribution of raw parameters per year on Rif within the settled polygons

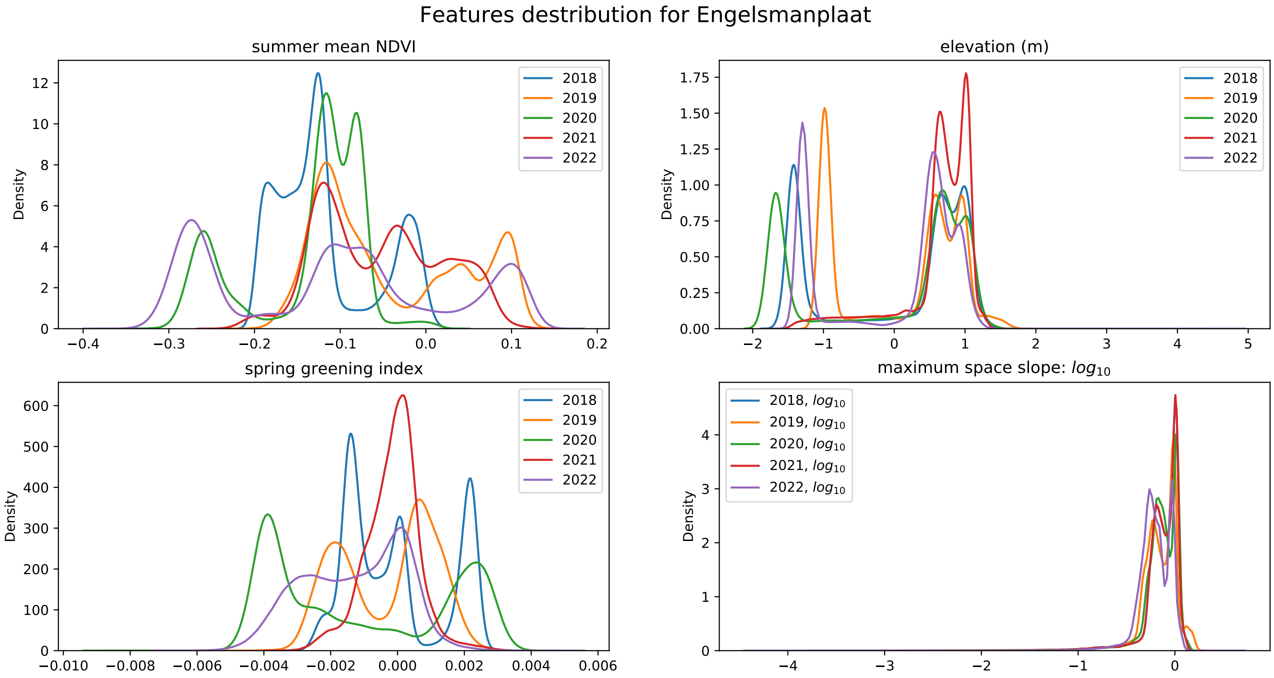


Figure D.16: Distribution of raw parameters per year on Engelsmanplaat within the settled polygons

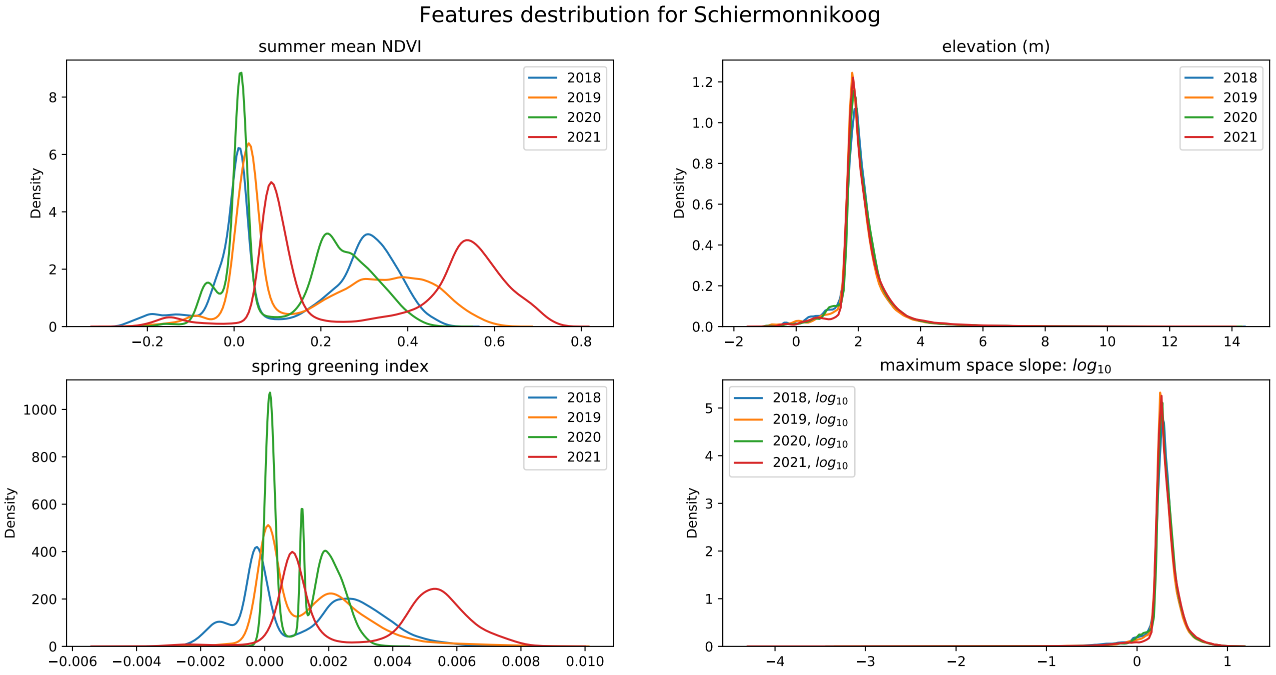


Figure D.17: Distribution of raw parameters per year on Schiermonnikoog within the settled polygons

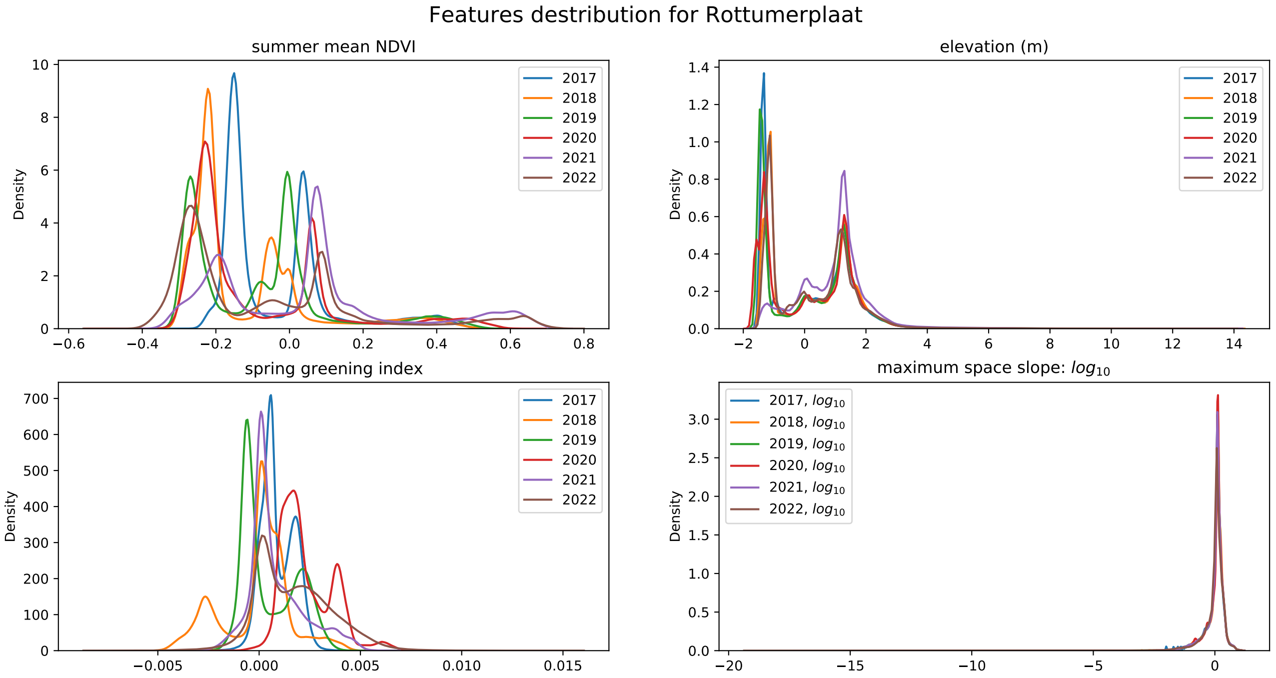


Figure D.18: Distribution of raw parameters per year on Rottumerplaat within the settled polygons

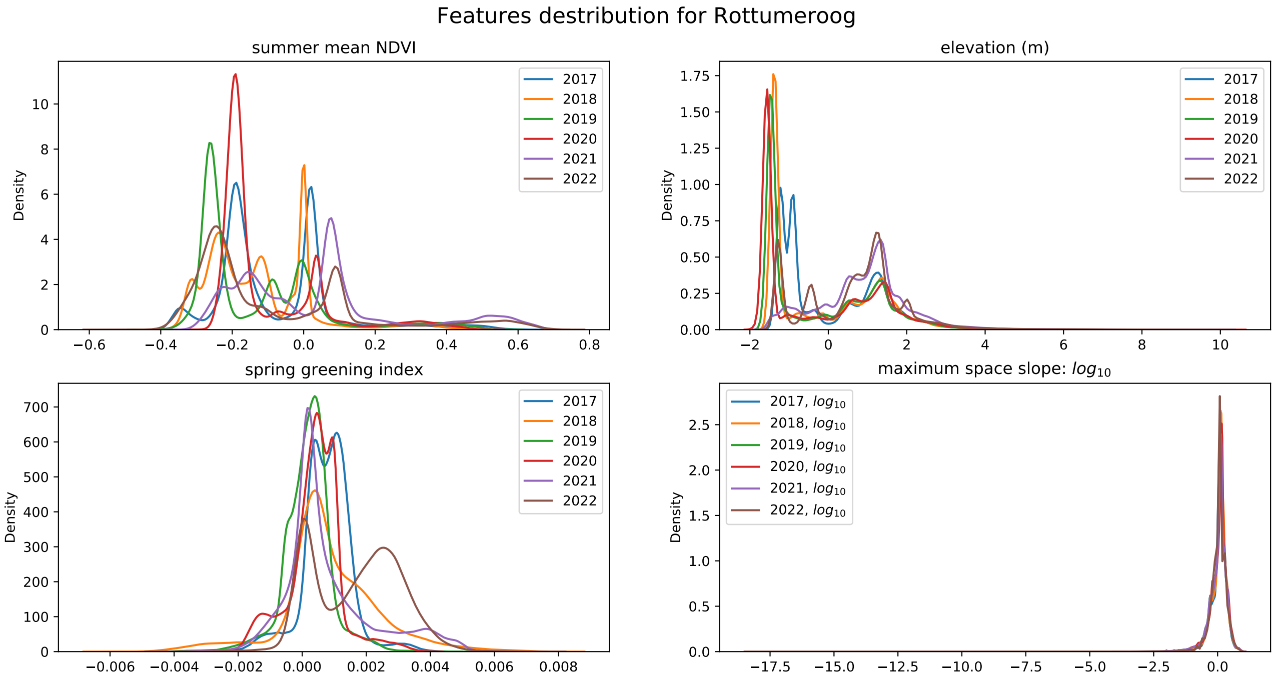


Figure D.19: Distribution of raw parameters per year on Rottumeroog within the settled polygons

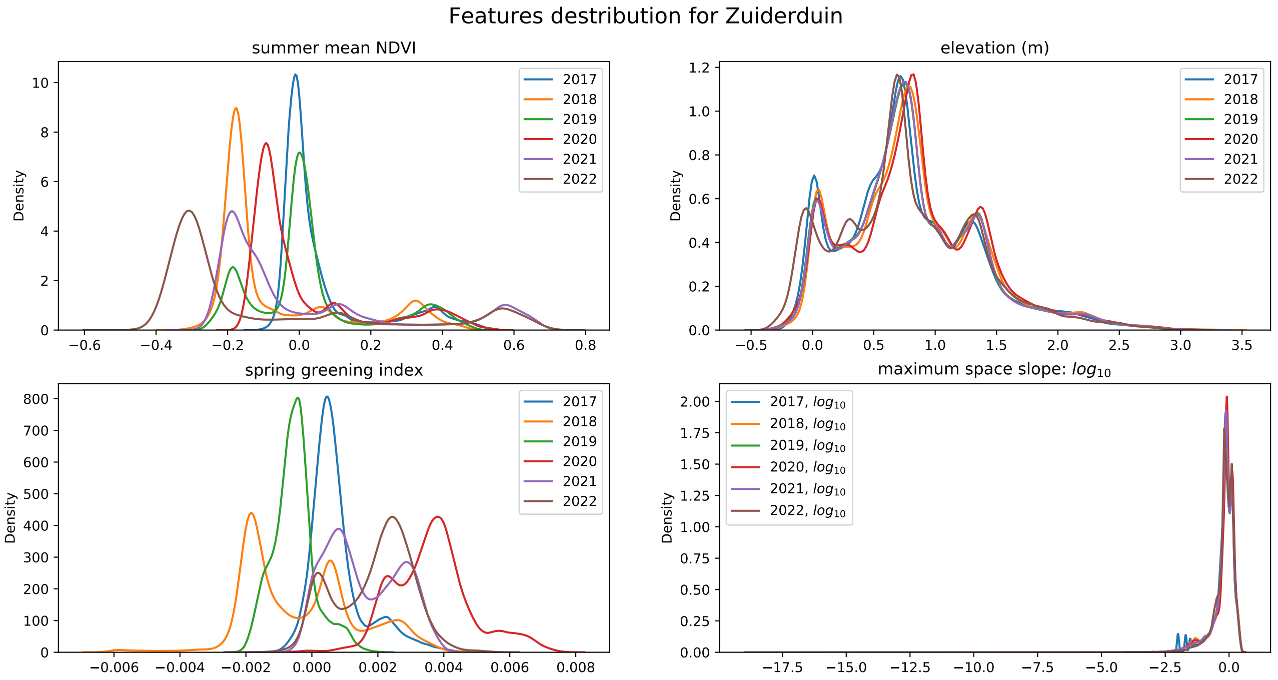
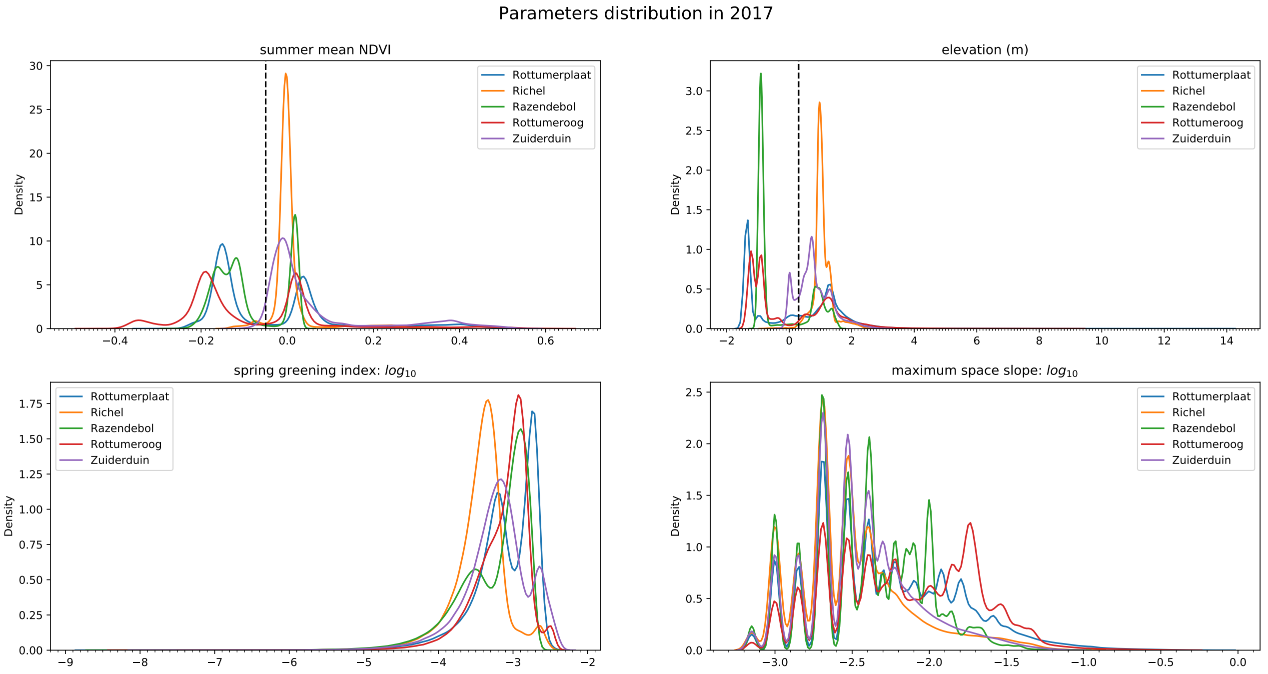


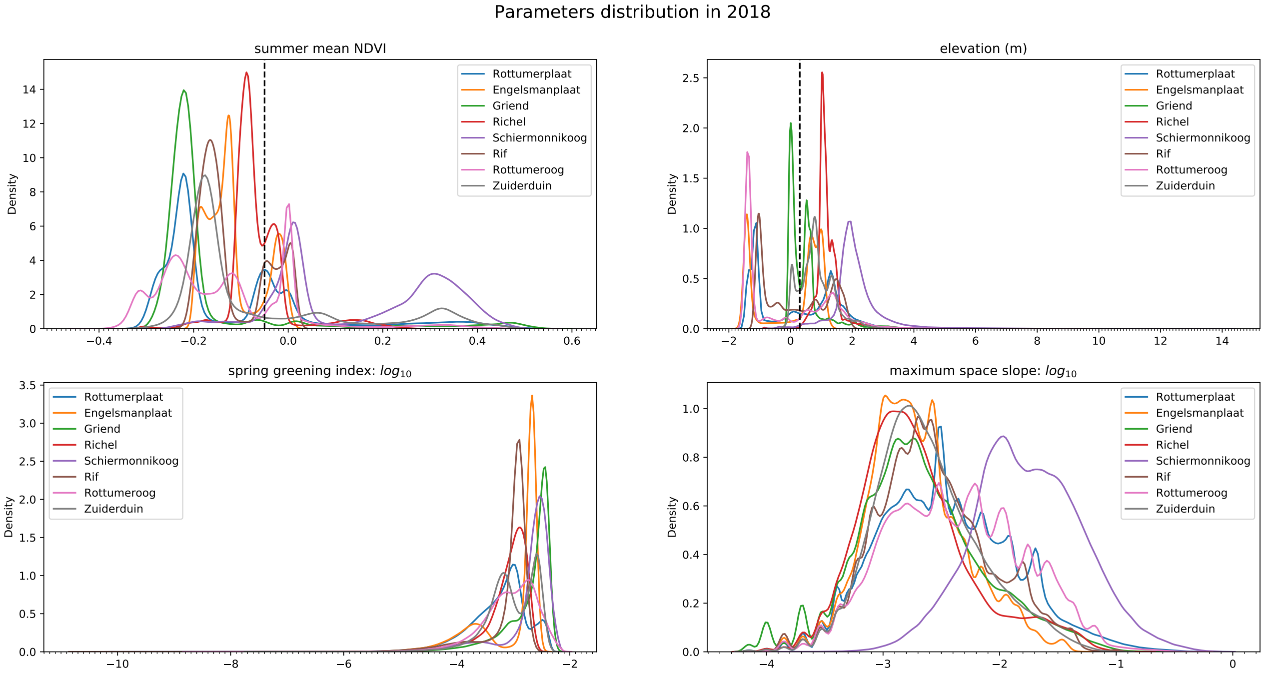
Figure D.20: Distribution of raw parameters per year on Zuiderduin within the settled polygons

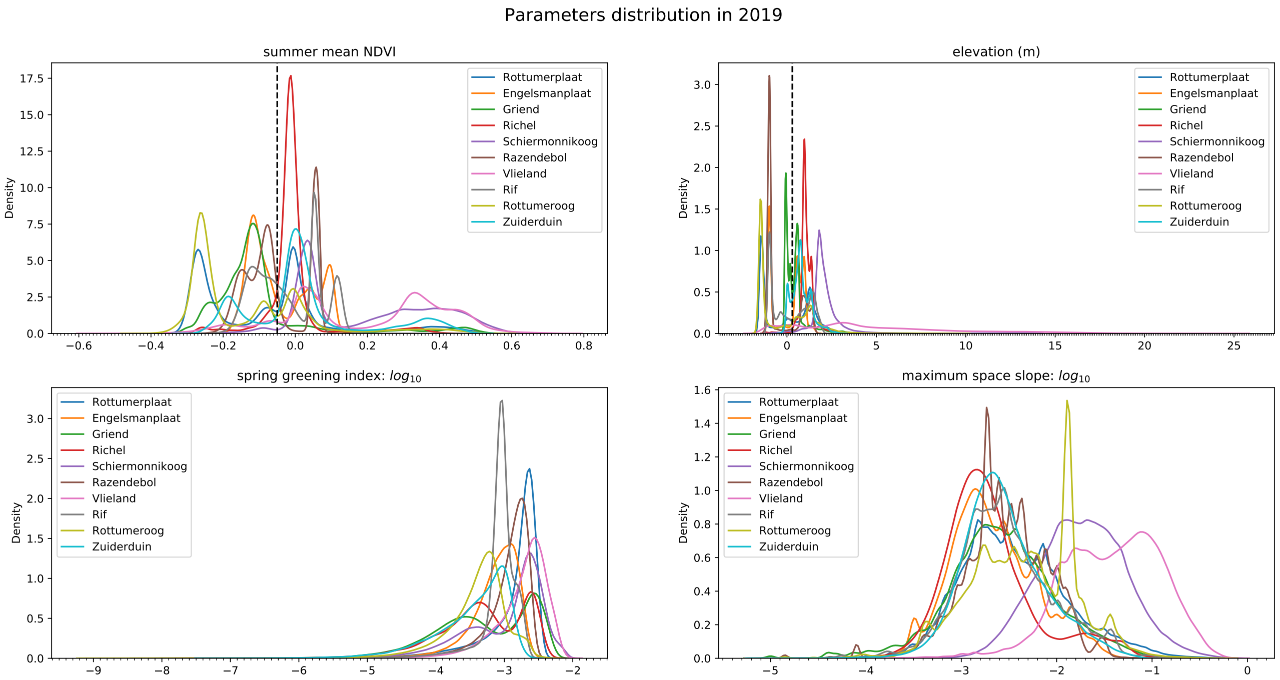
Appendix E

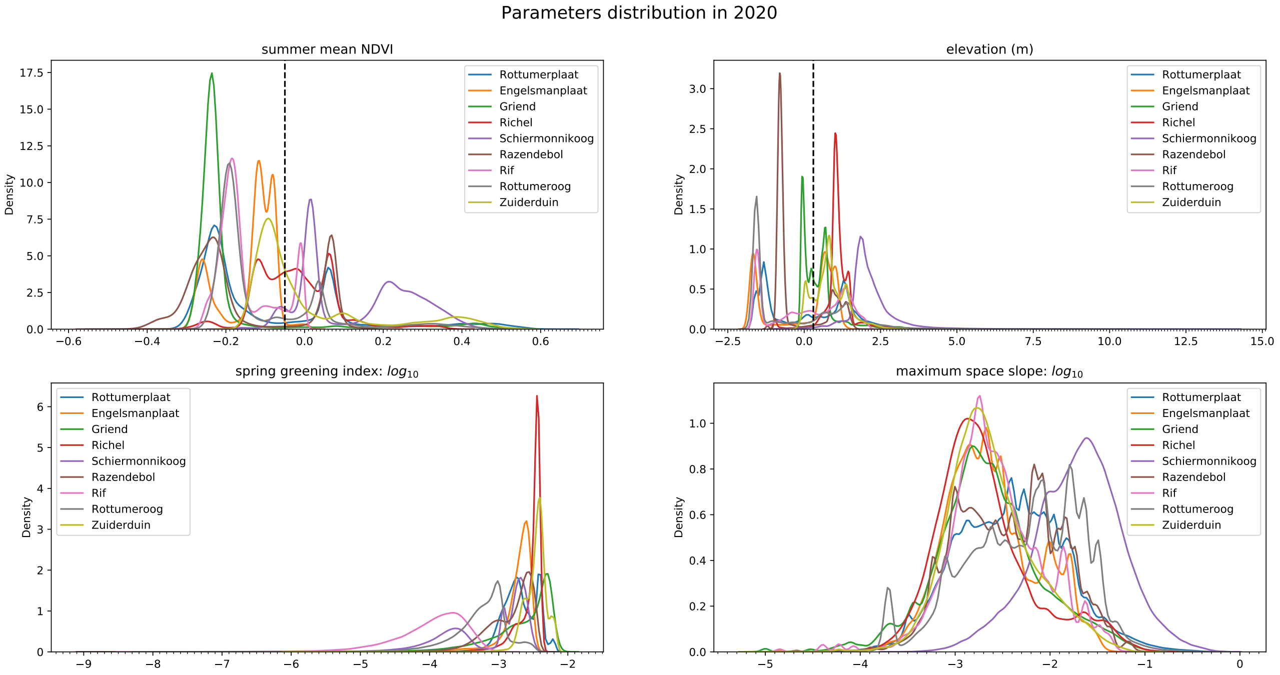
Clustering

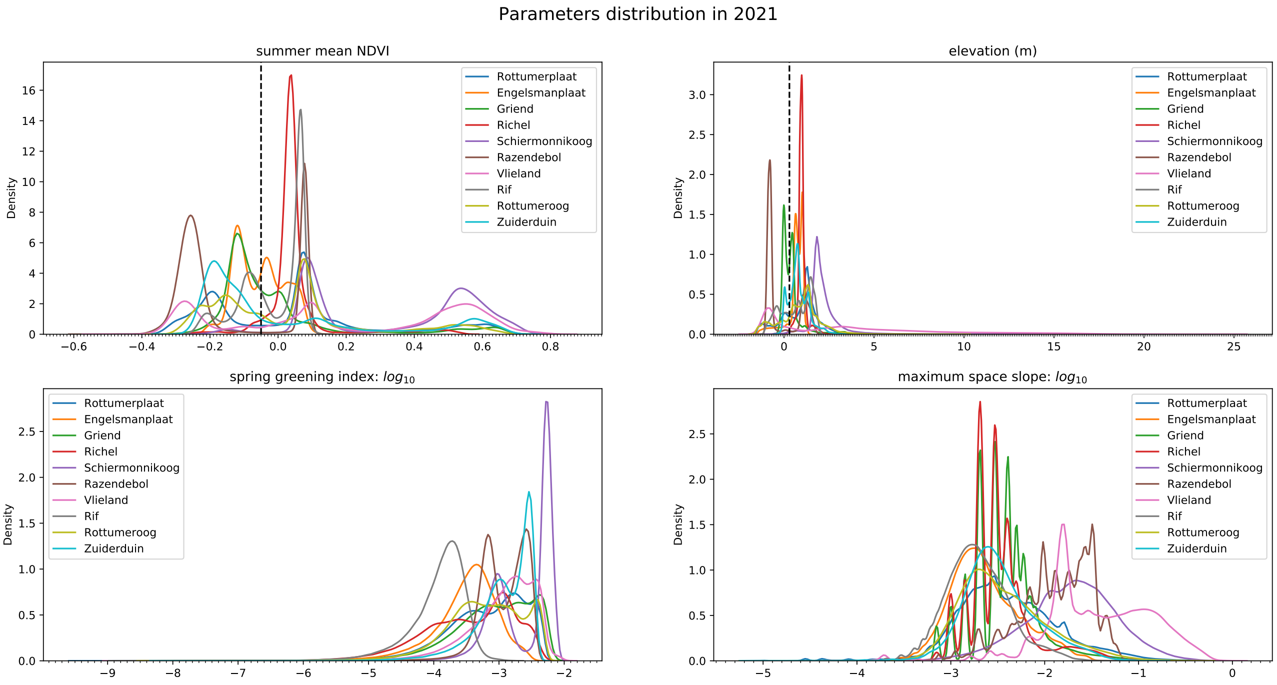
E.1 Clusters per year: unfiltered






Parameters distribution in 2019
summer mean NDVI
elevation (m)
spring greening index: log_{10}
maximum space slope: log_{10}
Density
Rottumerplaat
Engelsmanplaat
Griend
Richel
Schiermonnikoog
Razendebol
Vlieland
Rif
Rottumeroog
Zuiderduin
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
25
−9
−8
−7
−6
−5
−4
−3
−2
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
−5
−4
−3
−2
−1
0


Parameters distribution in 2020
summer mean NDVI
elevation (m)
spring greening index: log_{10}
maximum space slope: log_{10}
Density
Rottumerplaat
Engelsmanplaat
Griend
Richel
Schiermonnikoog
Razendebol
Rif
Rottumeroog
Zuiderduin
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.5
1.0
1.5
2.0
2.5
3.0
−2.5
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
1
2
3
4
5
6
−9
−8
−7
−6
−5
−4
−3
−2
0.2
0.4
0.6
0.8
1.0
−5
−4
−3
−2
−1
0



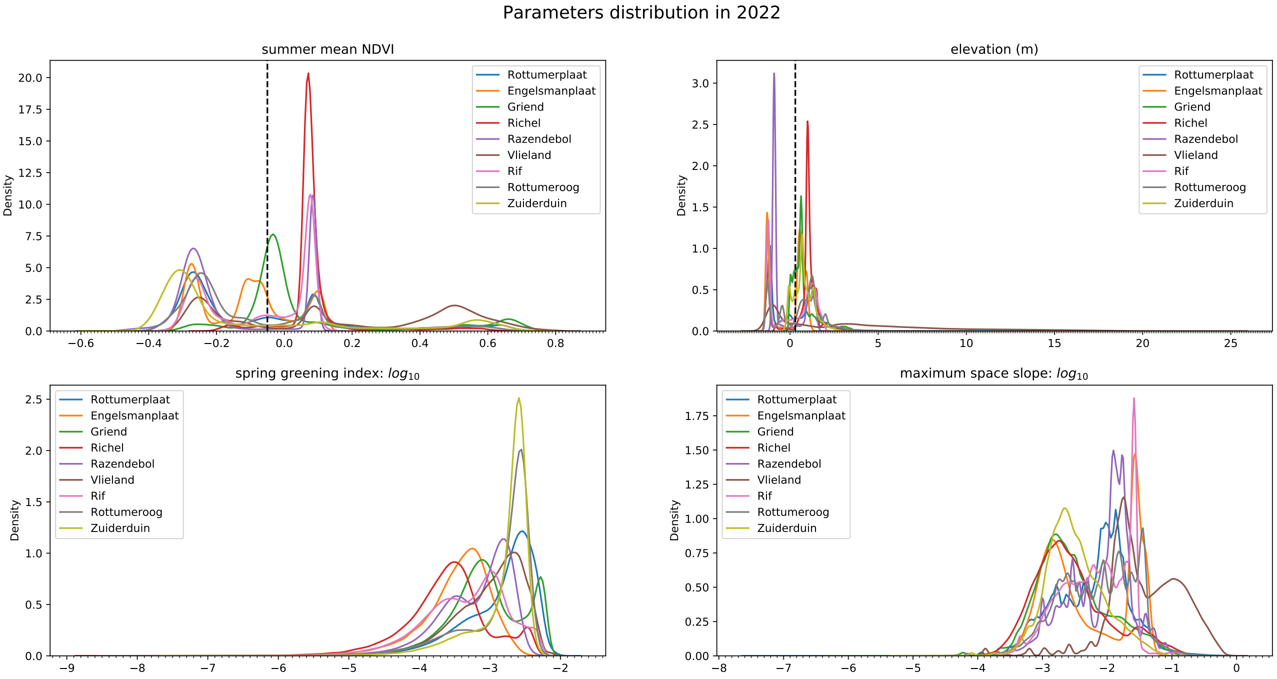
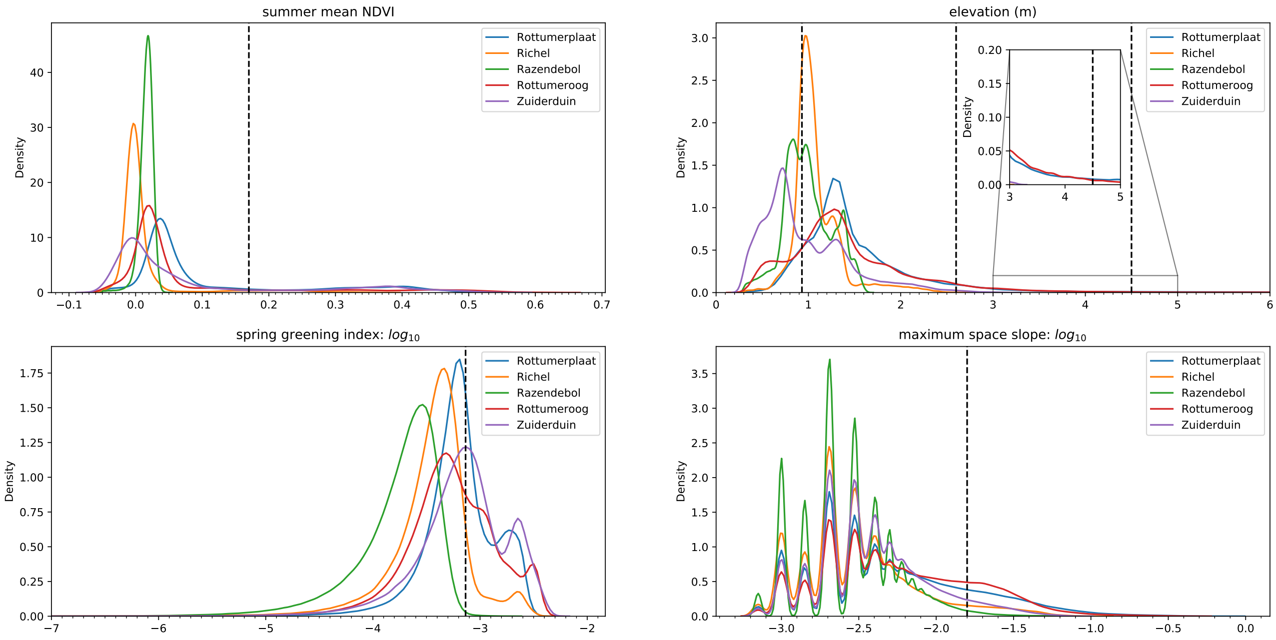
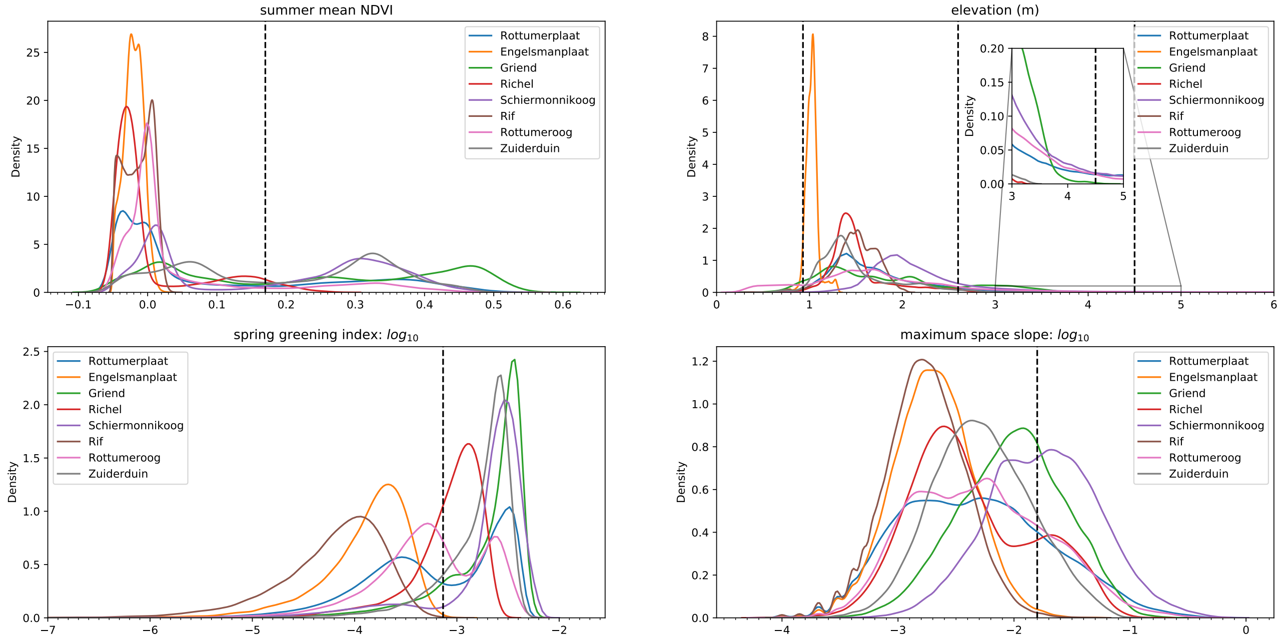


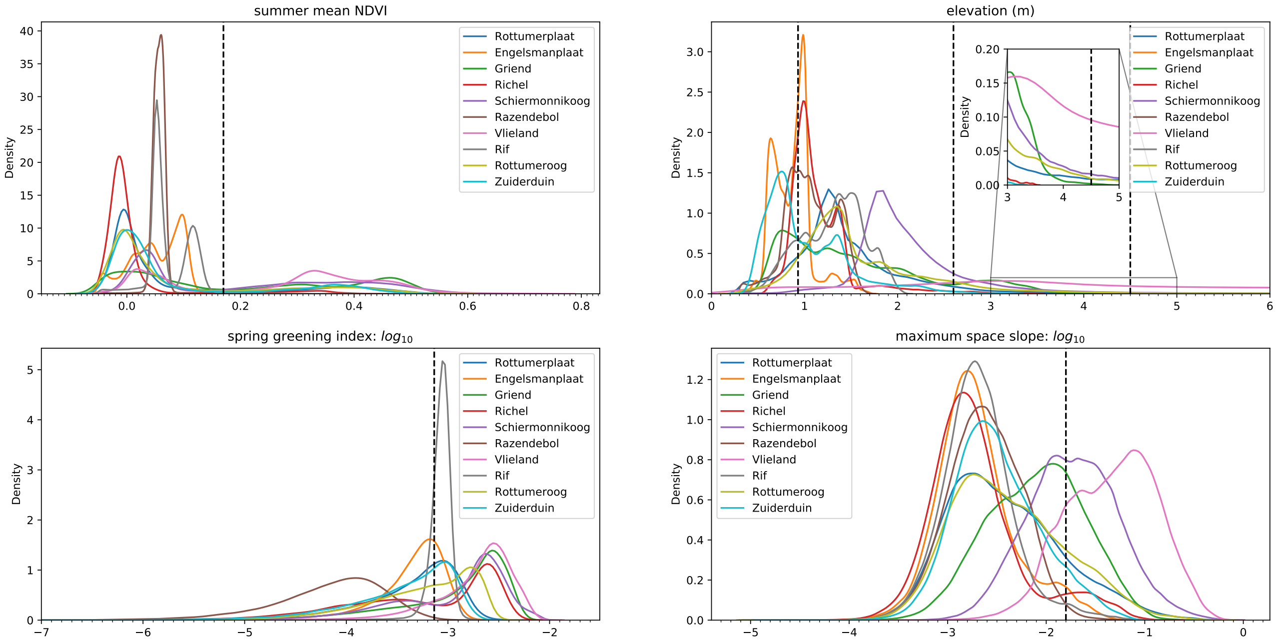
Figure E.1: Raw data within the settled polygons. The black dotted line represents the filtering threshold for the summer NDVI mean (-0.05) and the DEM height (0.3 m)

E.2 Clusters per year: filtered

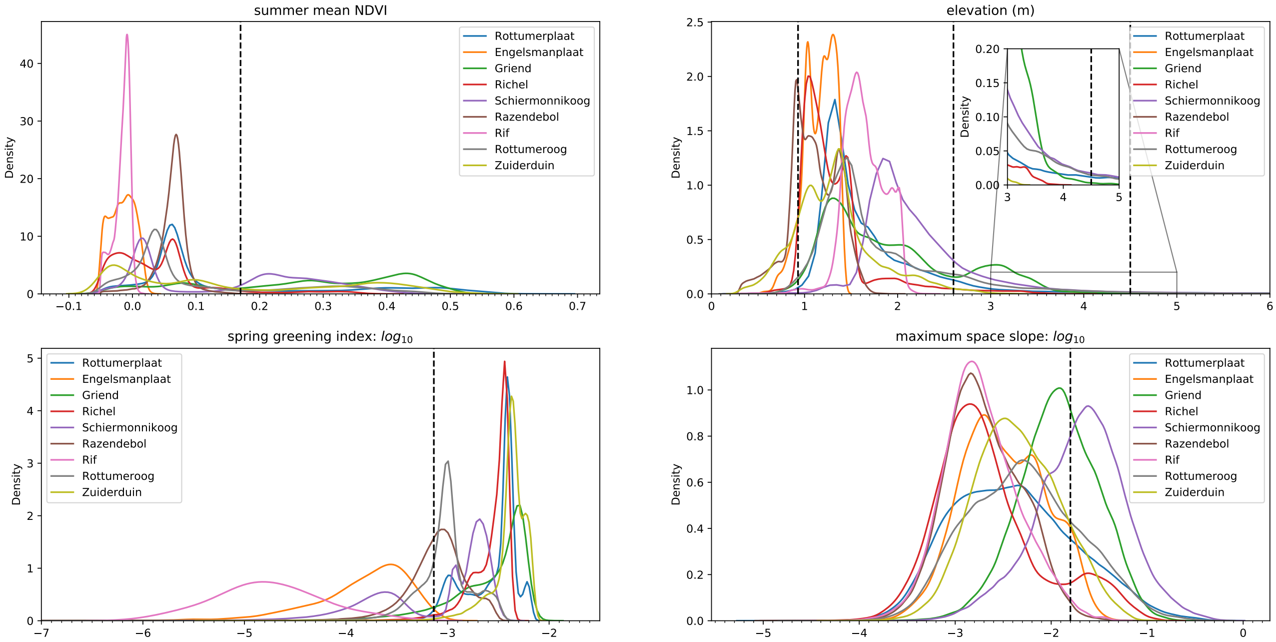

Parameters distribution with elevation > 0.3 m and mean NDVI > -0.05 in 2017


Parameters distribution with elevation > 0.3 m and mean NDVI > -0.05 in 2018

Parameters distribution with elevation > 0.3 m and mean NDVI > -0.05 in 2019



Parameters distribution with elevation > 0.3 m and mean NDVI > -0.05 in 2020



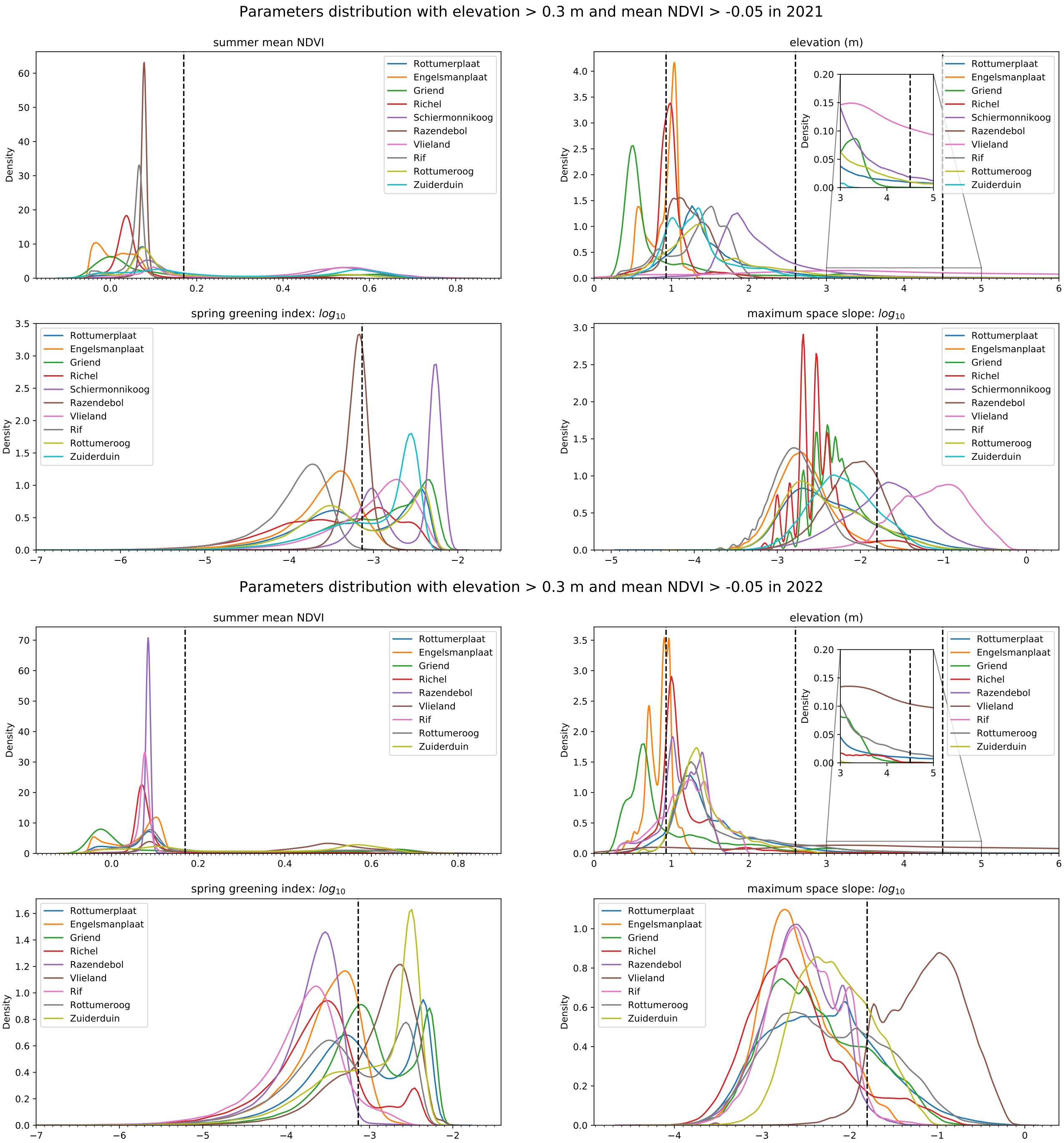
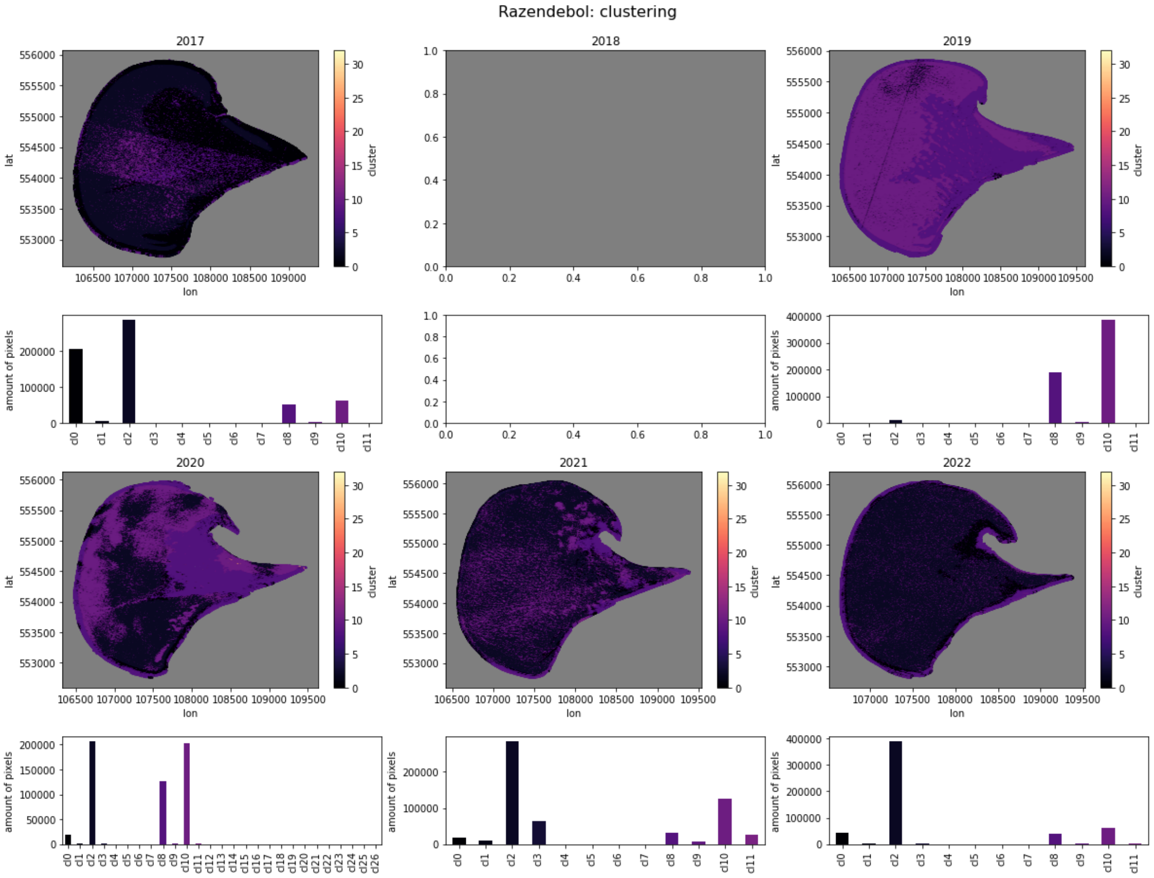
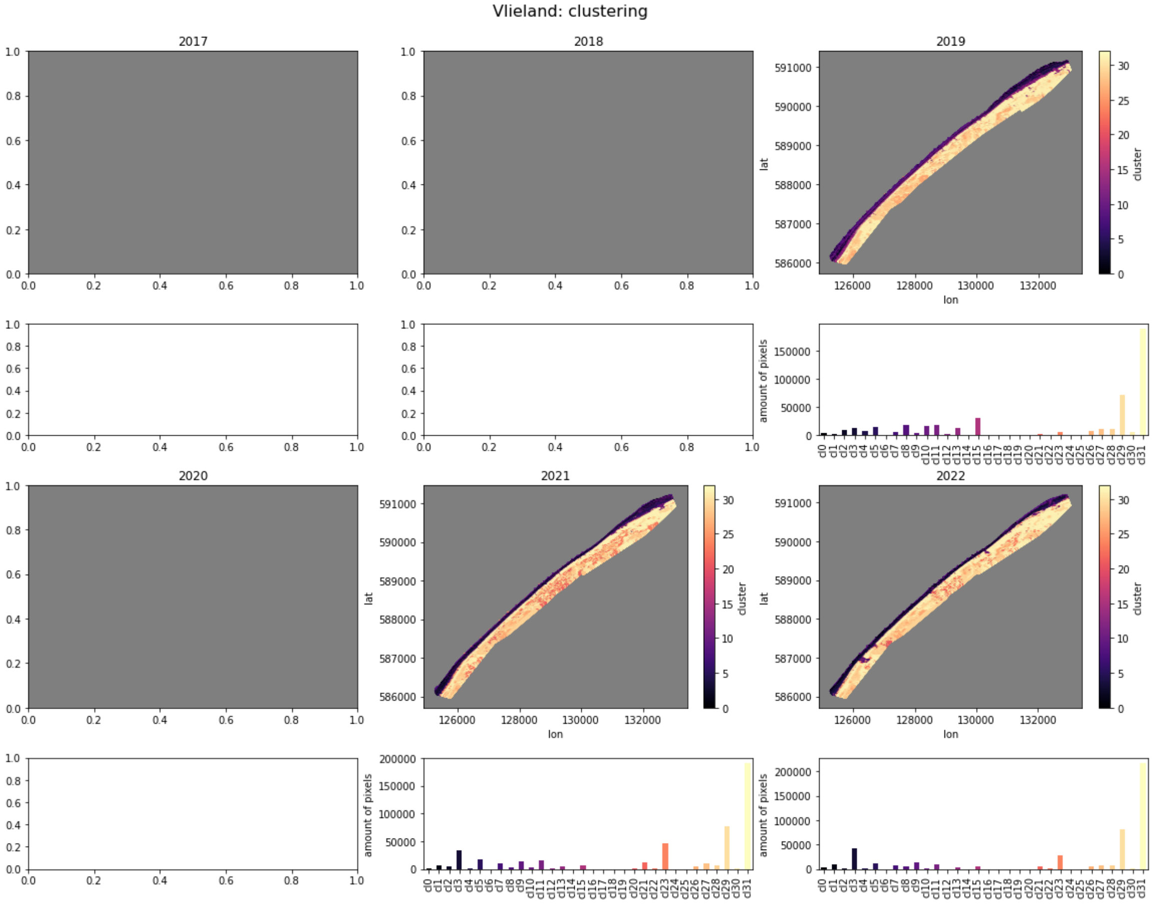
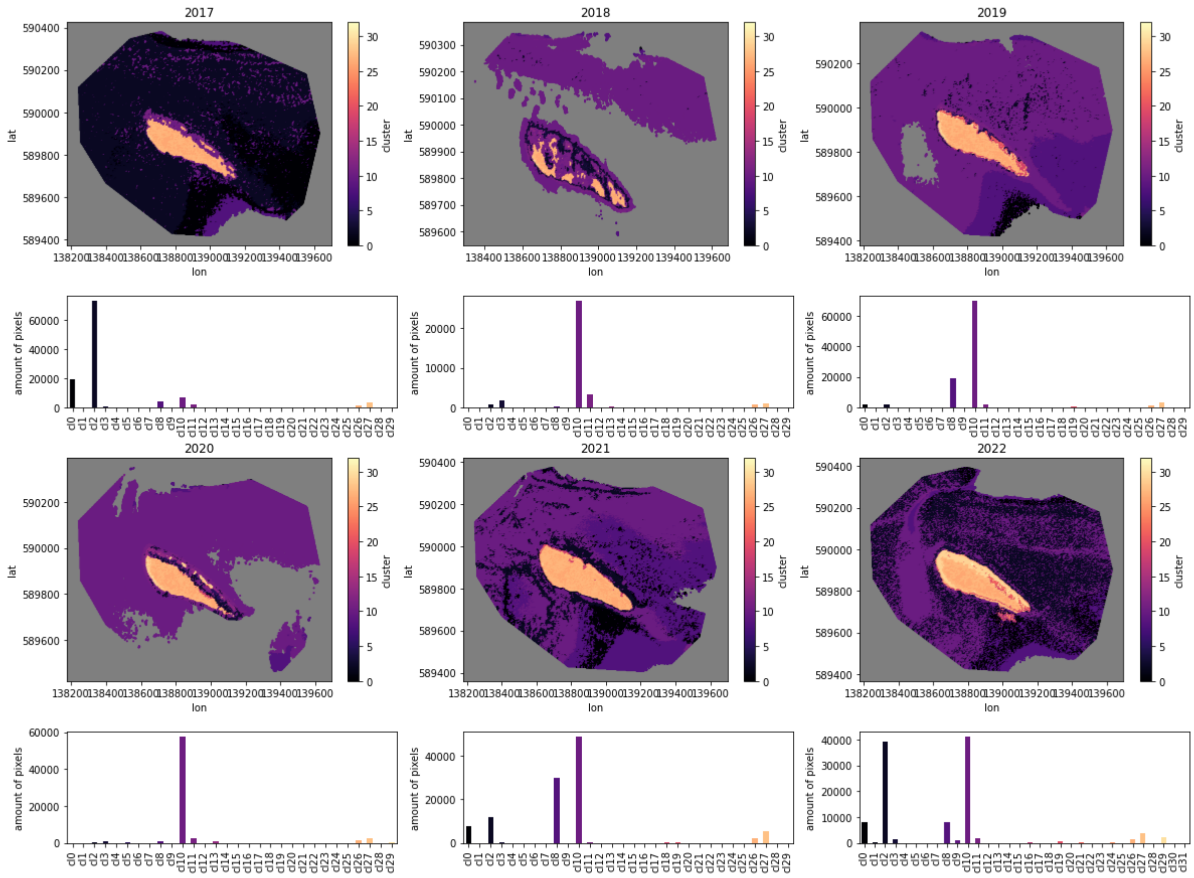


Figure E.2: Filtered raw data within the settled polygons. The black dotted line represents the breaks for clustering

E.3 Clusters per island







Richel: clustering

2017

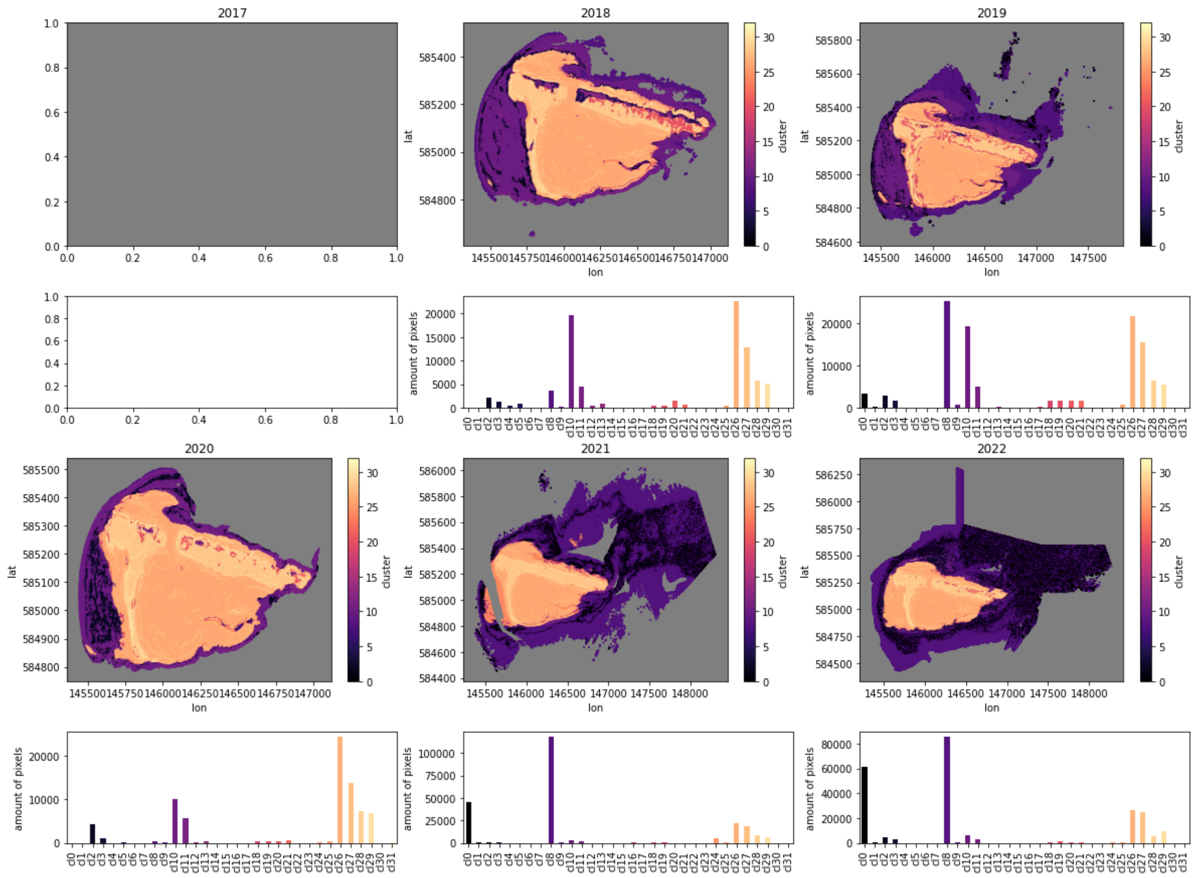
2018

2019

2020

2021

2022



Griend: clustering

2017

2018

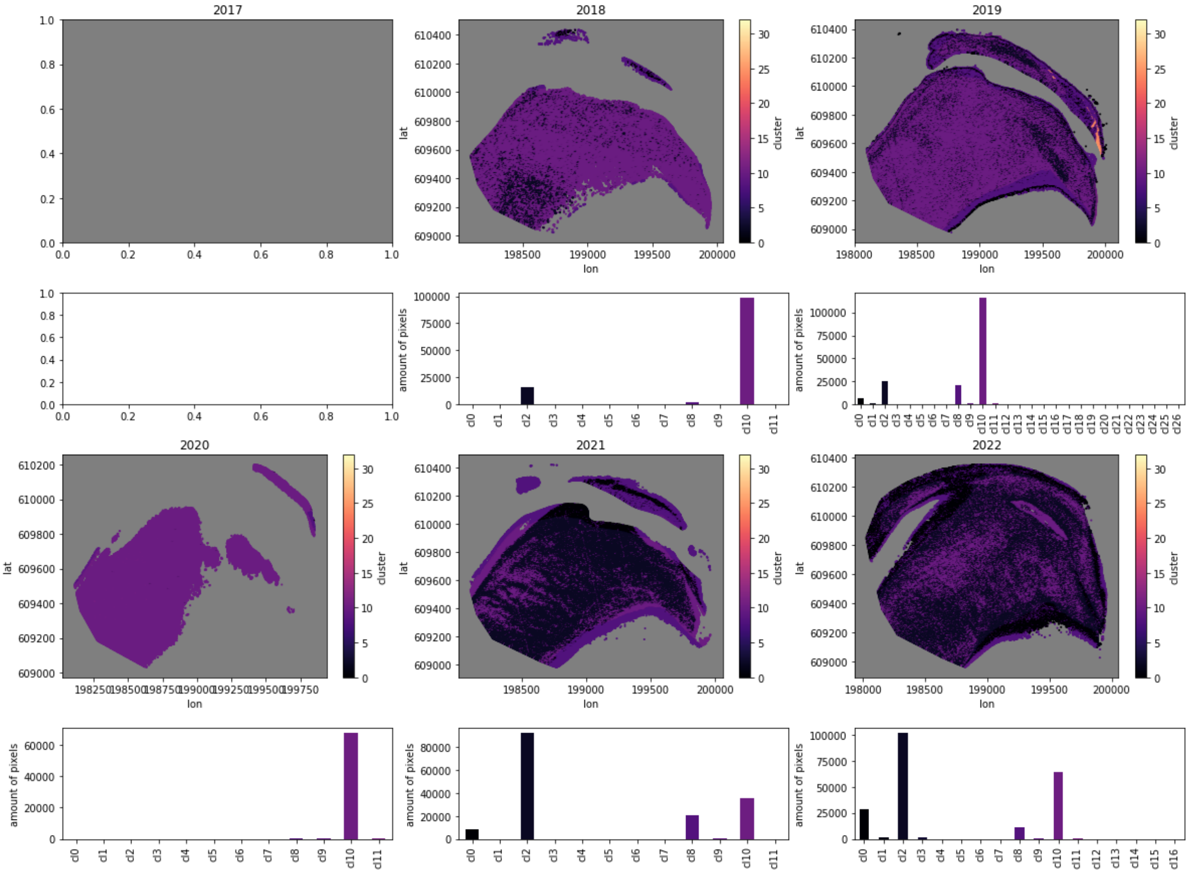
2019

2020

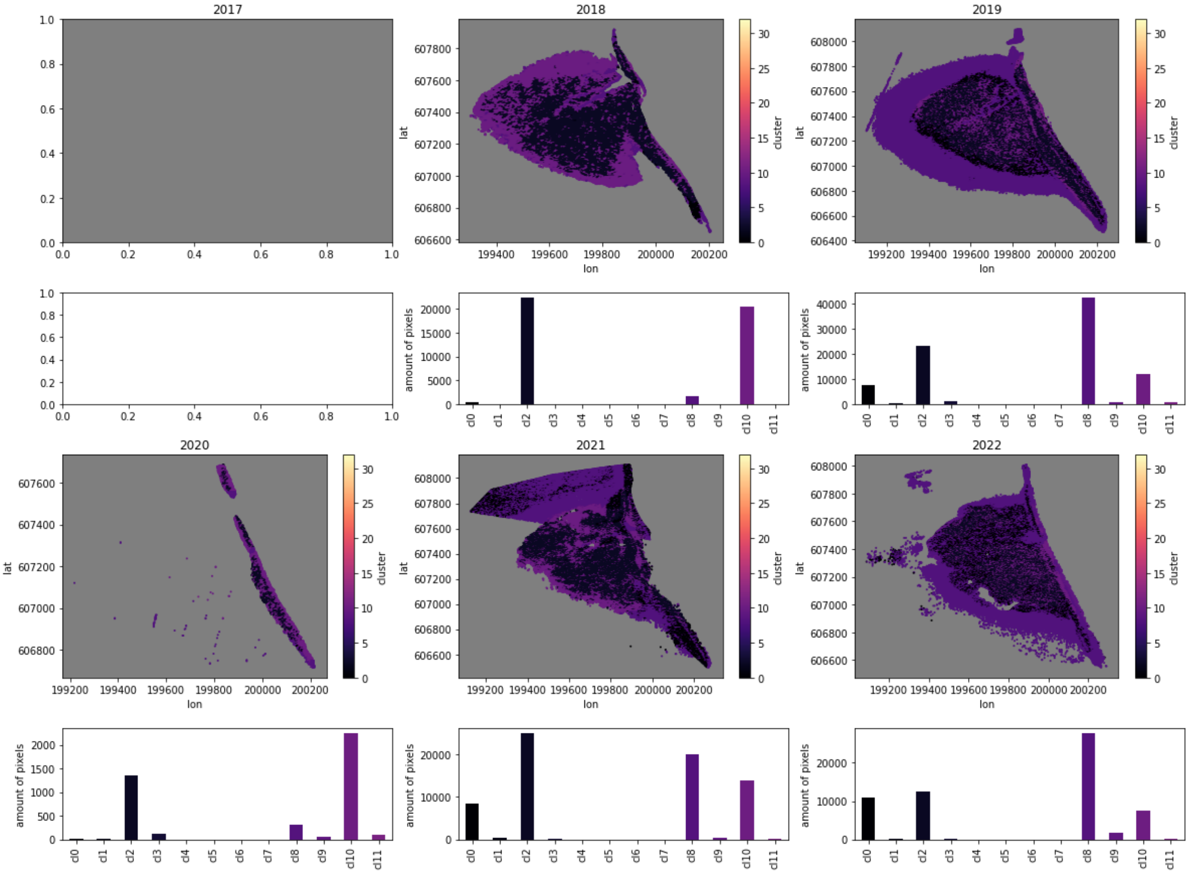
2021

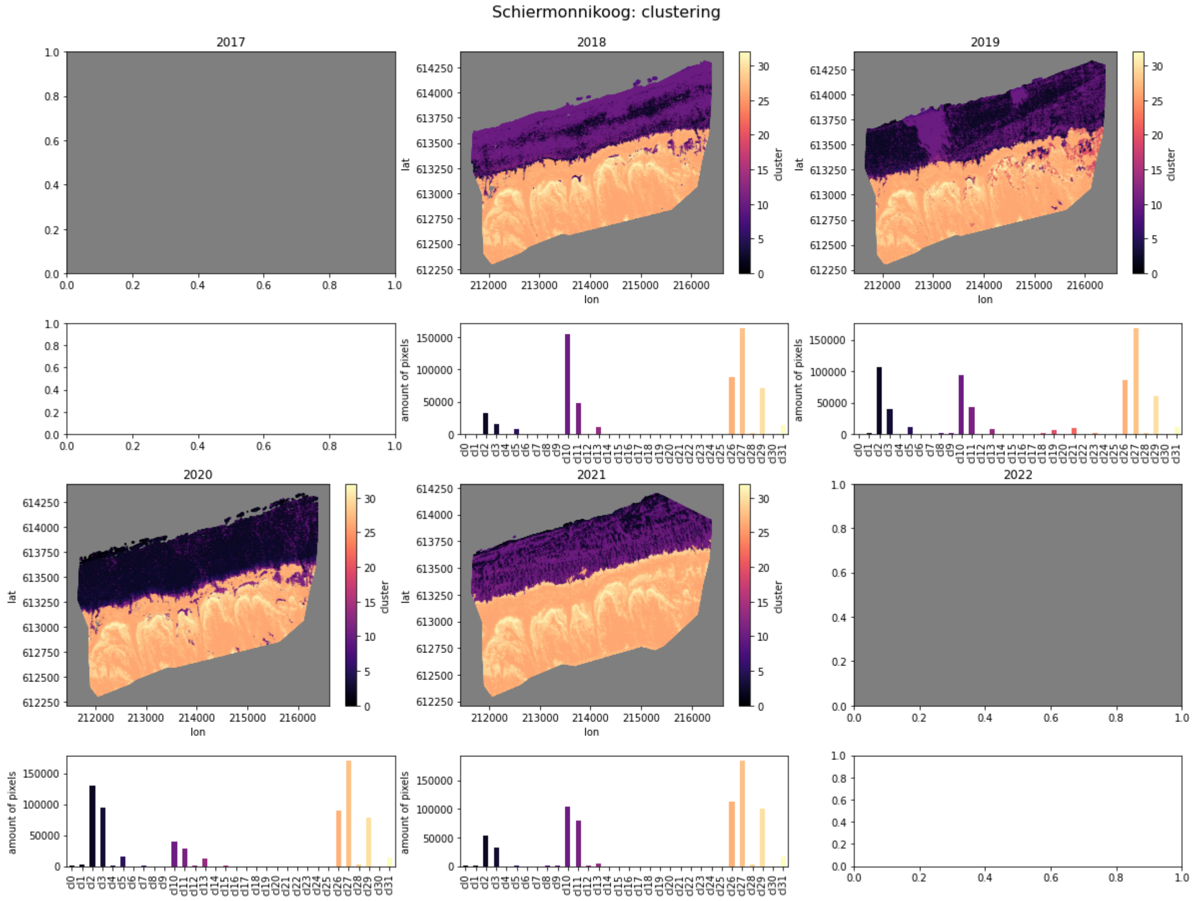
2022

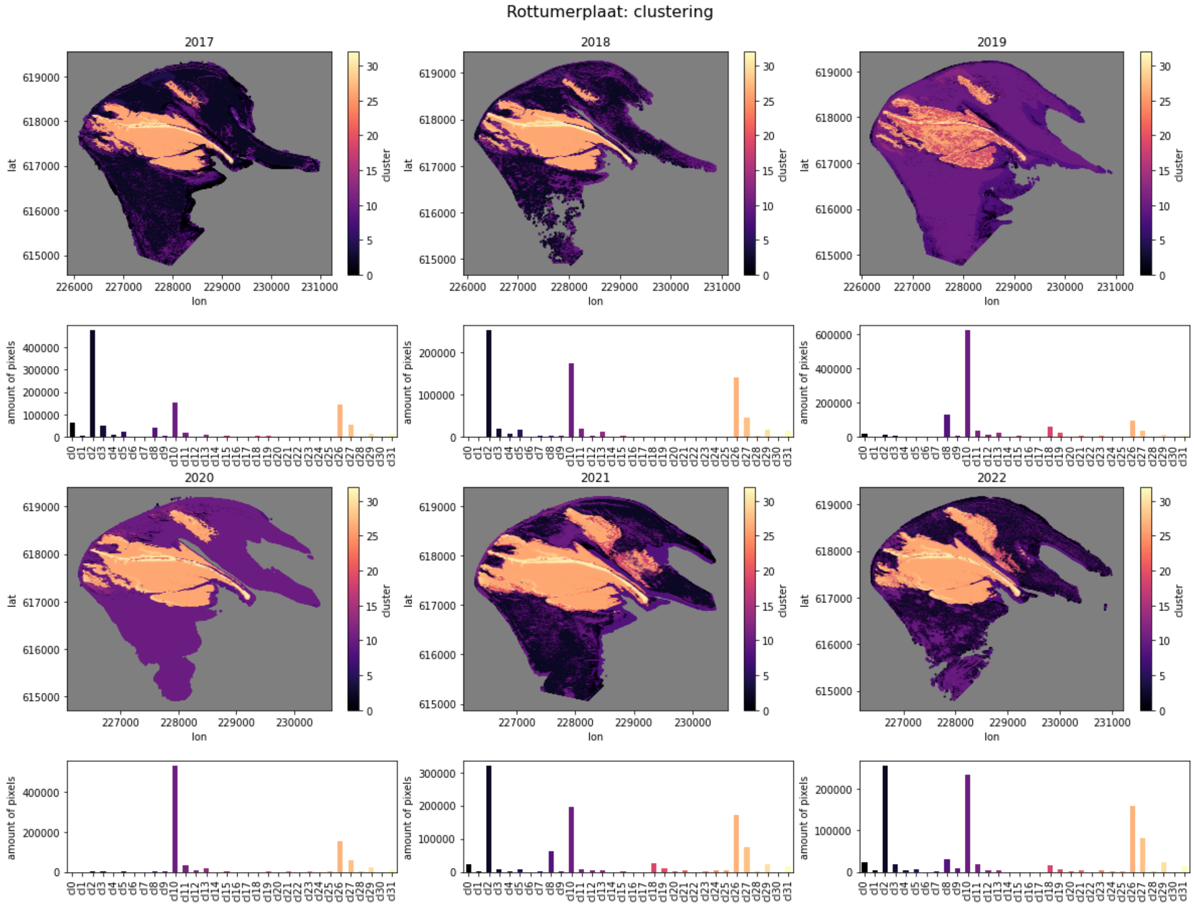
Rif: clustering

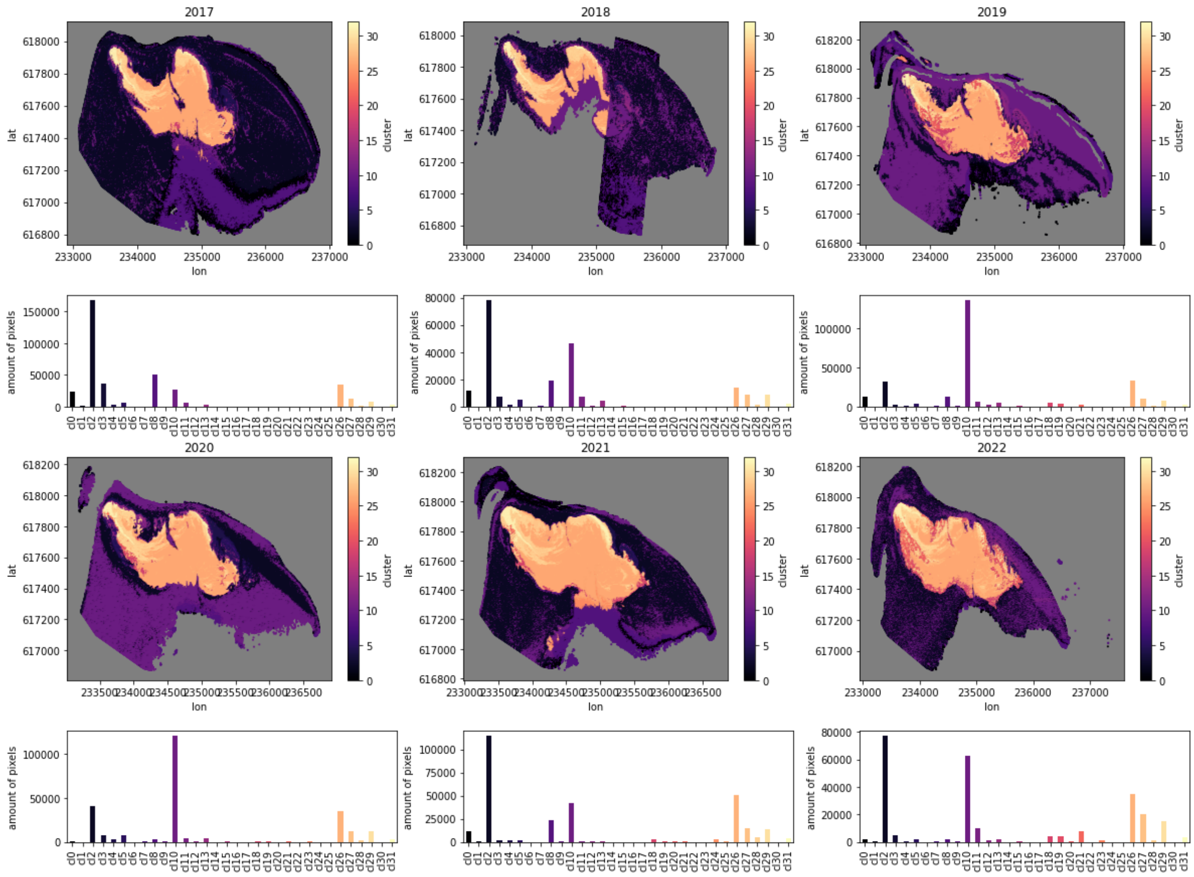


Engelsmanplaat: clustering

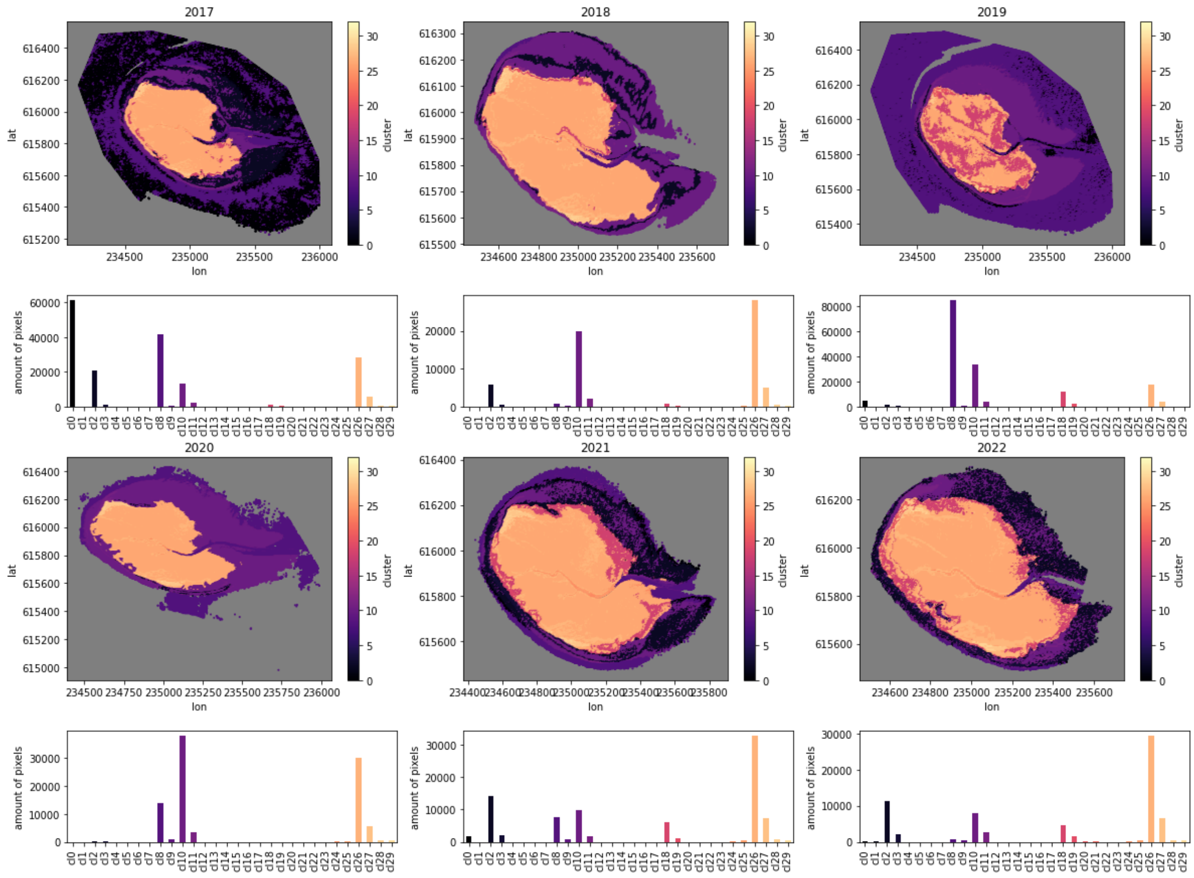



Schiermonnikoog: clustering


Rottumerplaat: clustering



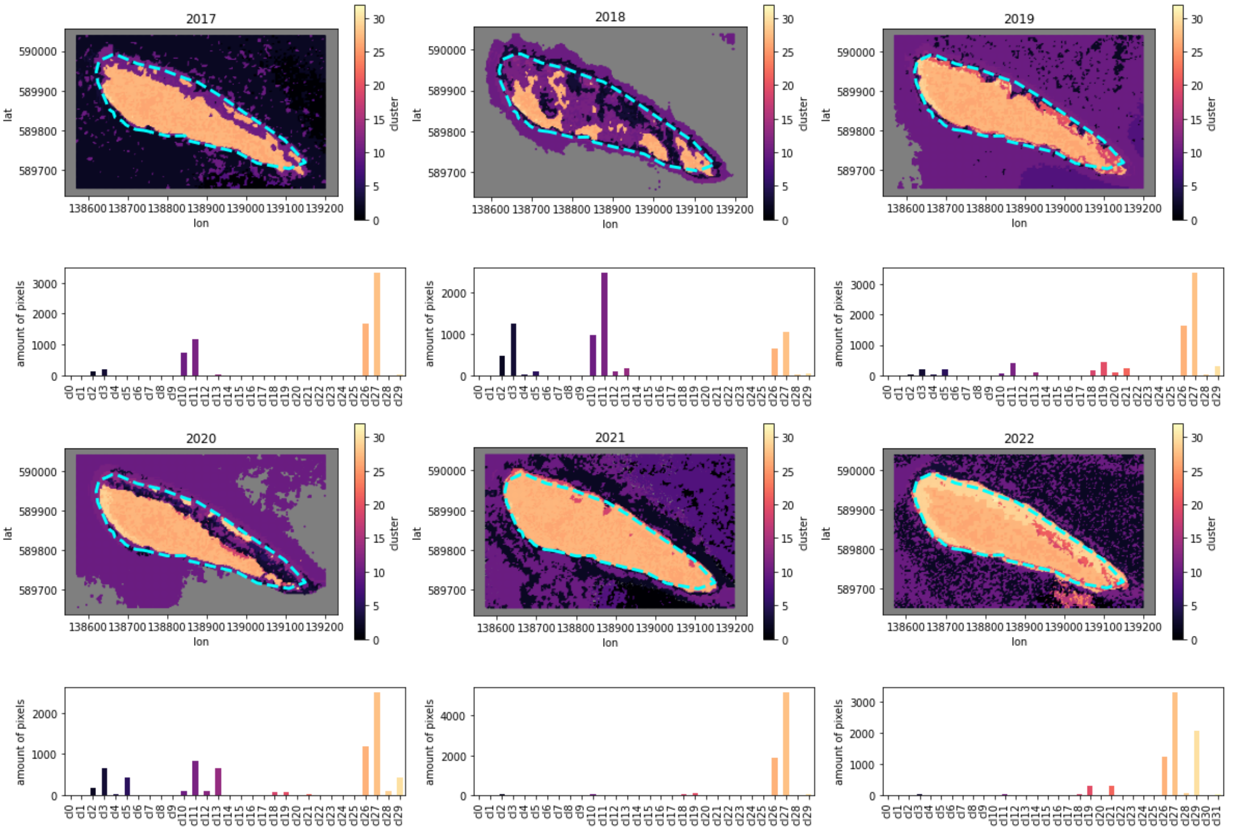
Rottumeroog: clustering



Zuiderduin: clustering

Figure E.3: Cluster distribution per island

E.4 Clusters per colony


Richel: a colony of *Larus argentatus* and *Larus fuscus*

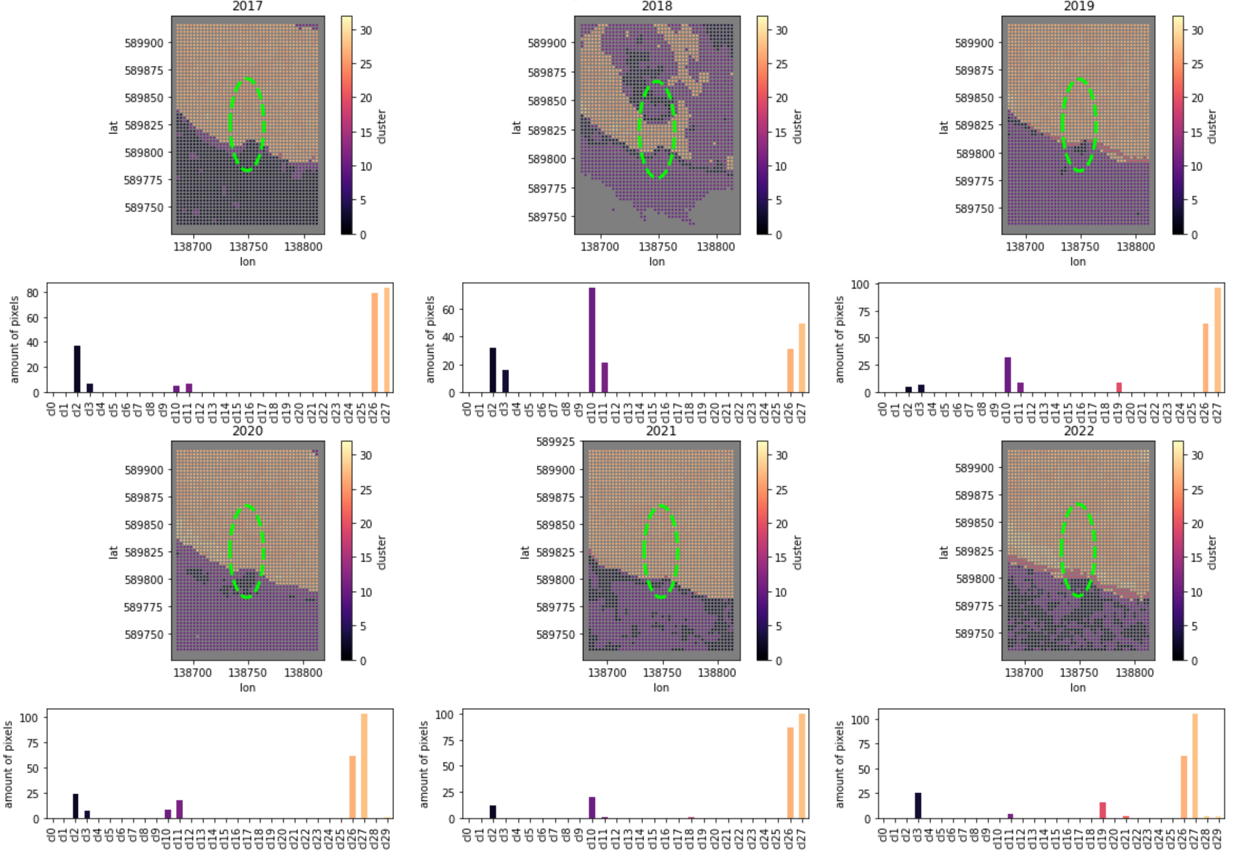
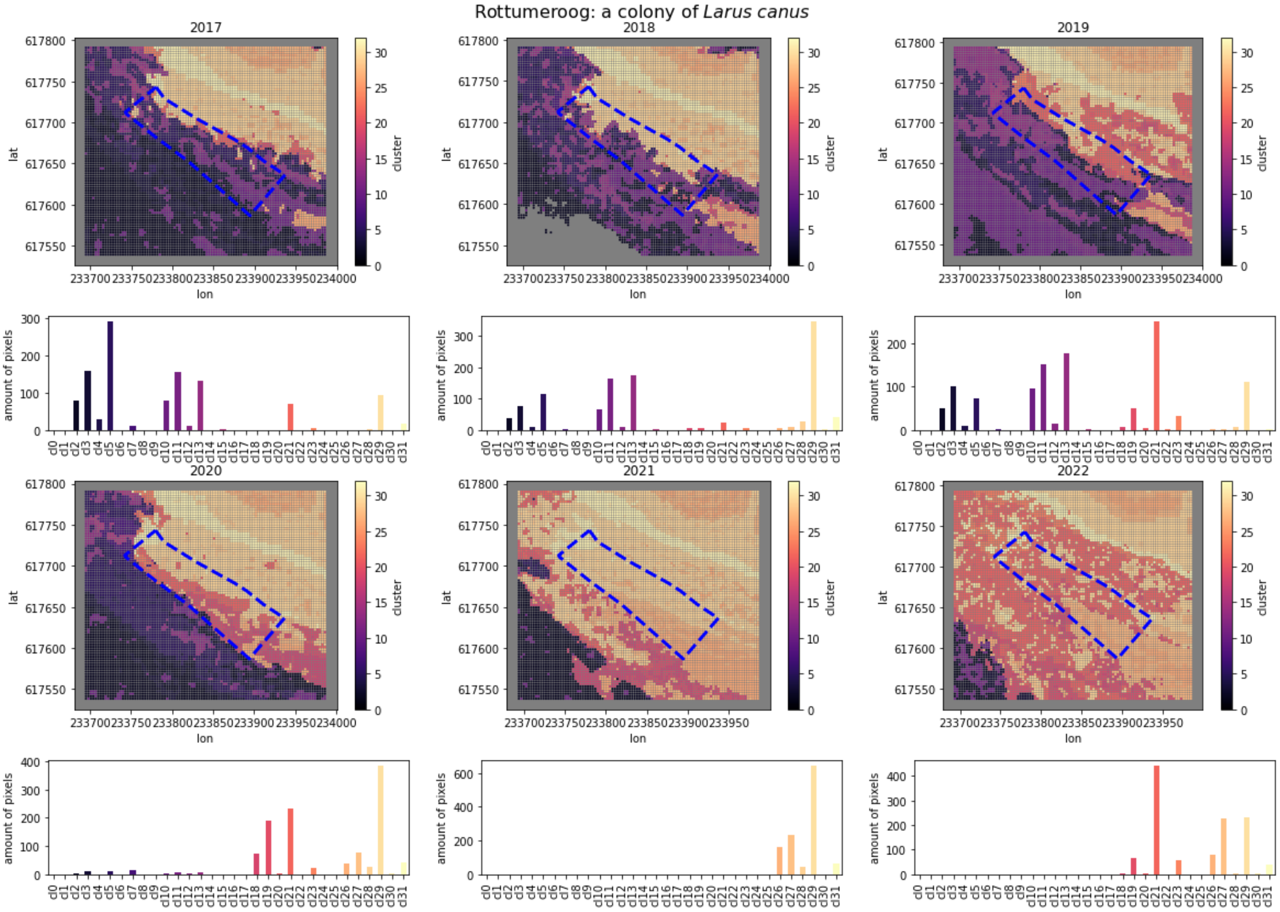
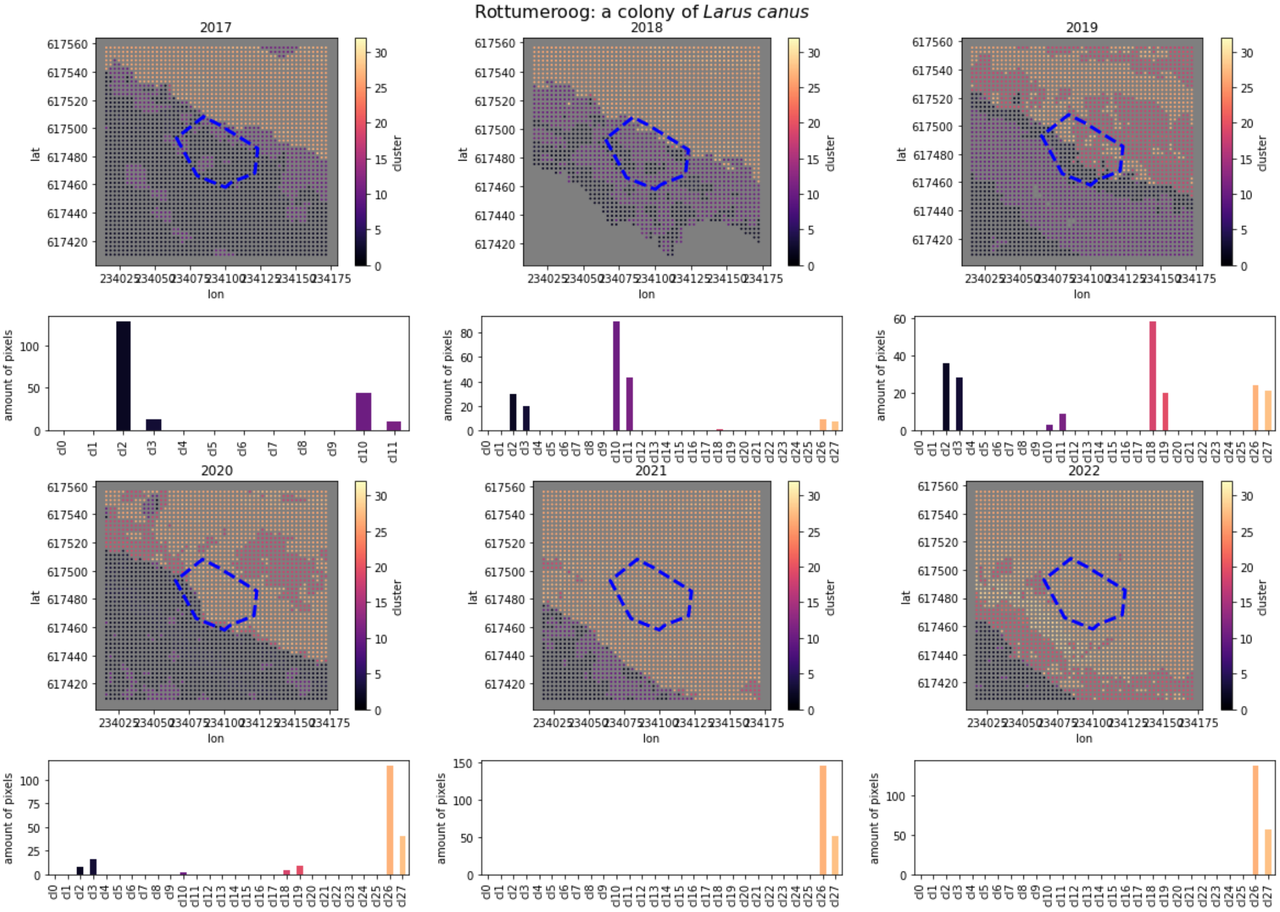

Richel: a colony of *Phalacrocorax carbo*

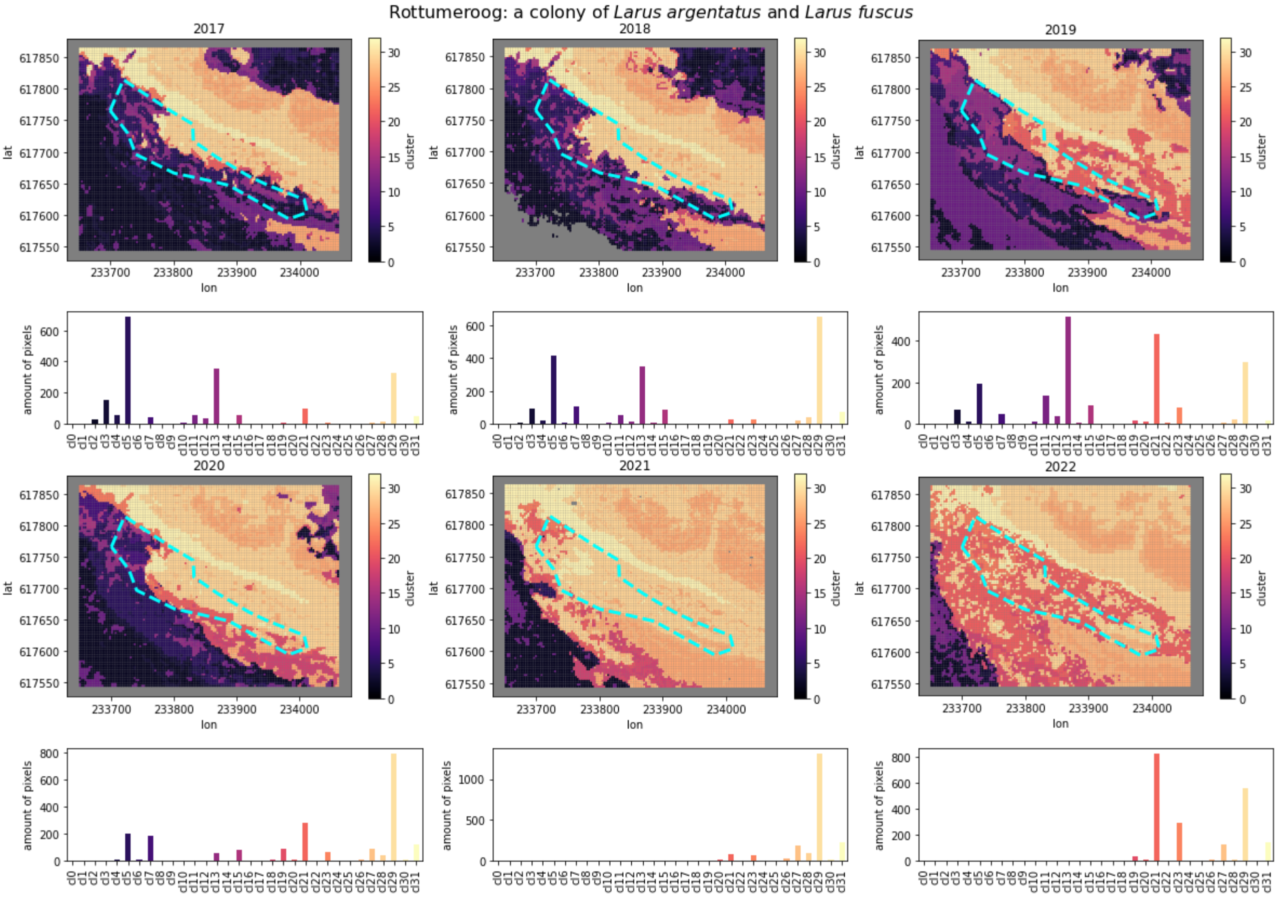
Figure E.4: Distribution of clusters per colony in Richel



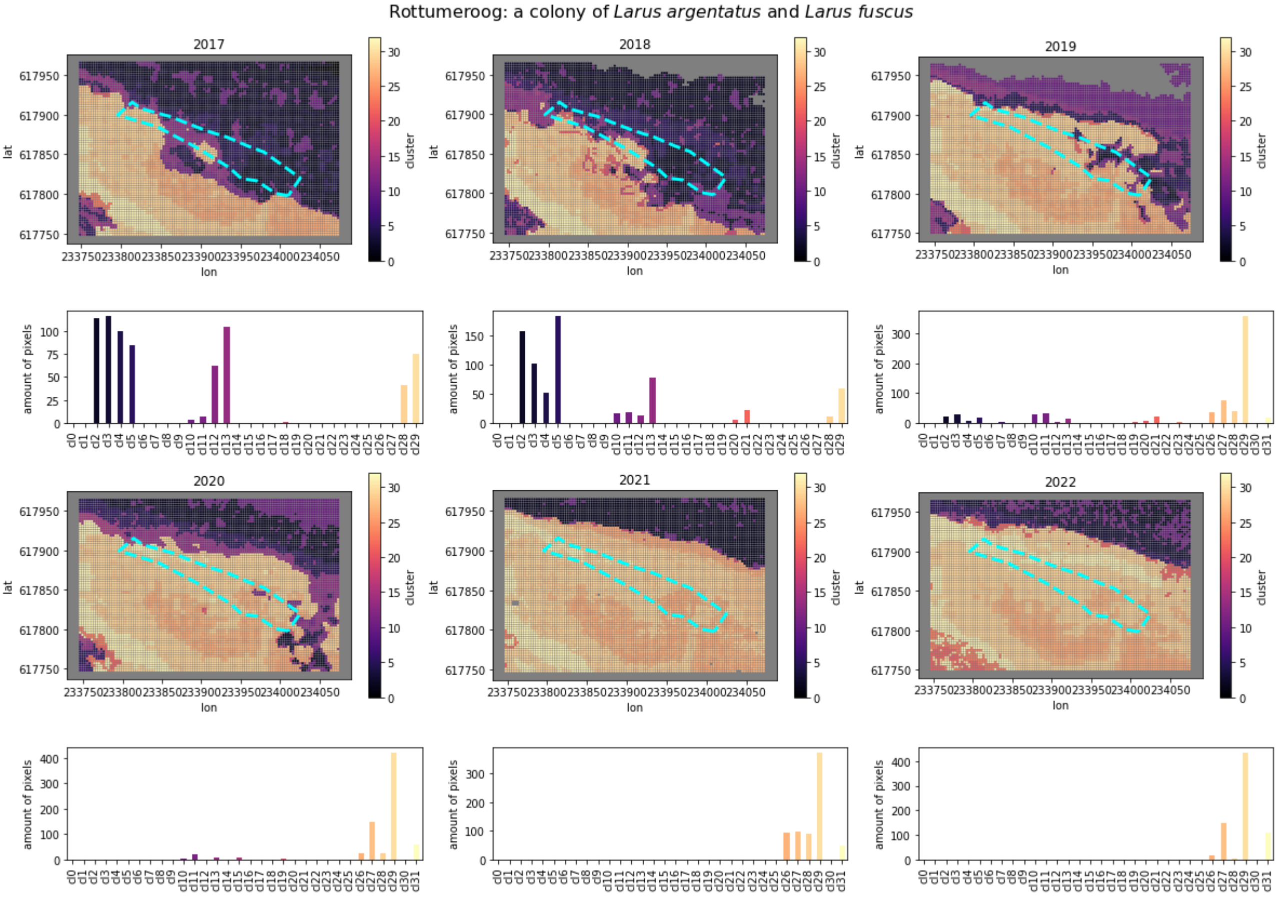
Rottumeroog: a colony of *Larus canus*



Rottumeroog: a colony of *Larus canus*

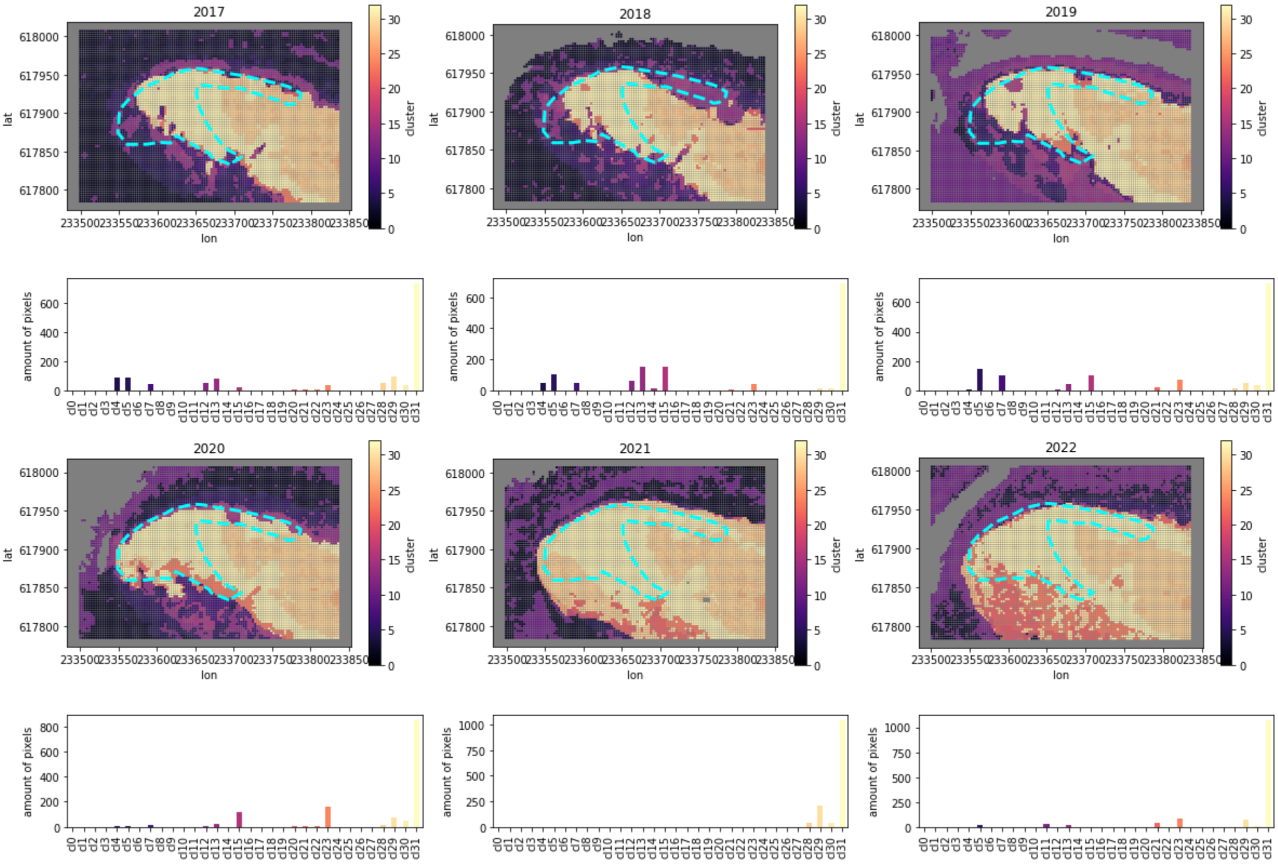


Rottumeroog: a colony of *Larus argentatus* and *Larus fuscus*

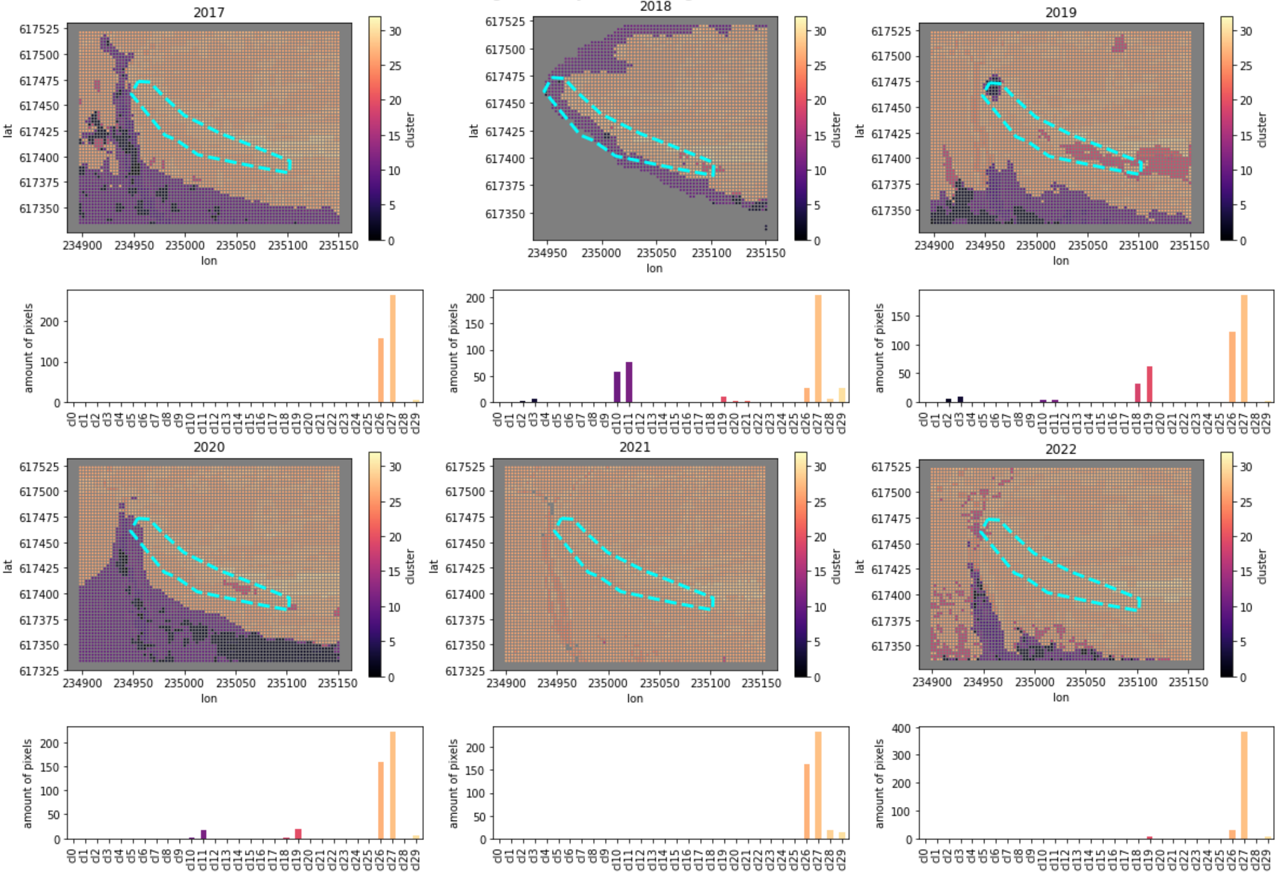


Rottumeroog: a colony of *Larus argentatus* and *Larus fuscus*

Rottumeroog: a colony of *Larus argentatus* and *Larus fuscus*



Rottumeroog: a colony of *Larus argentatus* and *Larus fuscus*



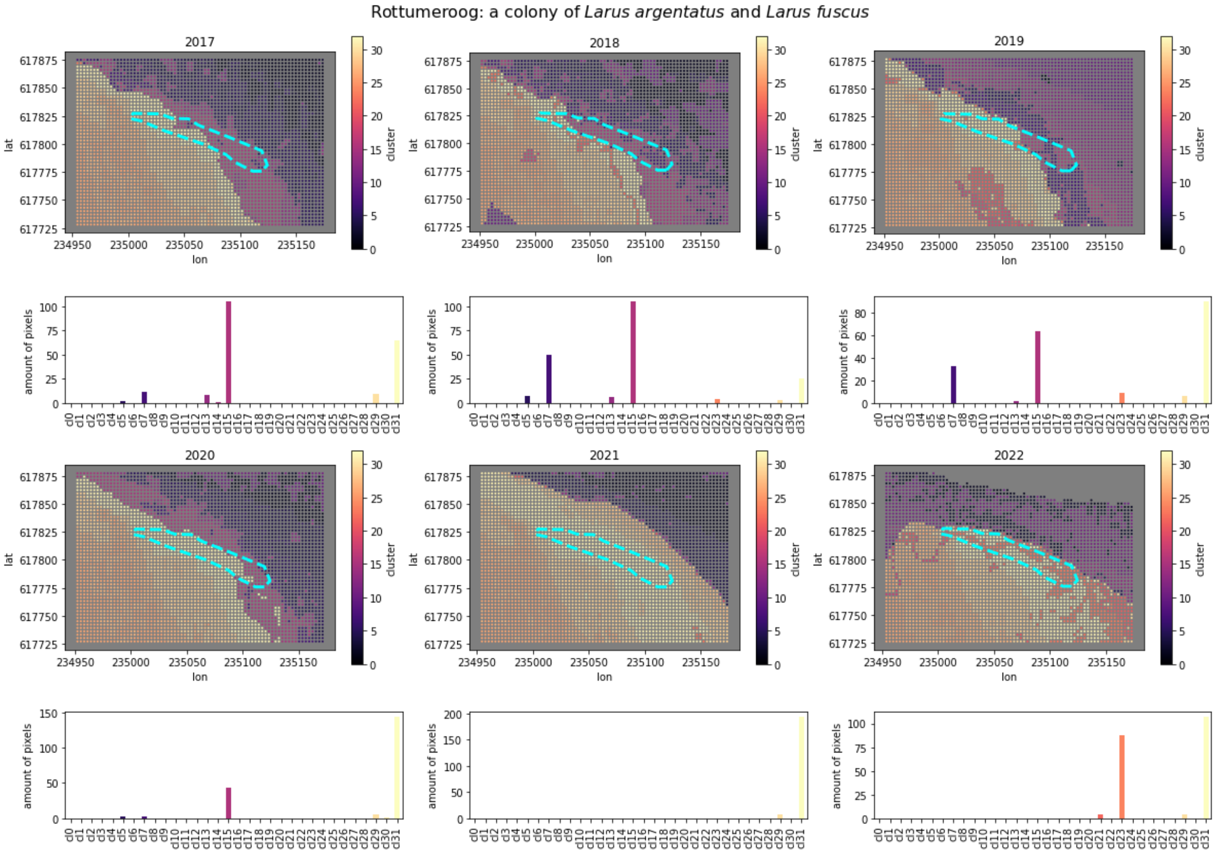


Figure E.5: Distribution of clusters per colony in Rottumeroog

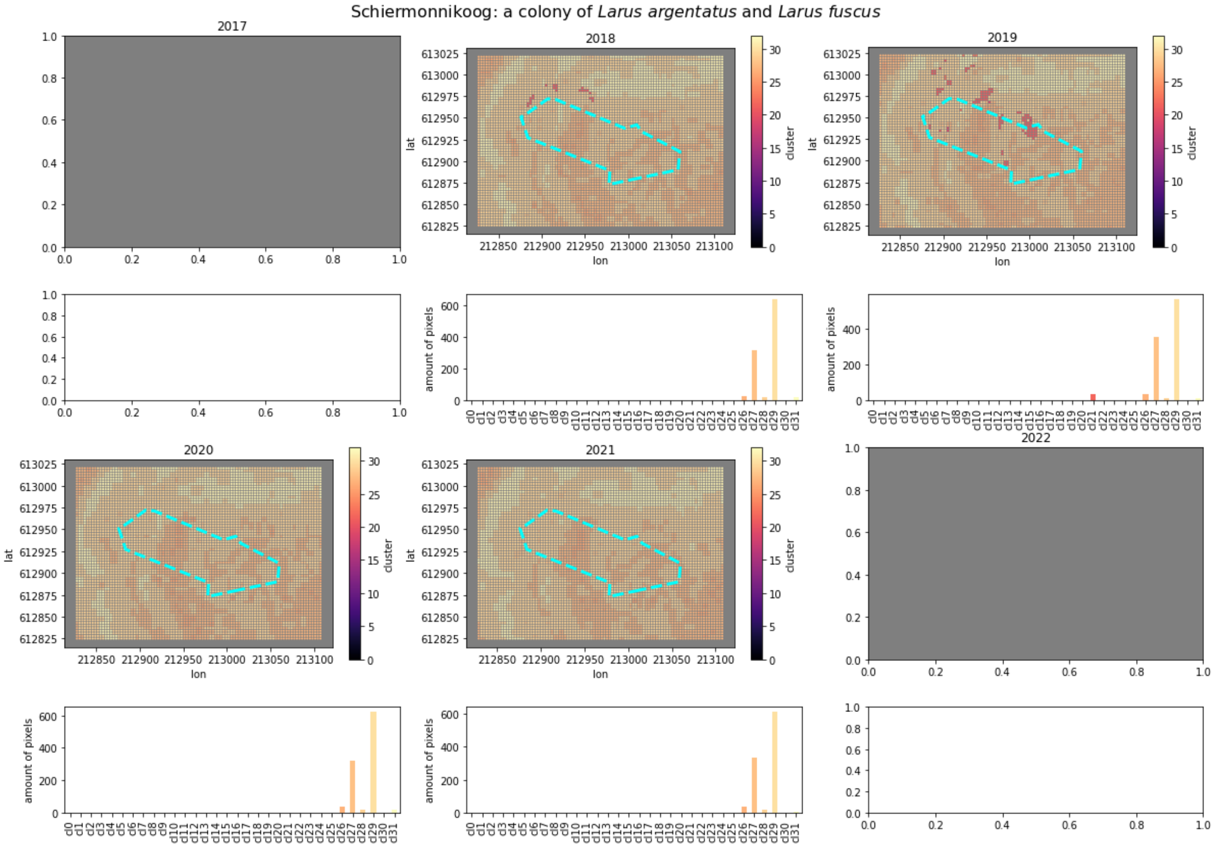
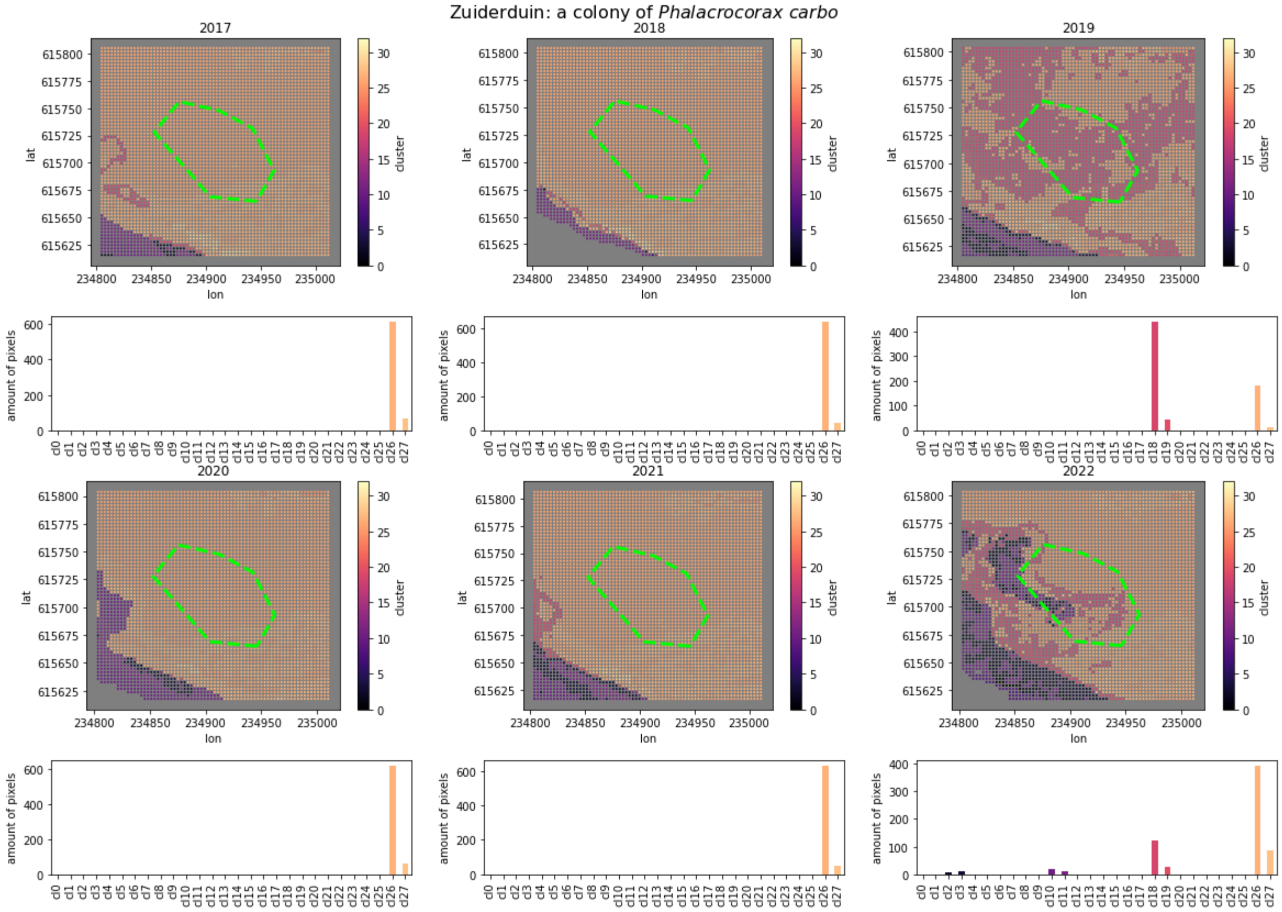
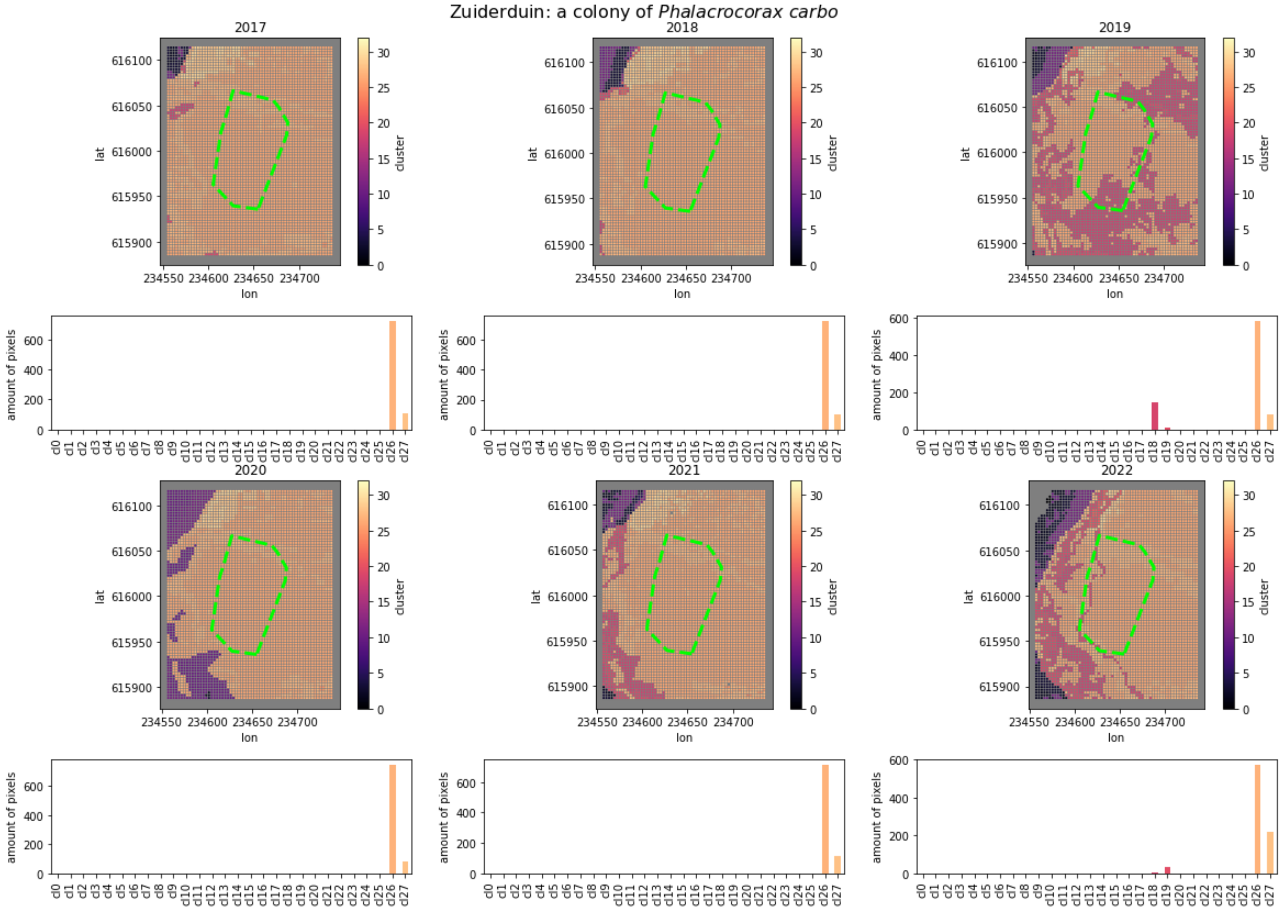
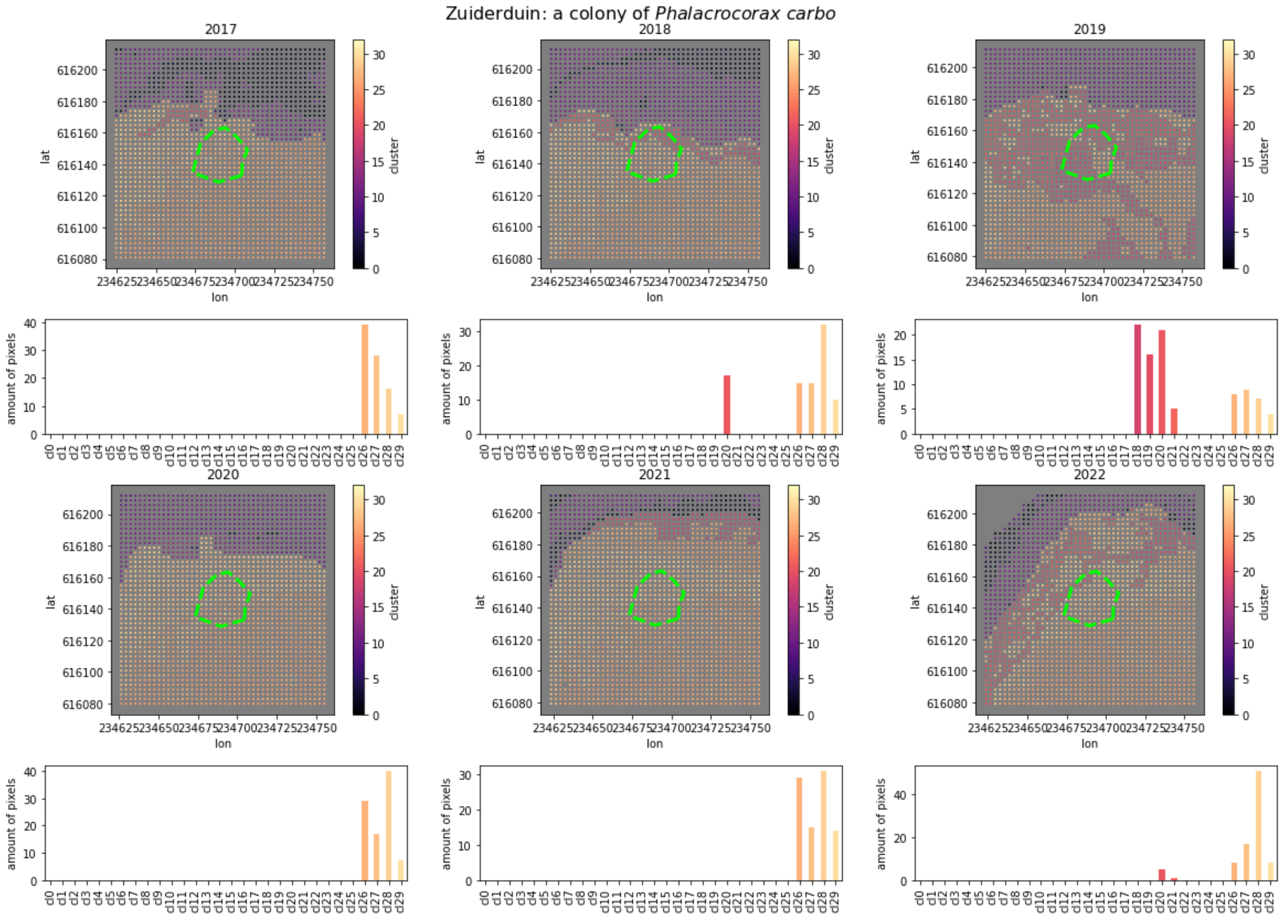


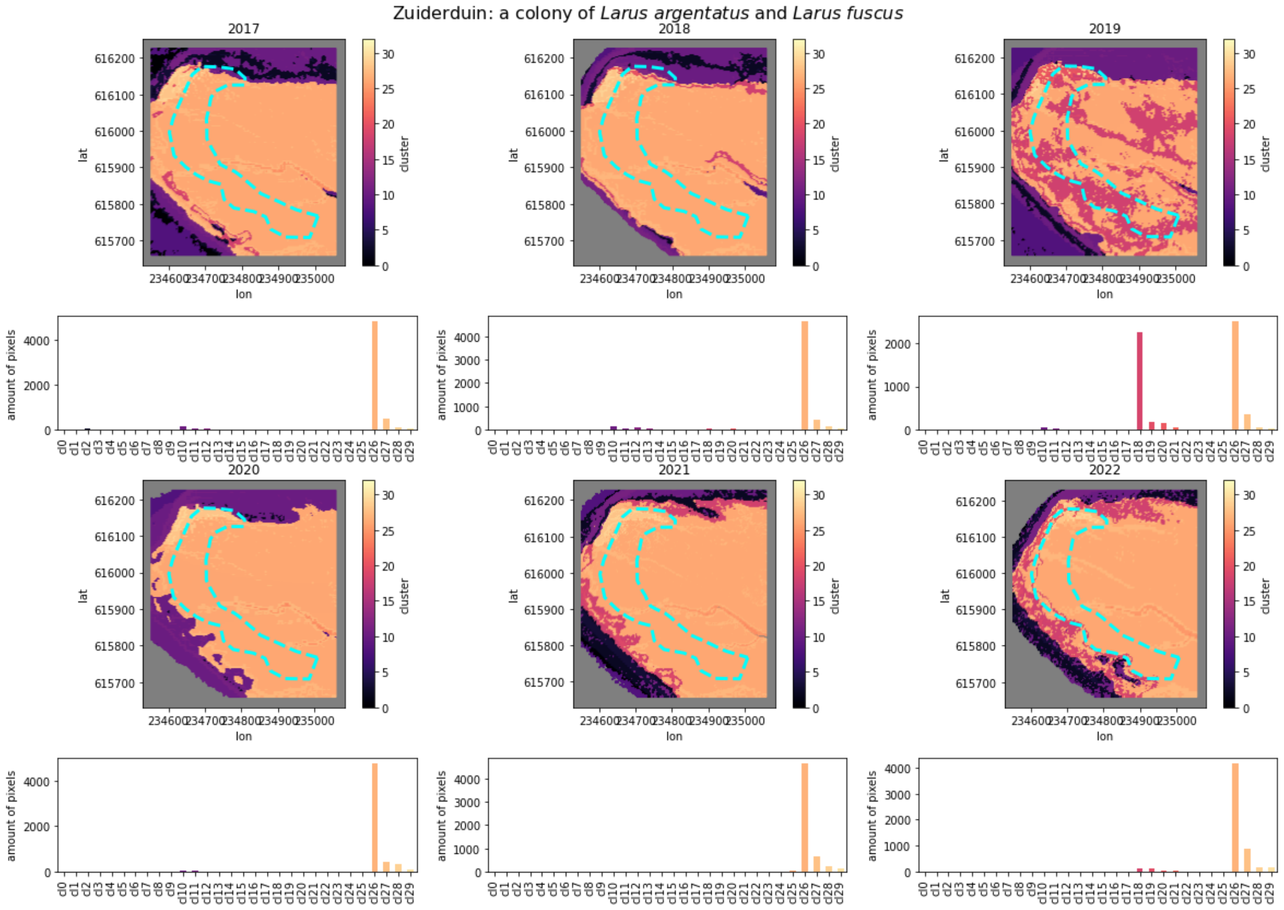
Figure E.6: Distribution of clusters per colony in Schiermonnikoog


Zuiderduin: a colony of *Phalacrocorax carbo*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
615625
615650
615675
615700
615725
615750
615775
615800
234800
234850
234900
234950
235000
d0 d1 d2 d3 d4 d5 d6 d7 d8 d9 d10 d11 d12 d13 d14 d15 d16 d17 d18 d19 d20 d21 d22 d23 d24 d25 d26 d27

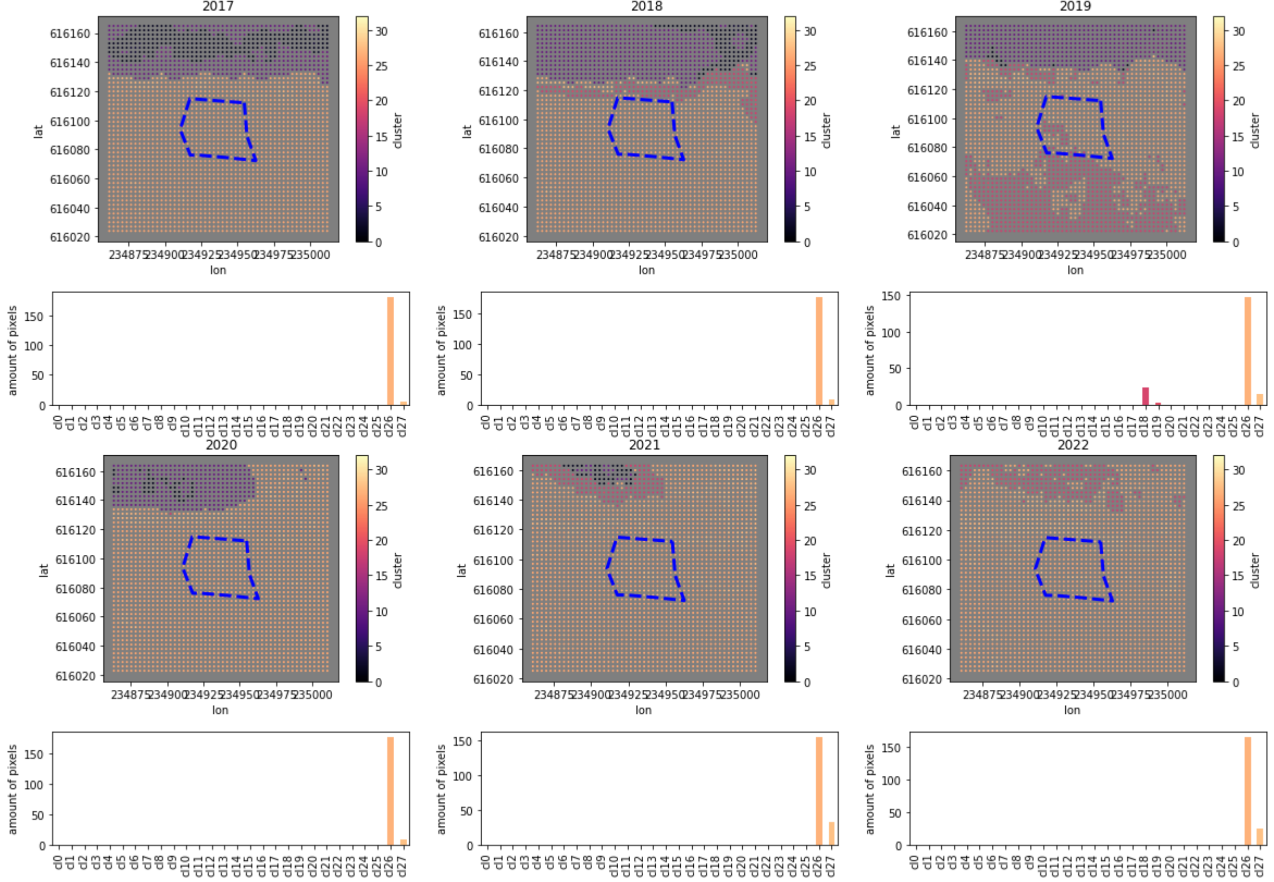

Zuiderduin: a colony of *Phalacrocorax carbo*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
615900
615950
616000
616050
616100
234550
234600
234650
234700
d0 d1 d2 d3 d4 d5 d6 d7 d8 d9 d10 d11 d12 d13 d14 d15 d16 d17 d18 d19 d20 d21 d22 d23 d24 d25 d26 d27



Zuiderduin: a colony of *Phalacrocorax carbo*



Zuiderduin: a colony of *Larus argentatus* and *Larus fuscus*


Zuiderduin: a colony of *Larus canus*

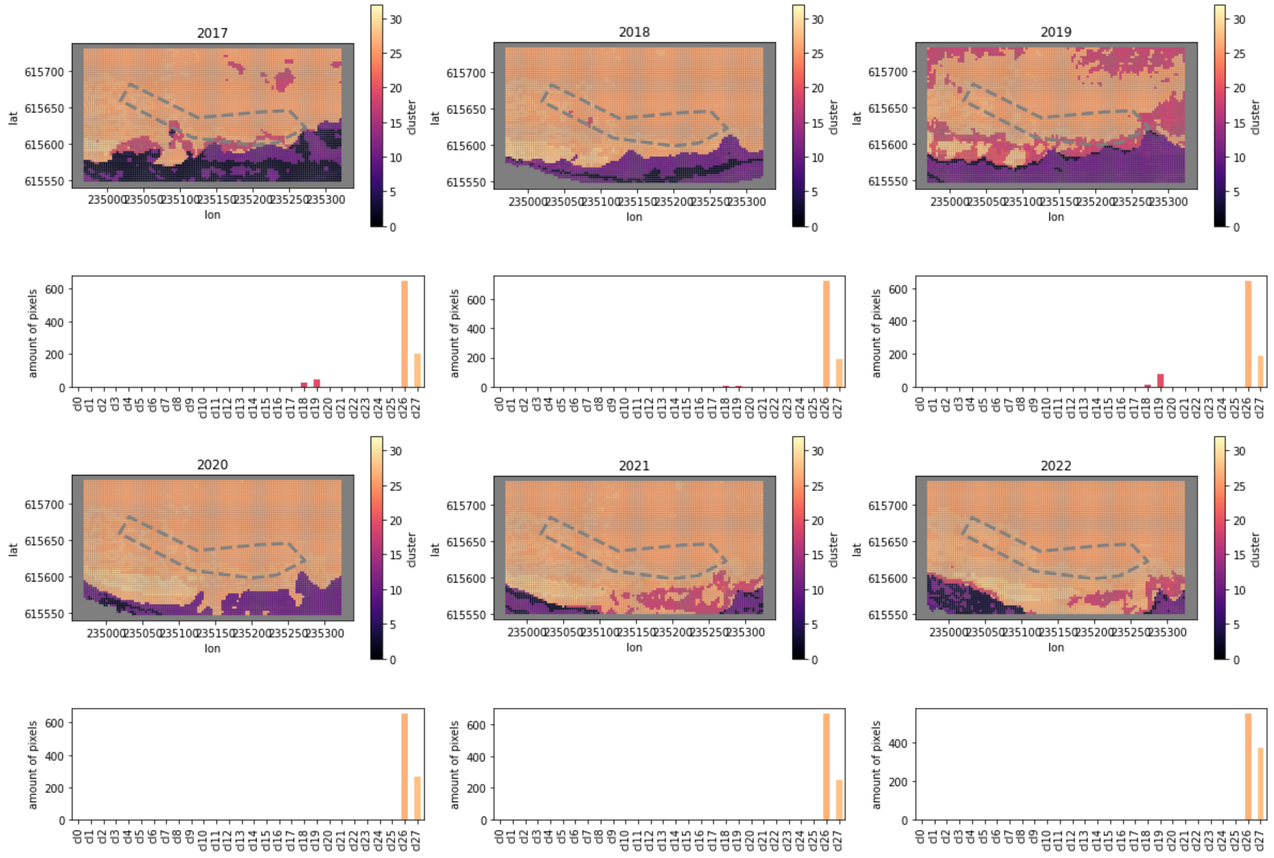
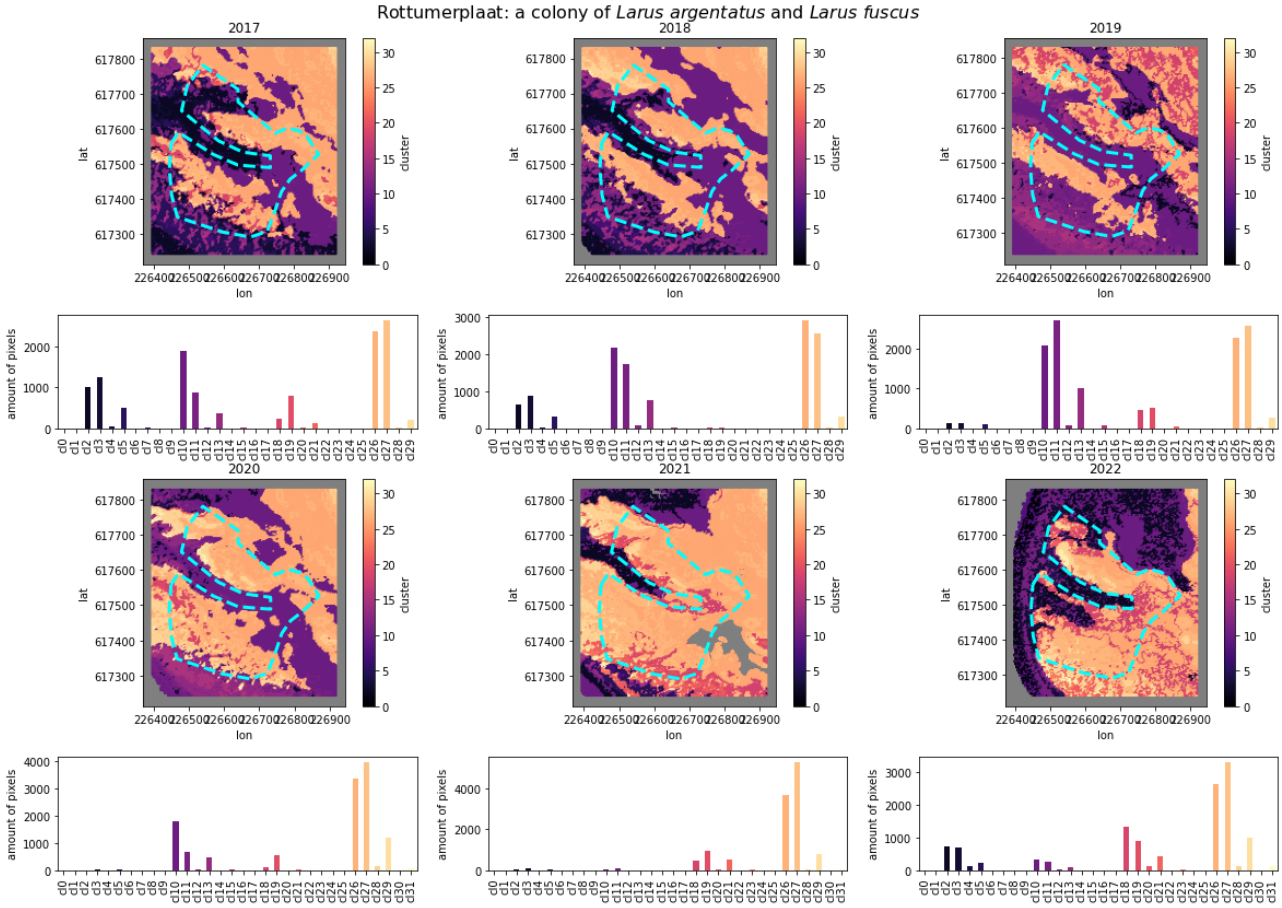
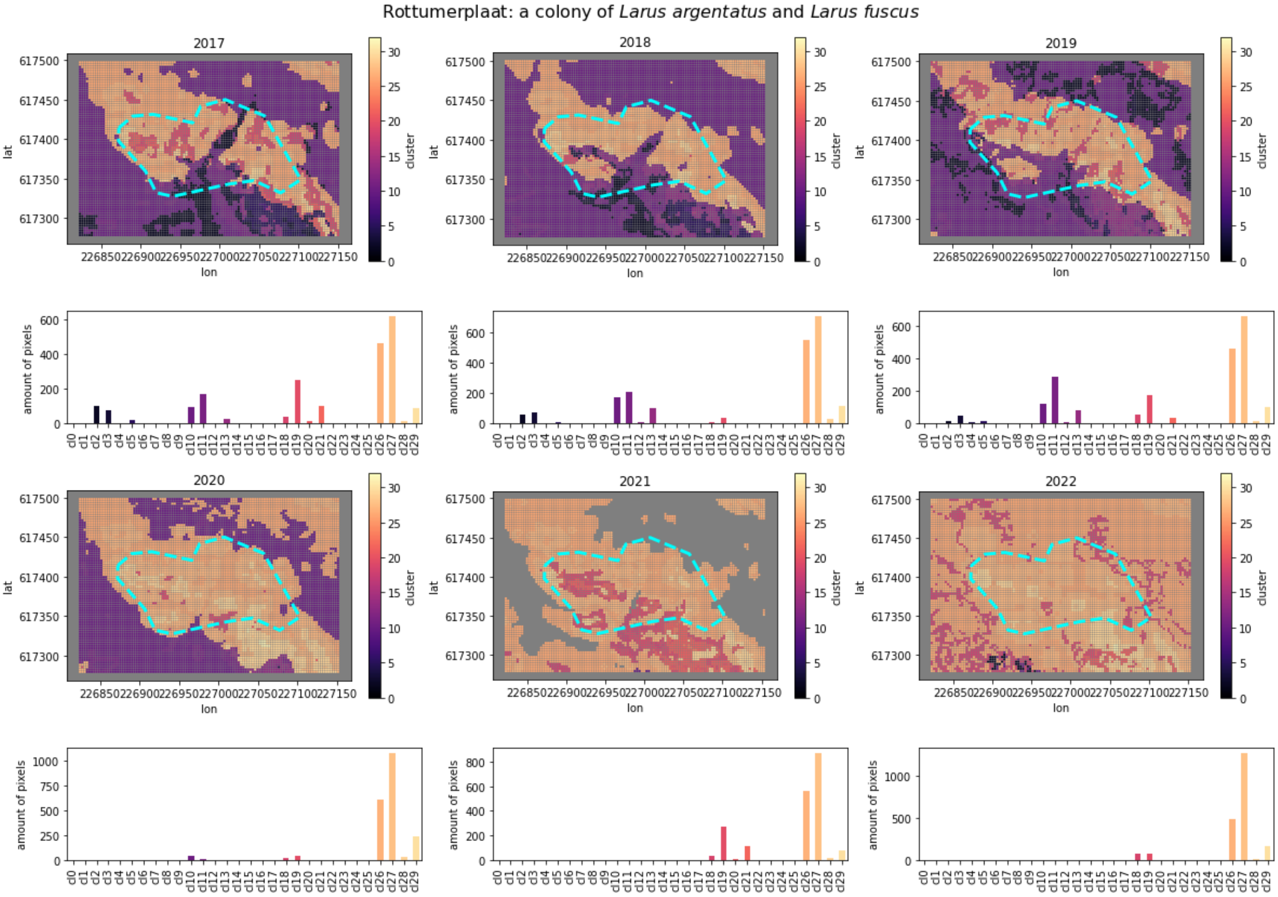
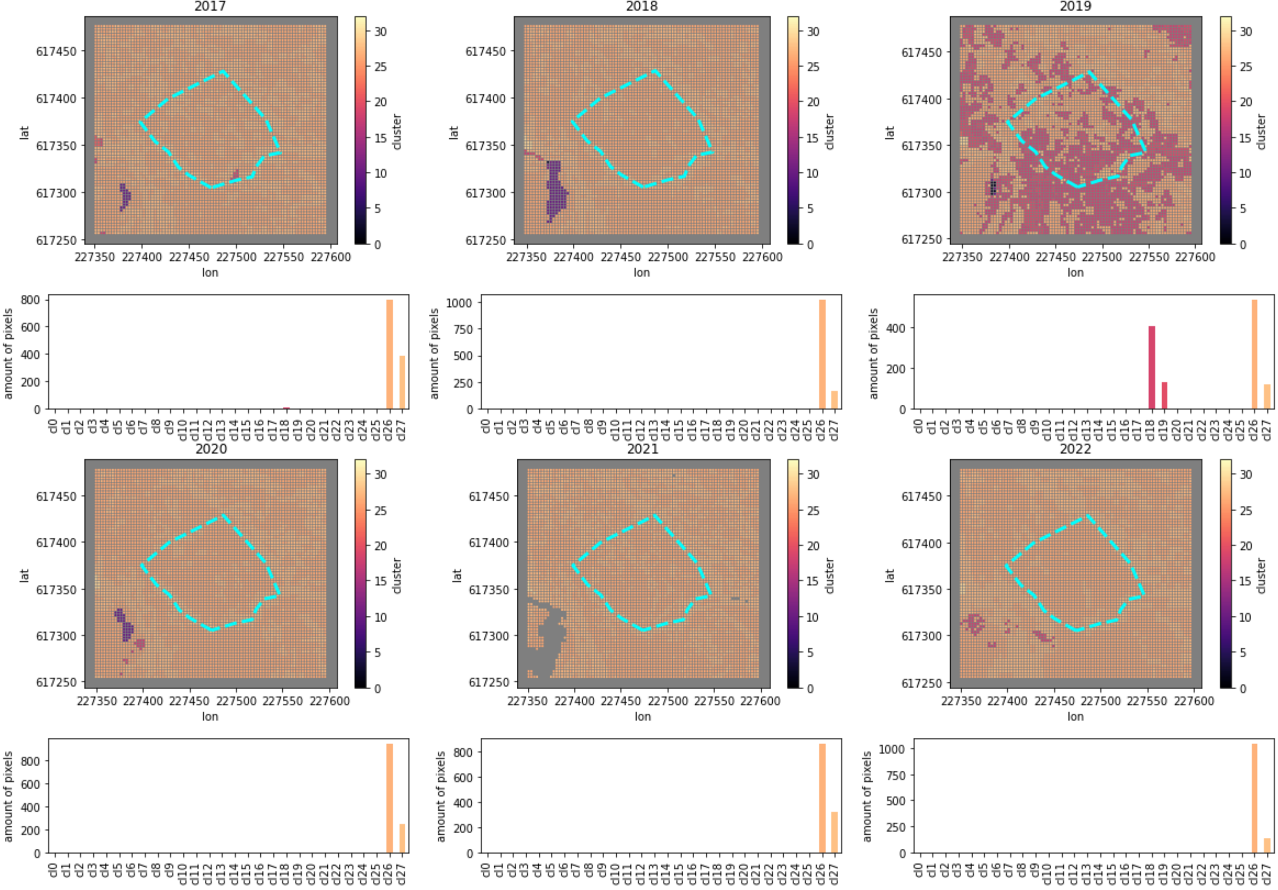

Zuiderduin: a colony of *Chroicocephalus ridibundus*

Figure E.7: Distribution of clusters per colony in Zuiderduin

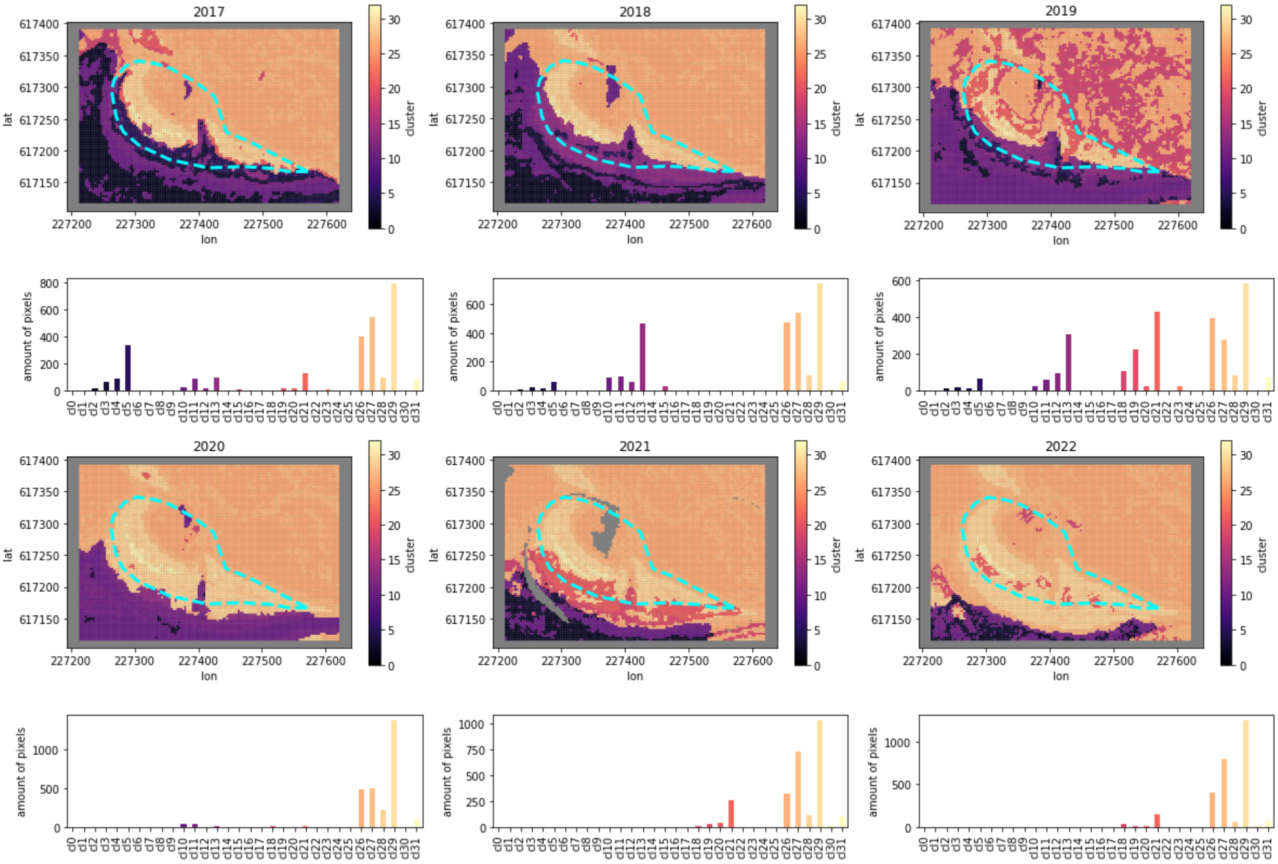

Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
617300
617400
617500
617600
617700
617800
226400
226500
226600
226700
226800
226900
0
5
10
15
20
25
30
d0 … d31

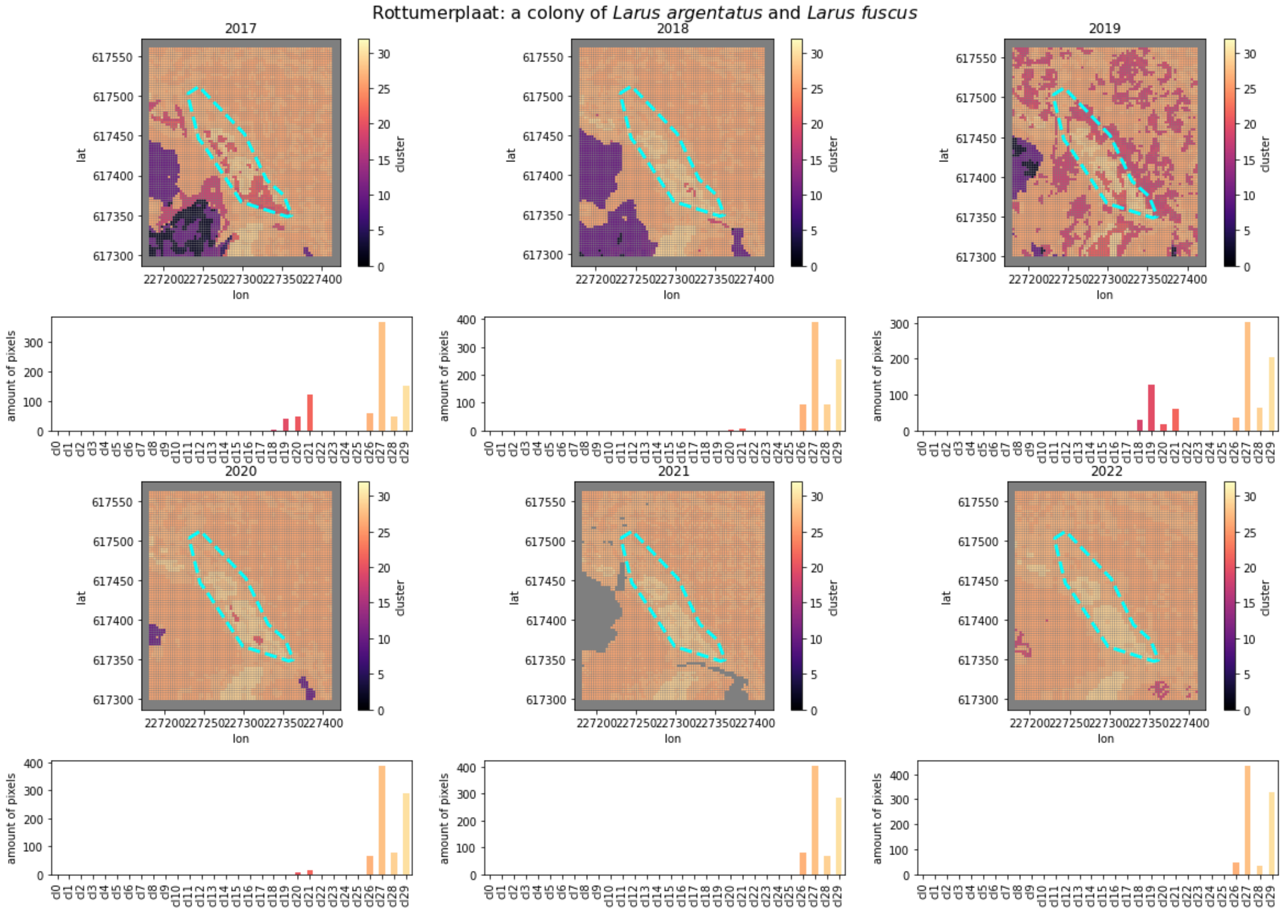

Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
617300
617350
617400
617450
617500
226850
226900
226950
227000
227050
227100
227150
0
5
10
15
20
25
30
d0 … d29

Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

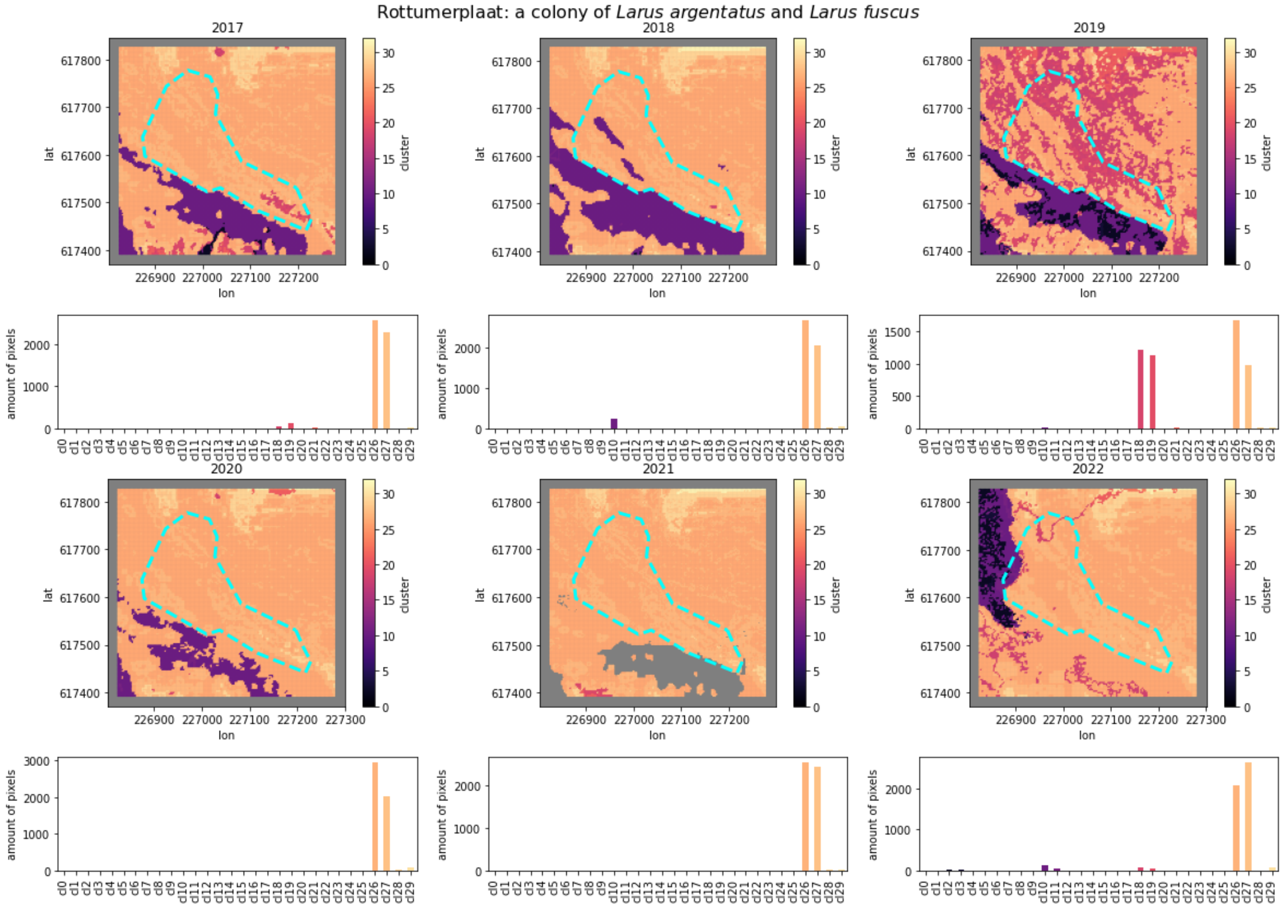


Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

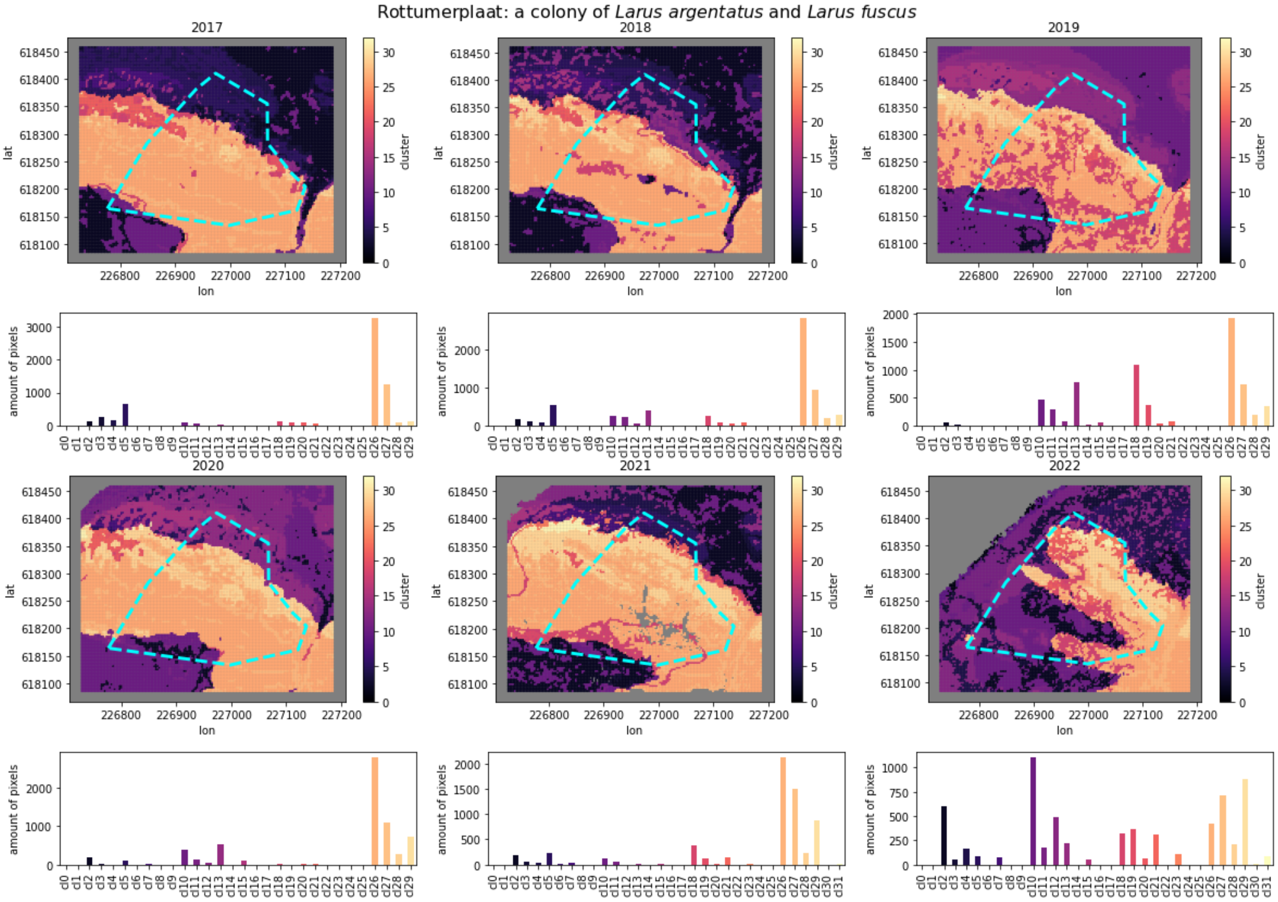




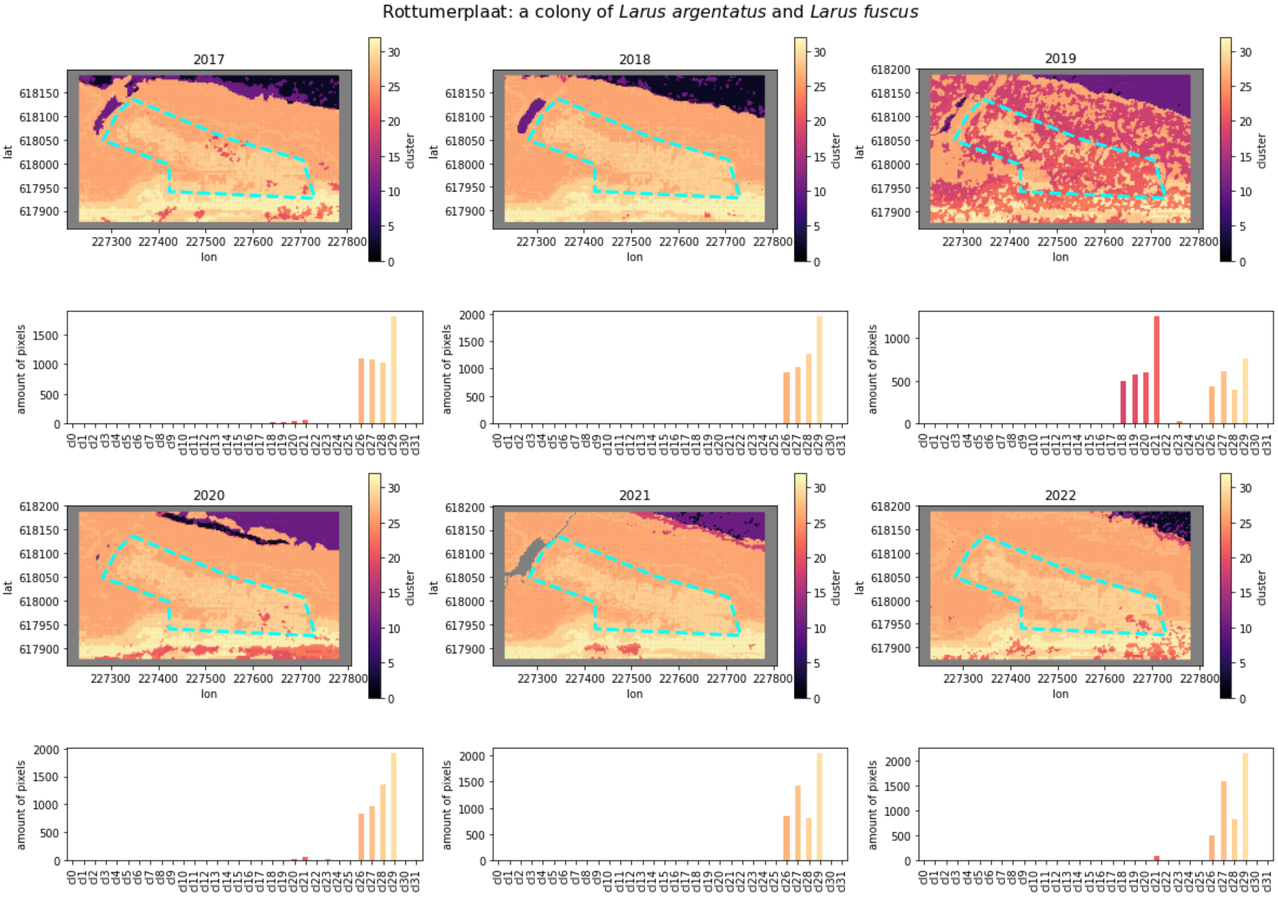
Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*



Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

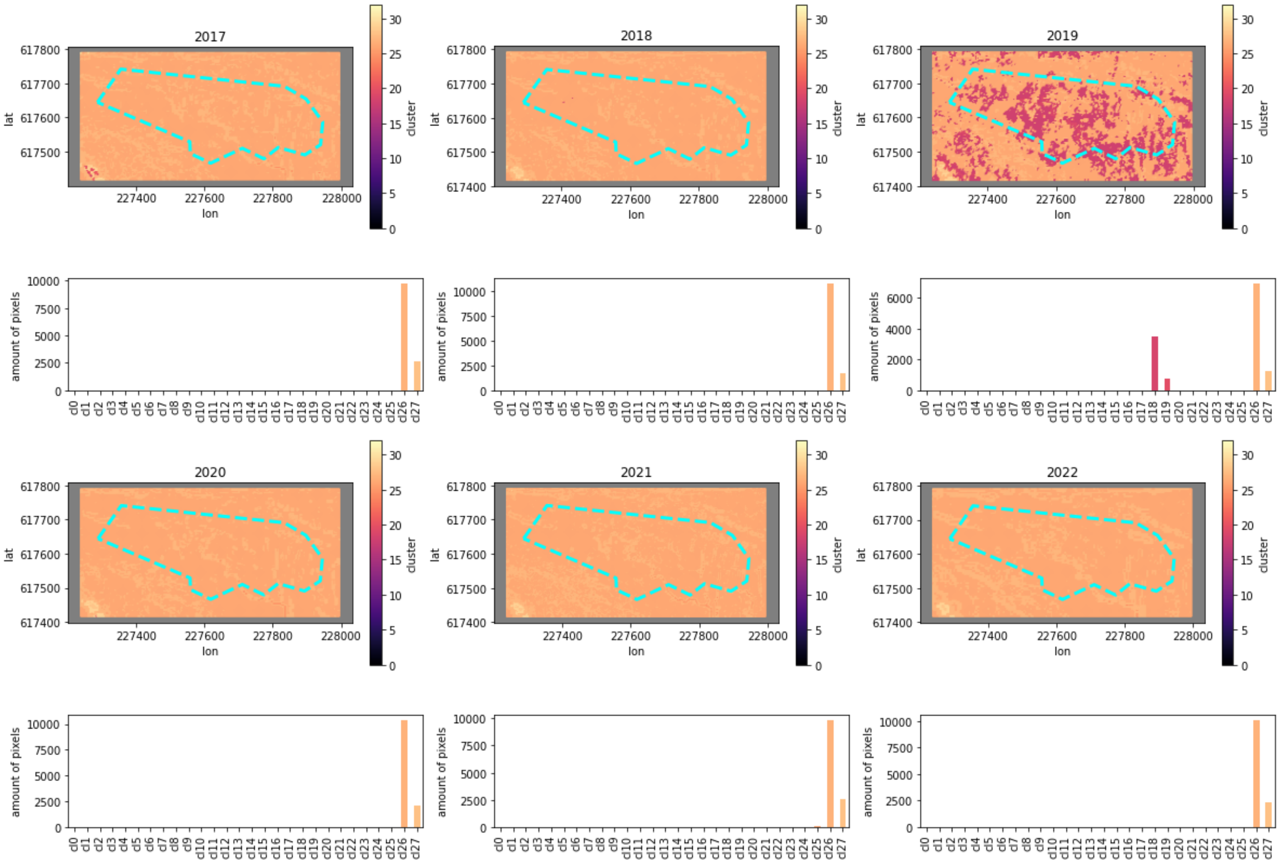


Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

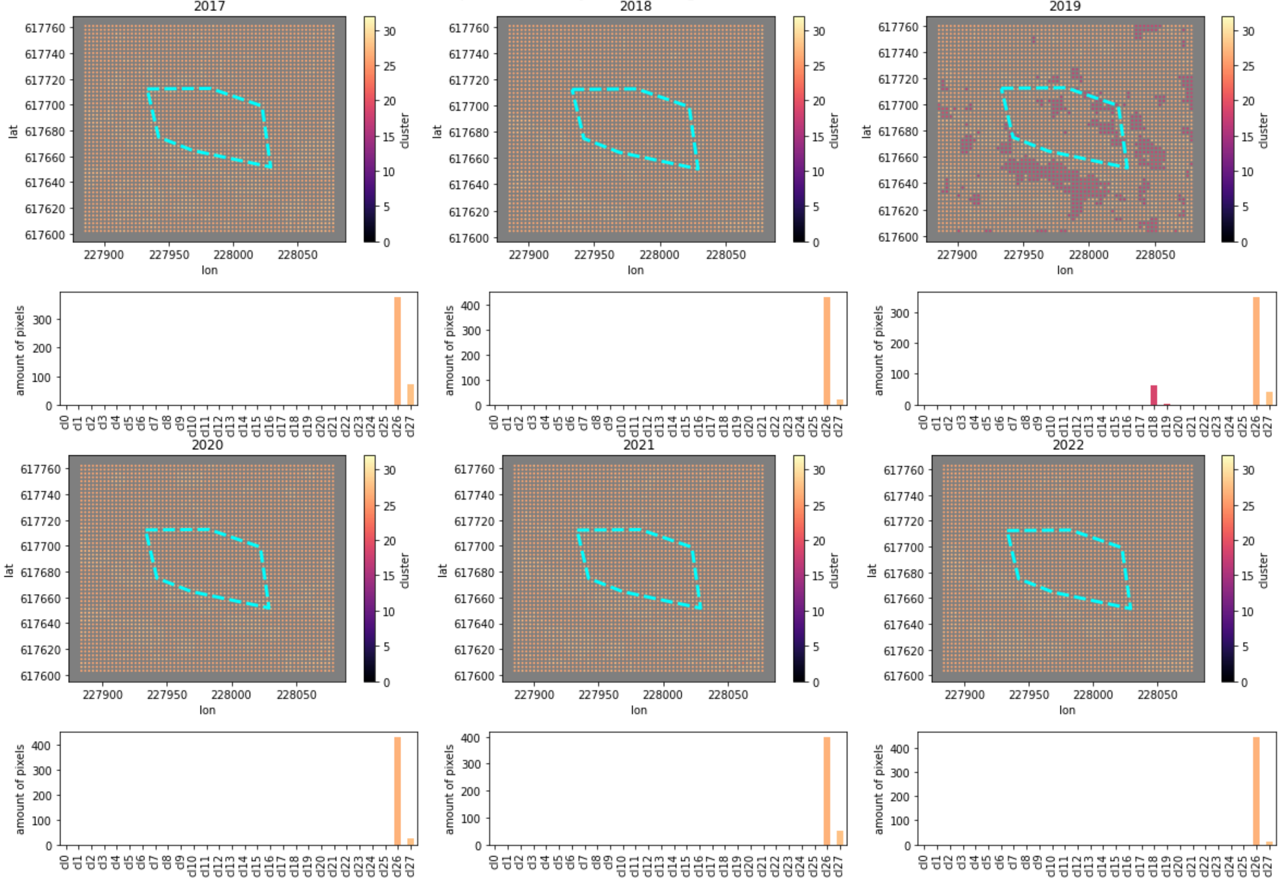


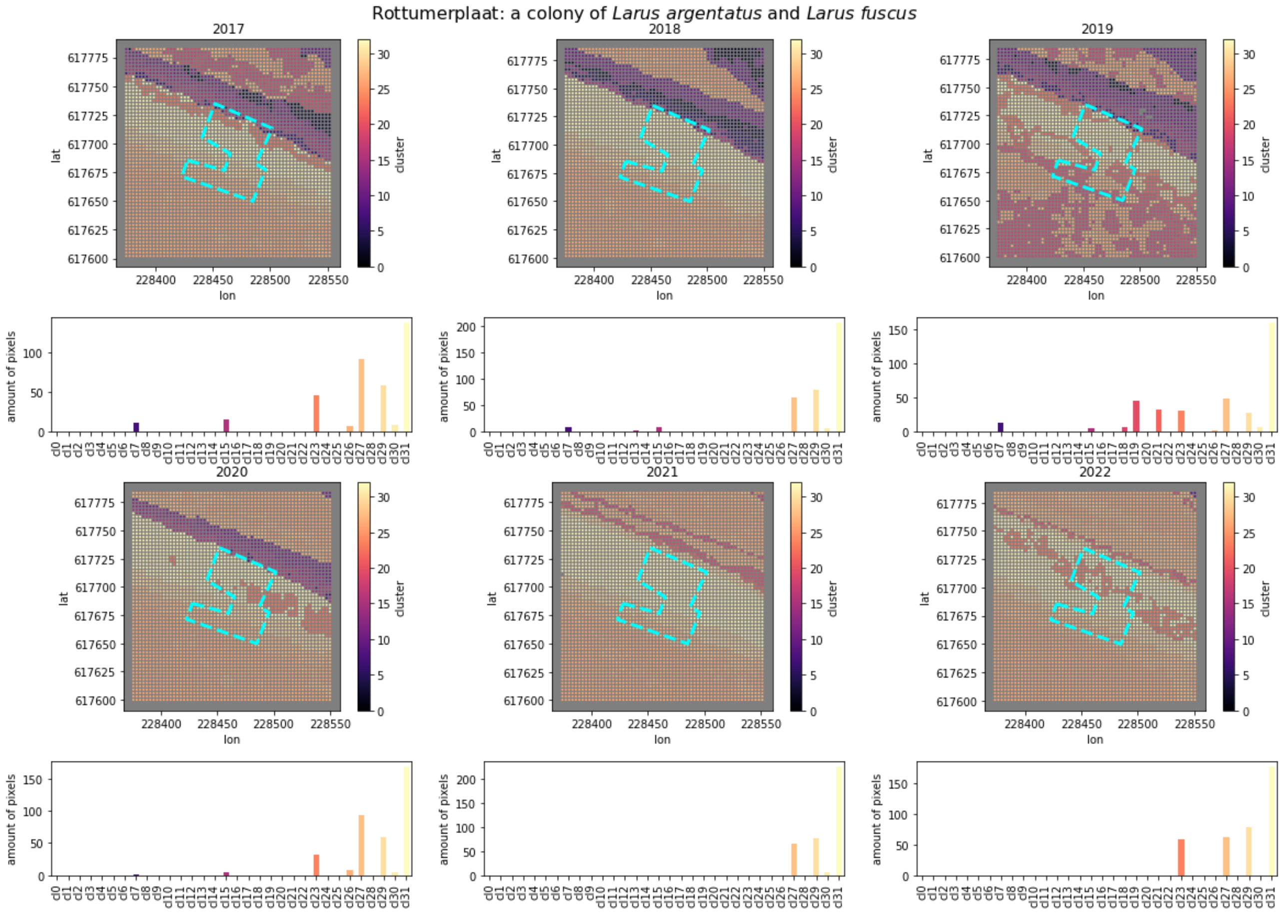
Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

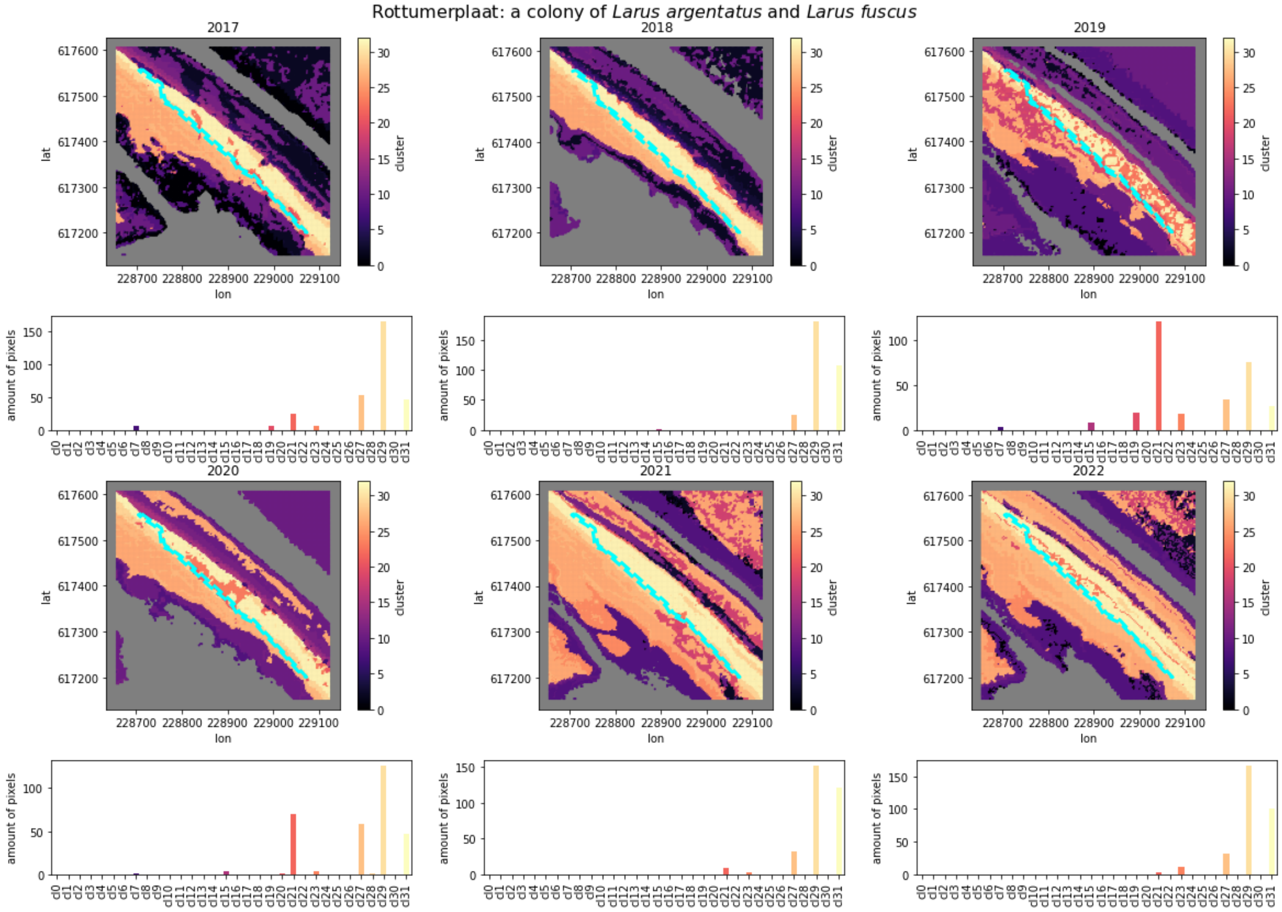
Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

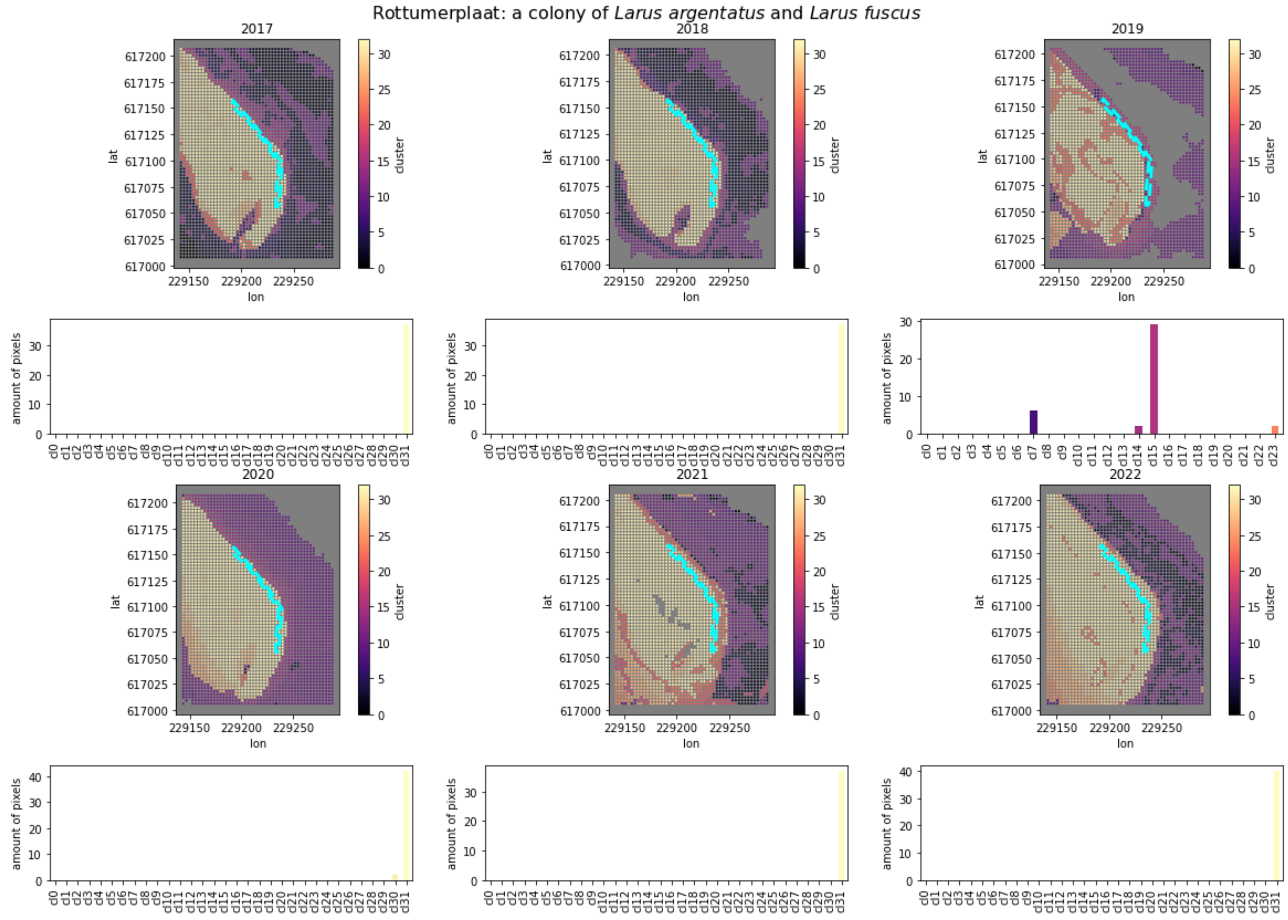


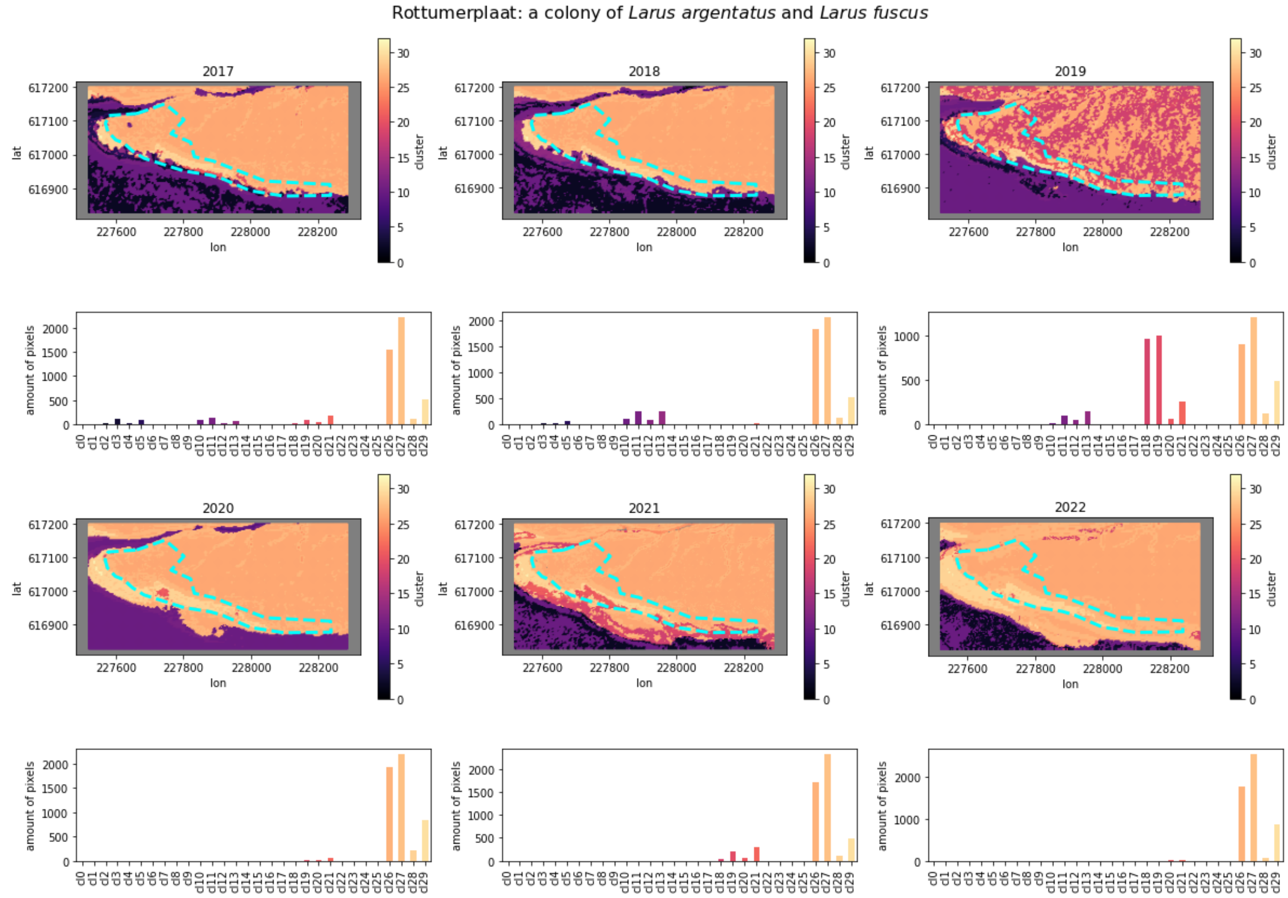
Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

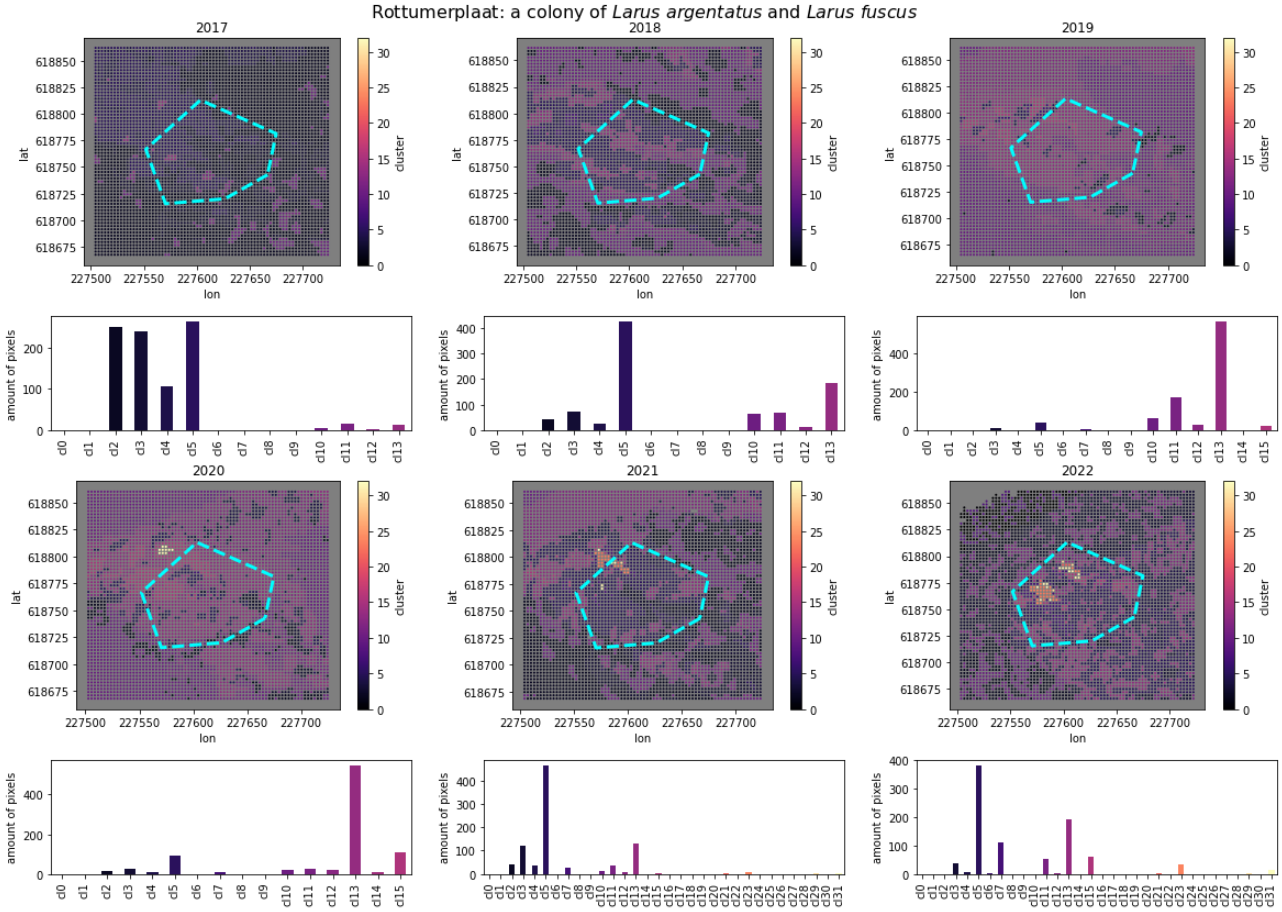



Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

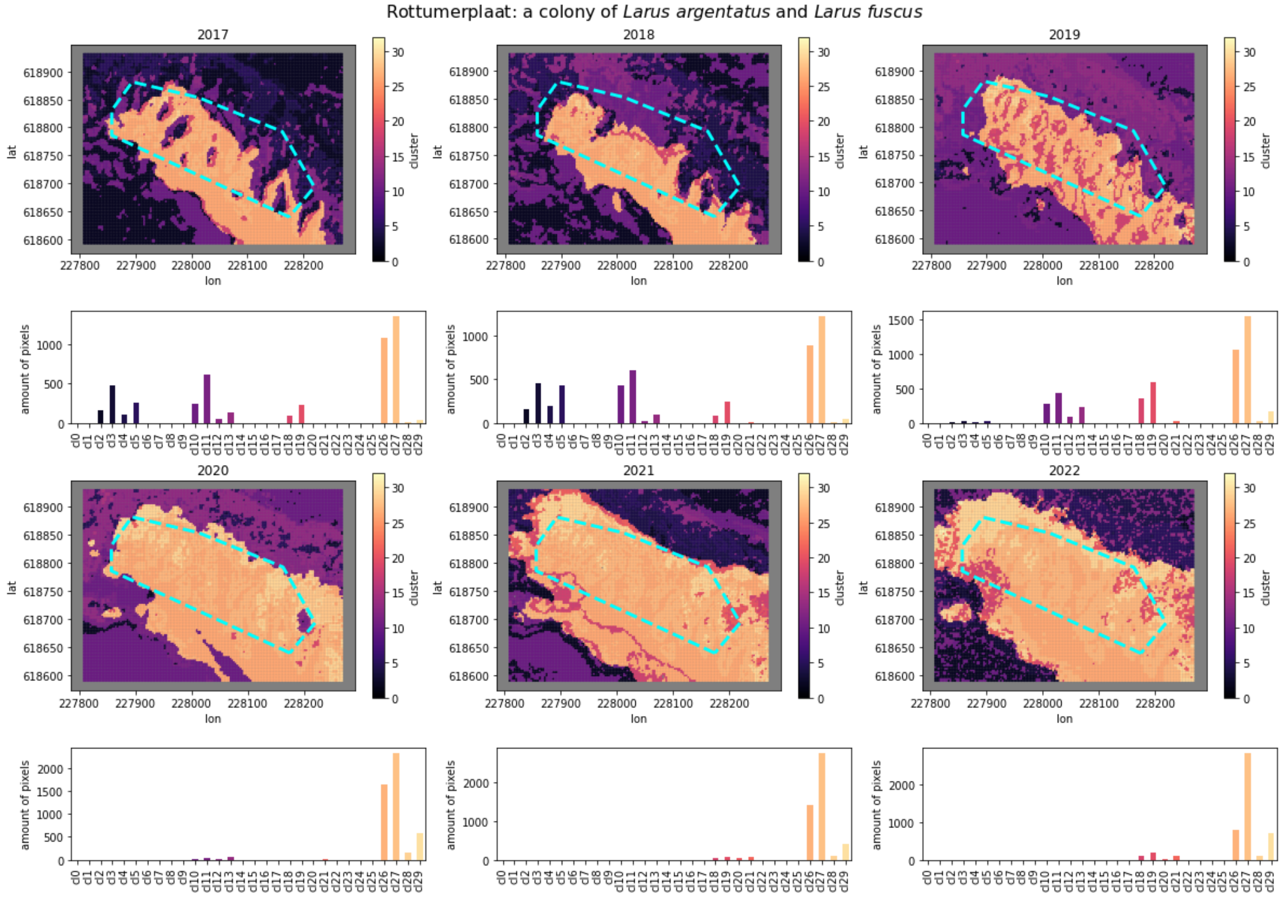

Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*


Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
617000
617025
617050
617075
617100
617125
617150
617175
617200
229150
229200
229250
0
5
10
15
20
25
30
amount of pixels
c0 c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18 c19 c20 c21 c22 c23 c24 c25 c26 c27 c28 c29 c30 c31


Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
616900
617000
617100
617200
227600
227800
228000
228200
0
5
10
15
20
25
30
amount of pixels
0
500
1000
1500
2000
c0 c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18 c19 c20 c21 c22 c23 c24 c25 c26 c27 c28 c29



Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*



Rottumerplaat: a colony of *Larus argentatus* and *Larus fuscus*

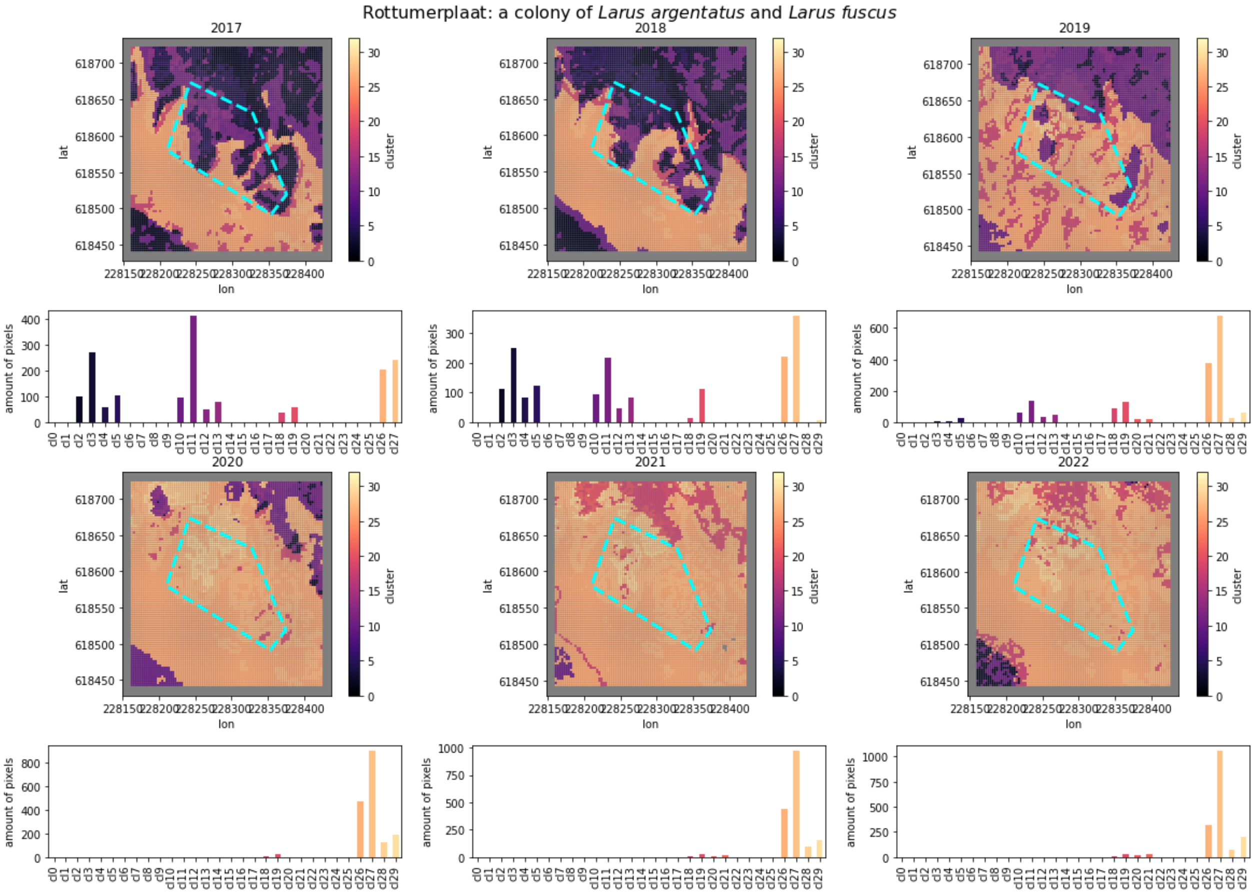
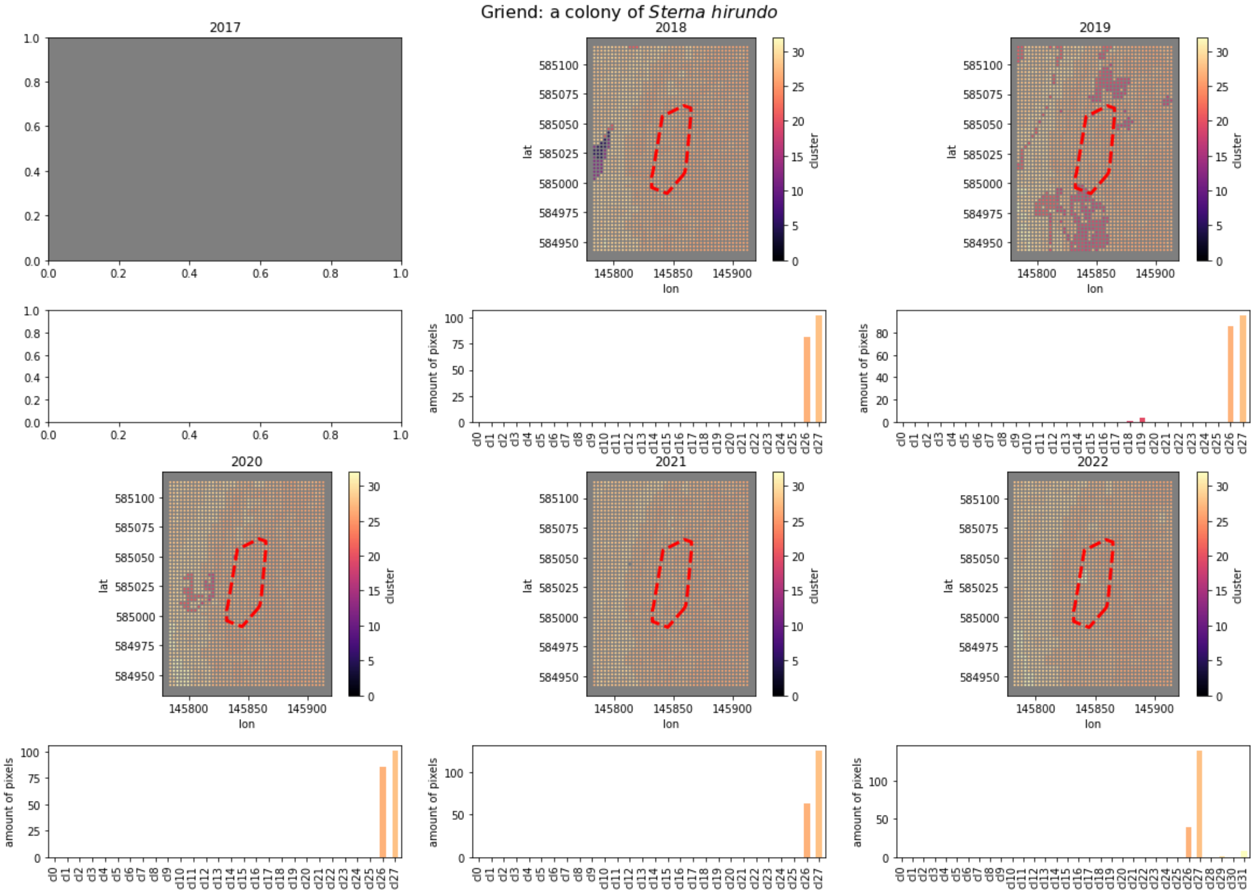
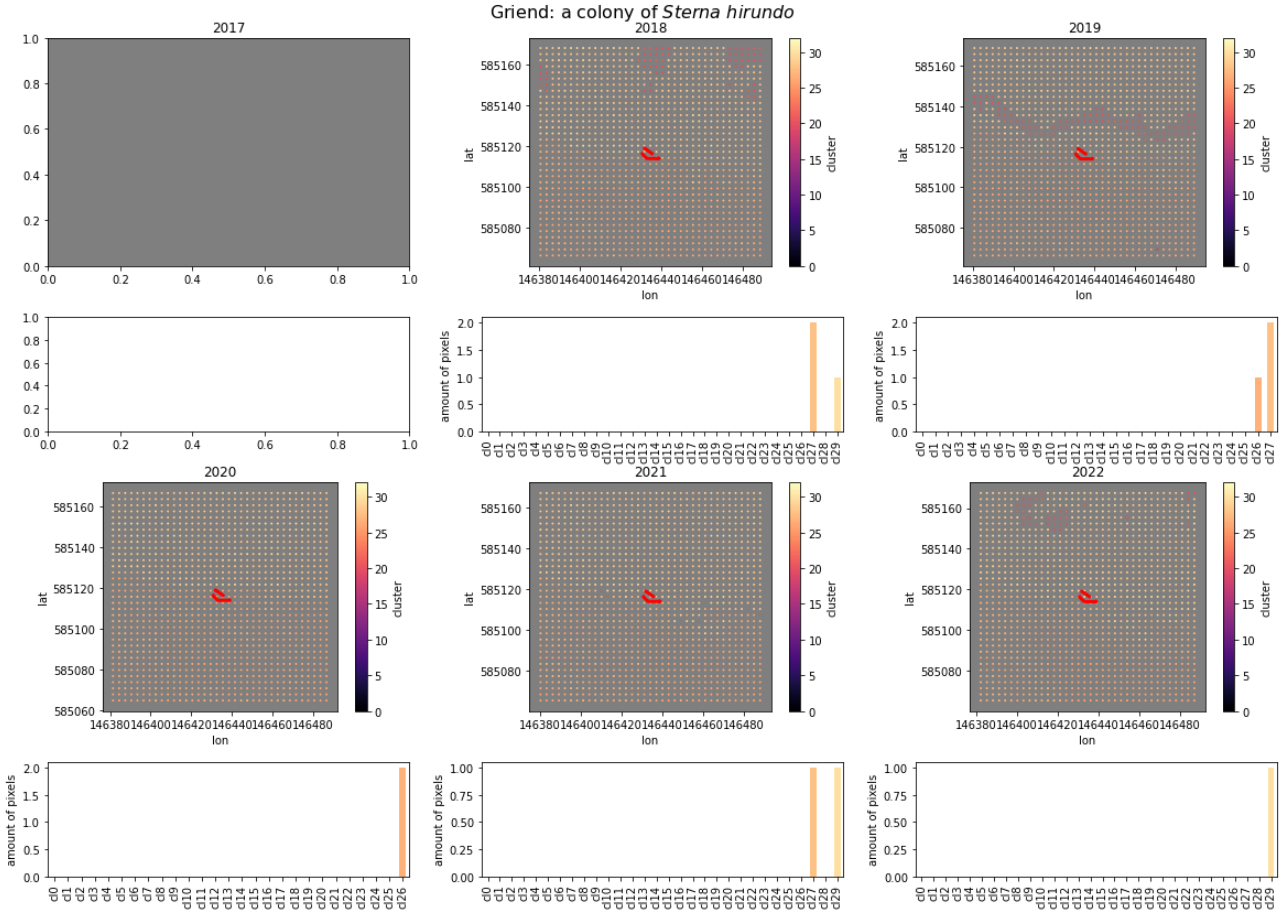
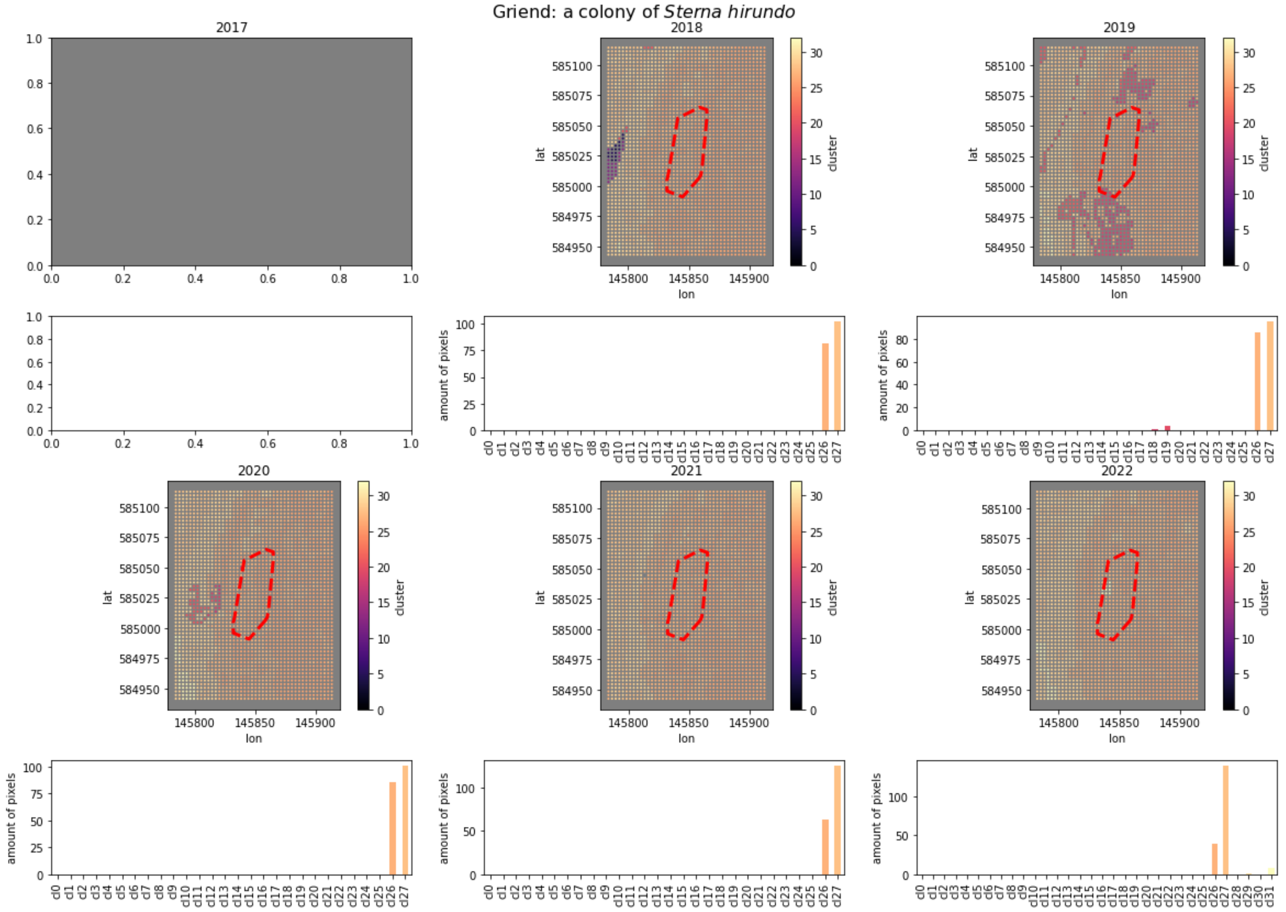


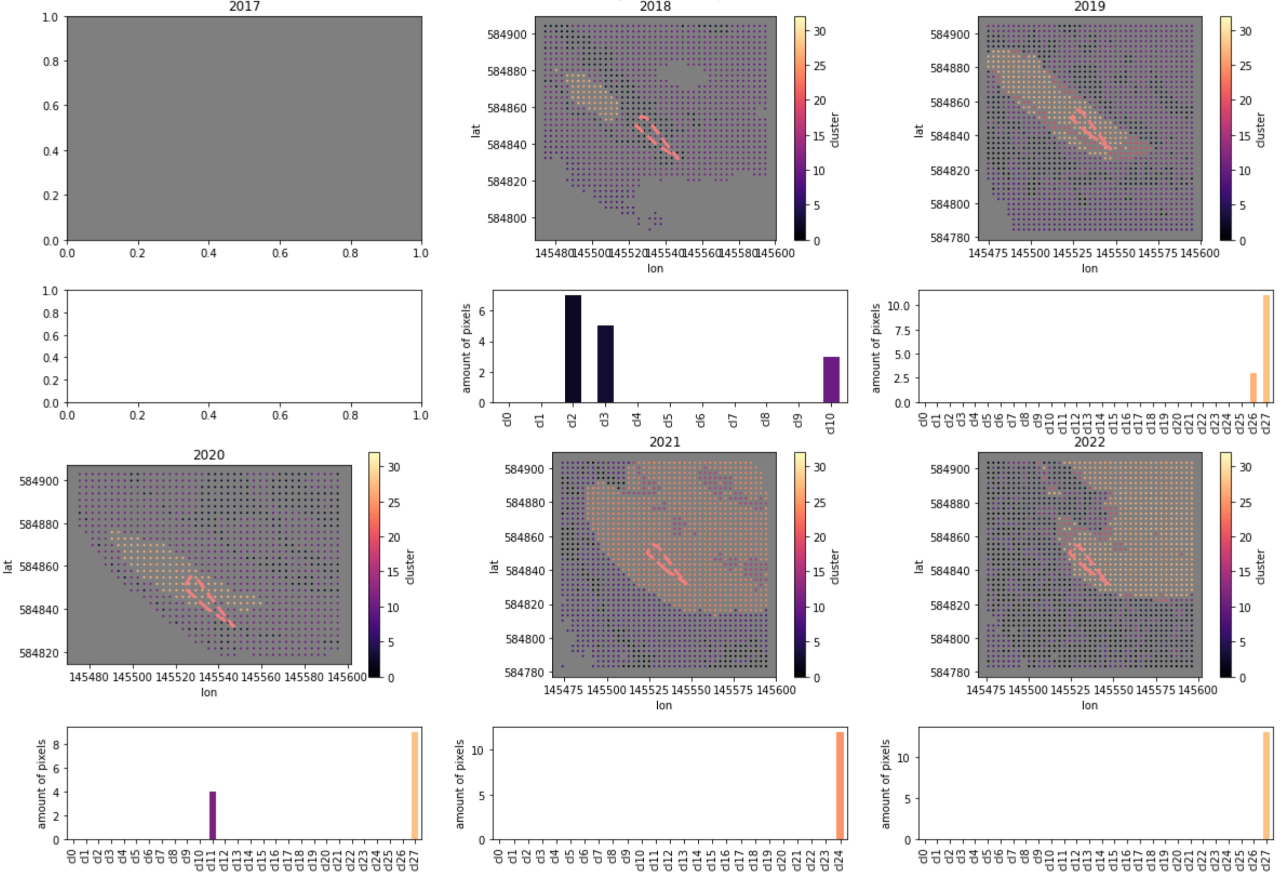
Figure E.8: Distribution of clusters per colony in Rottumerplaat



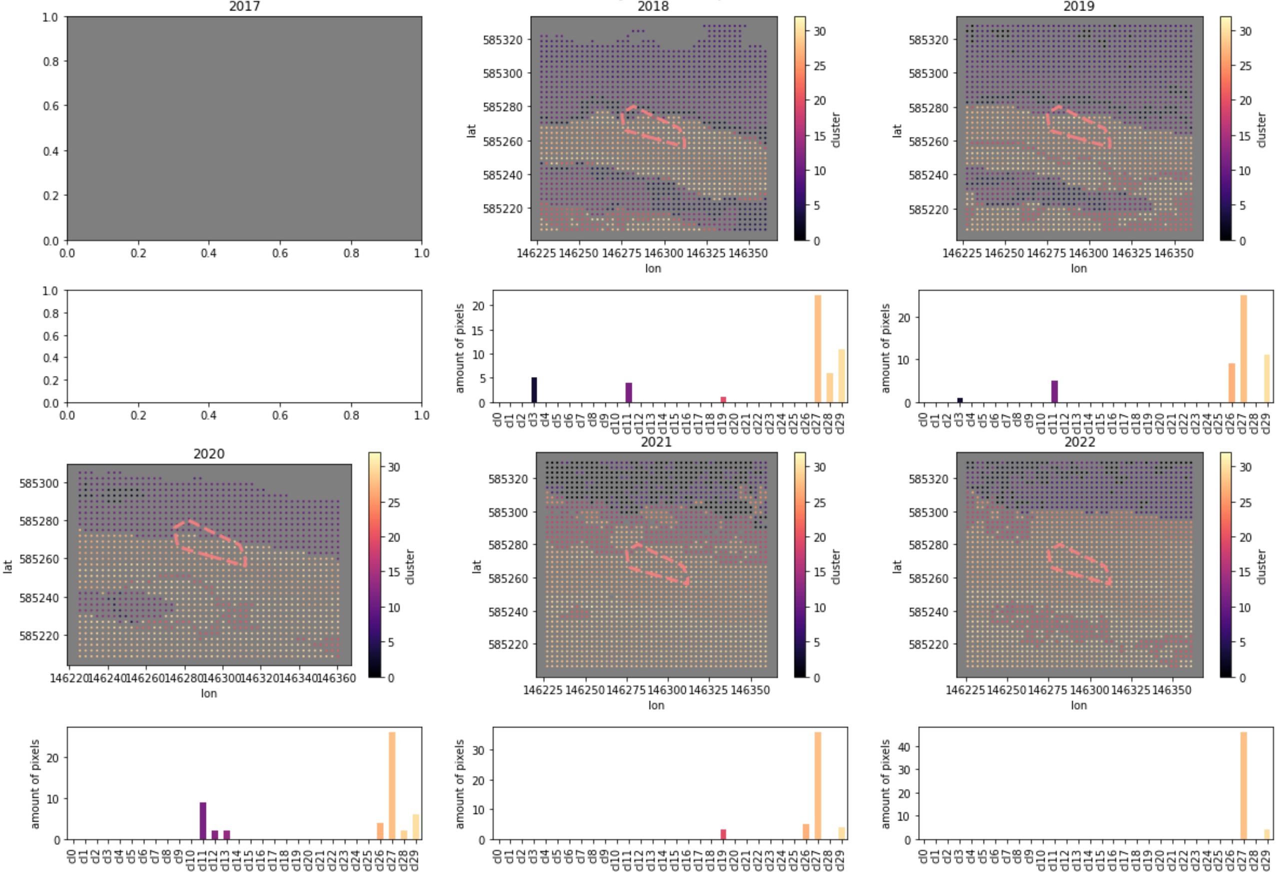

Griend: a colony of *Sterna hirundo*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels

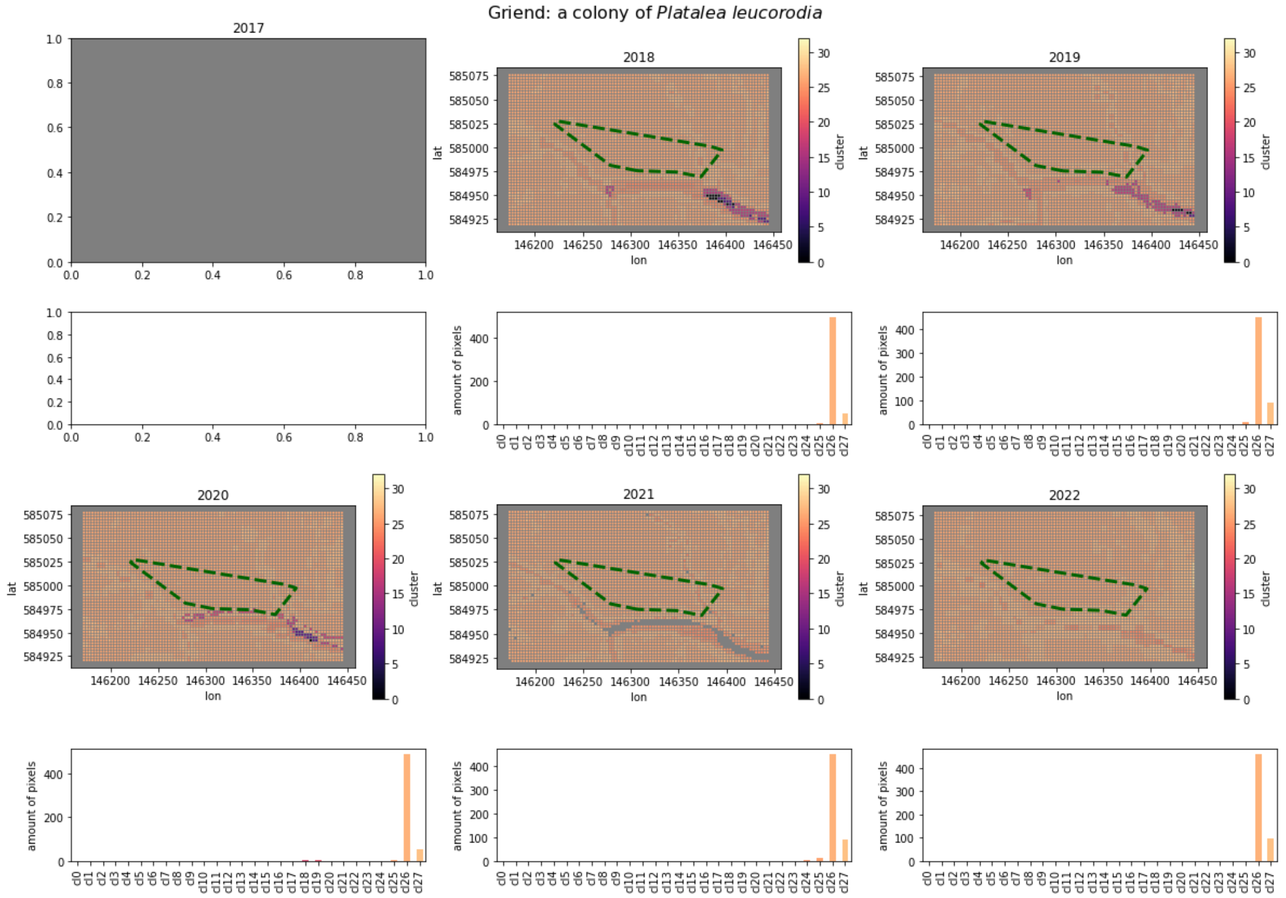

Griend: a colony of *Sterna hirundo*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels

Griend: a colony of *Sterna paradisaea*

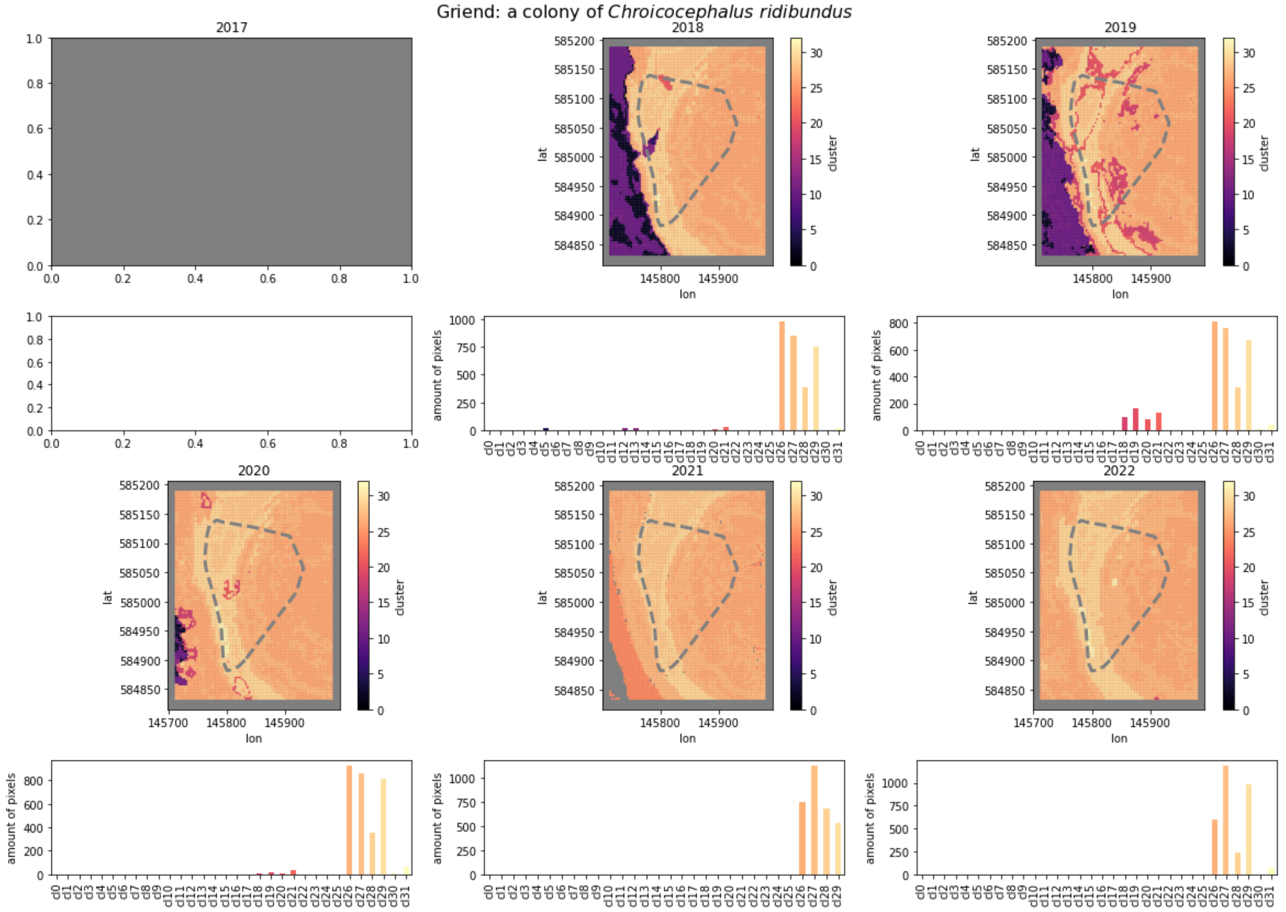


Griend: a colony of *Sterna paradisaea*

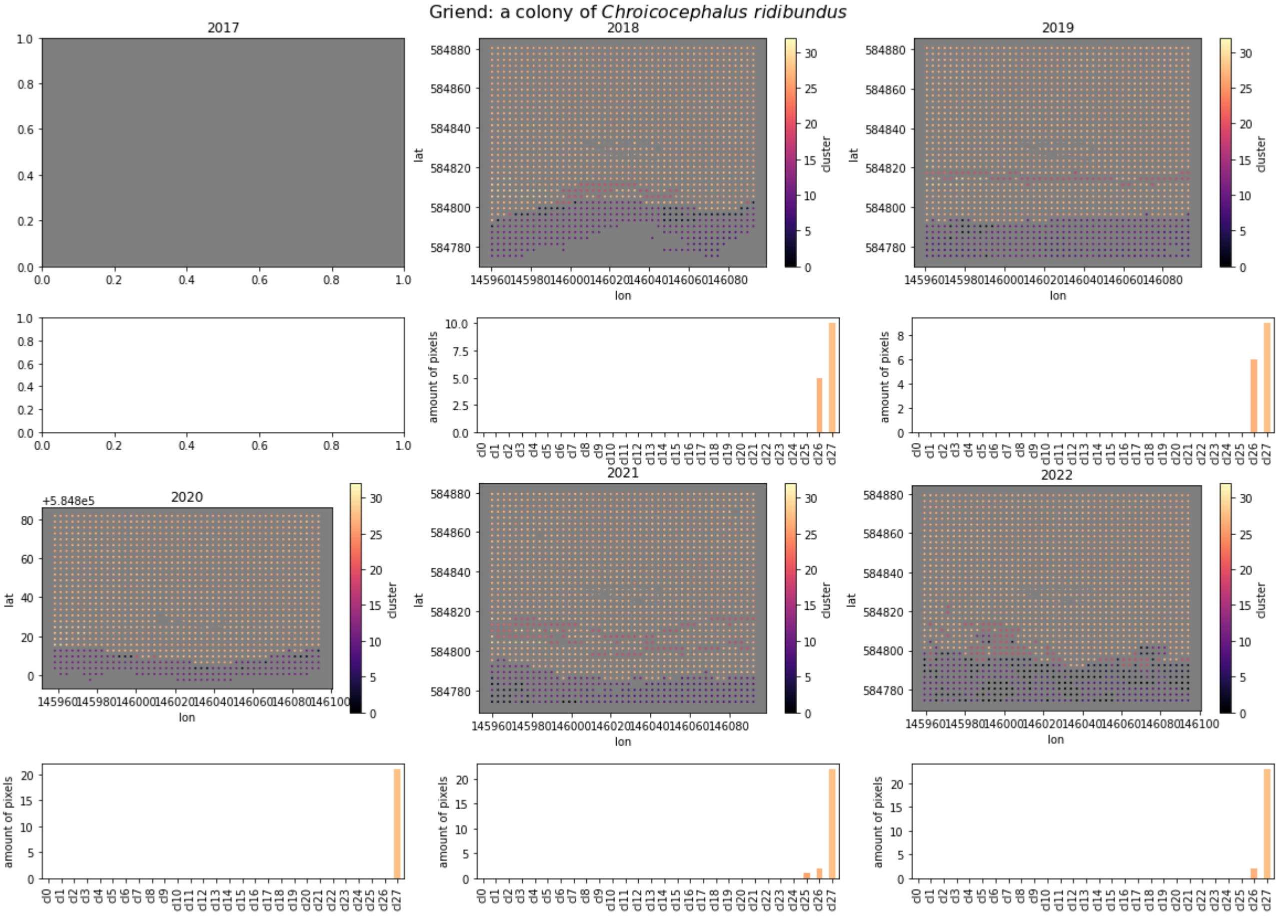


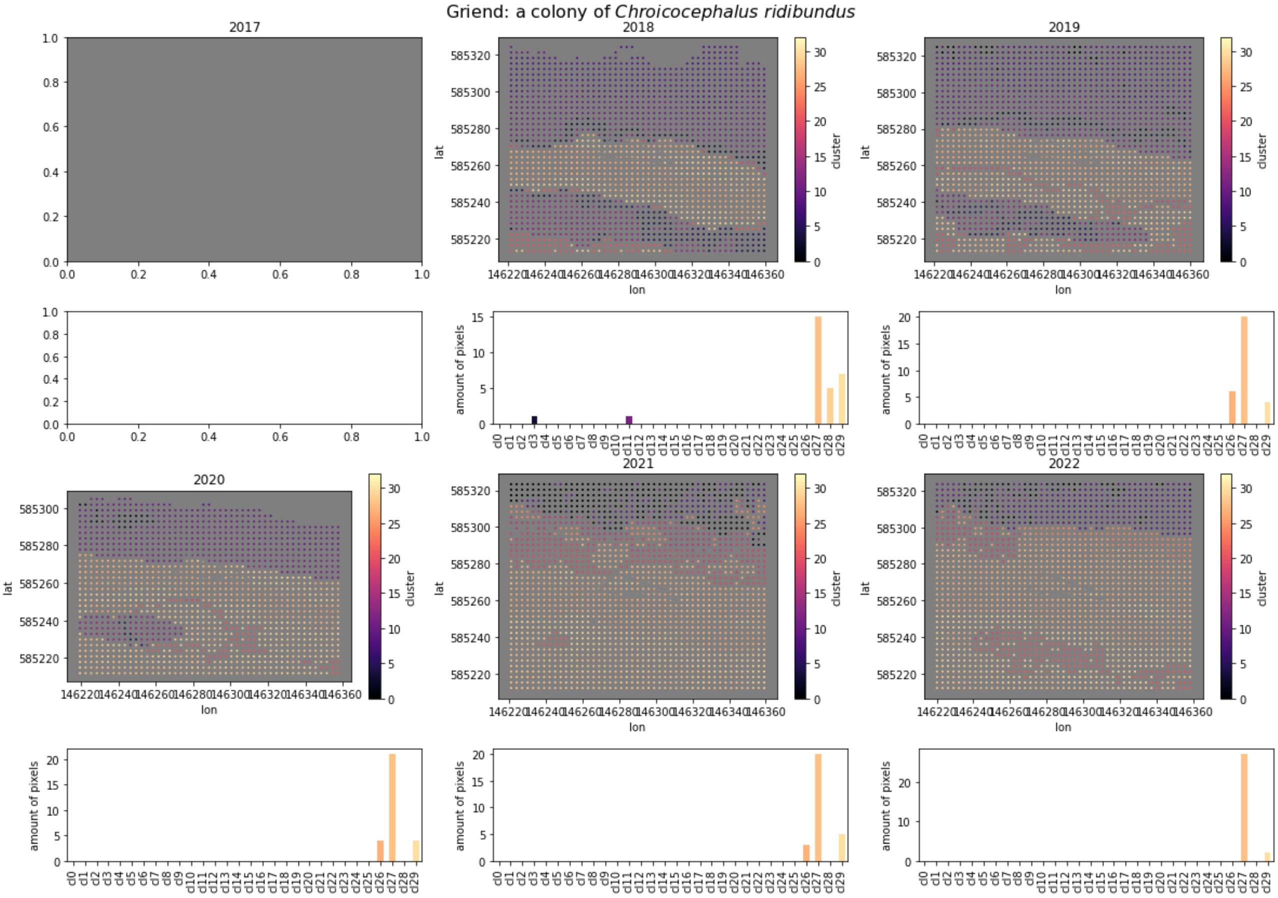


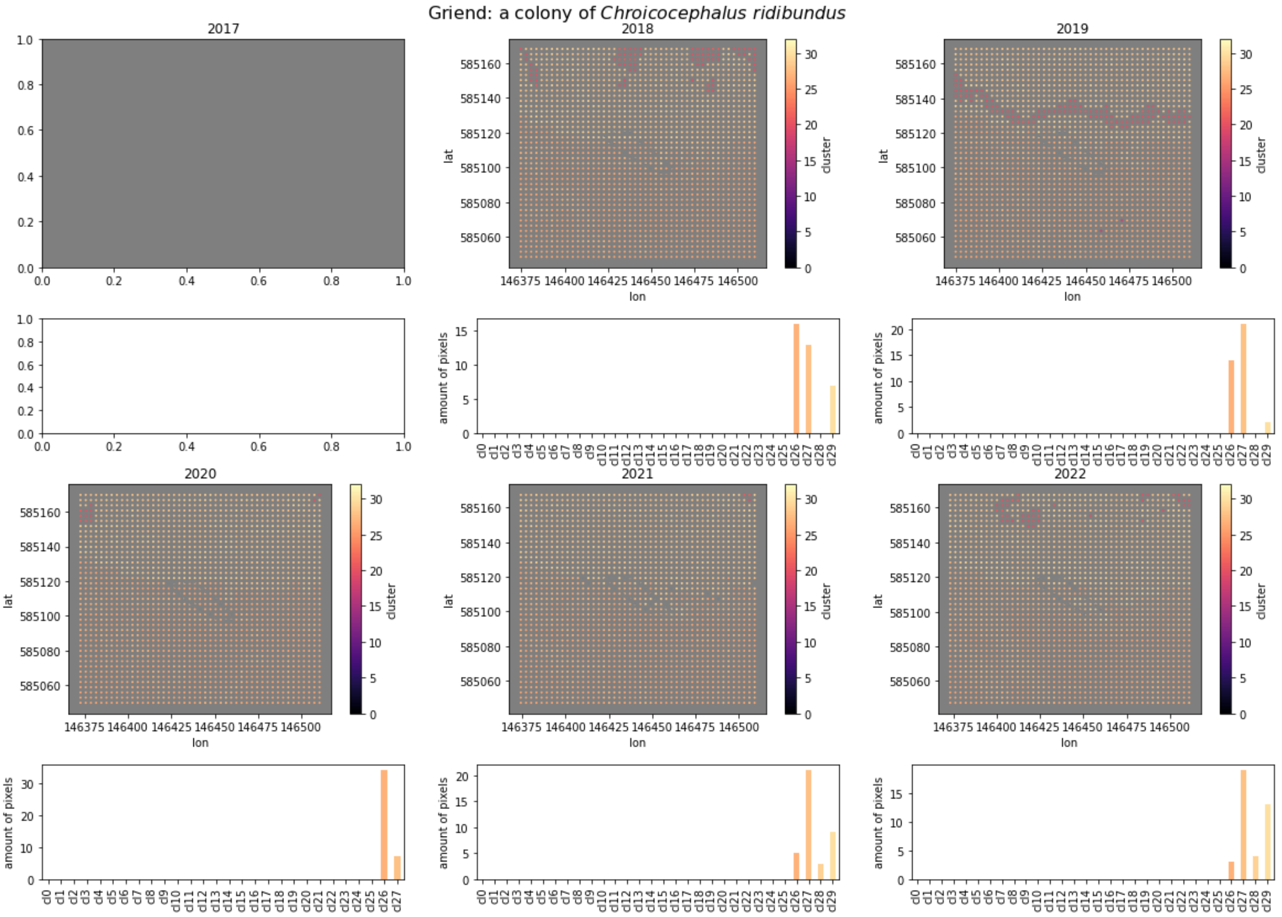
Griend: a colony of *Platalea leucorodia*

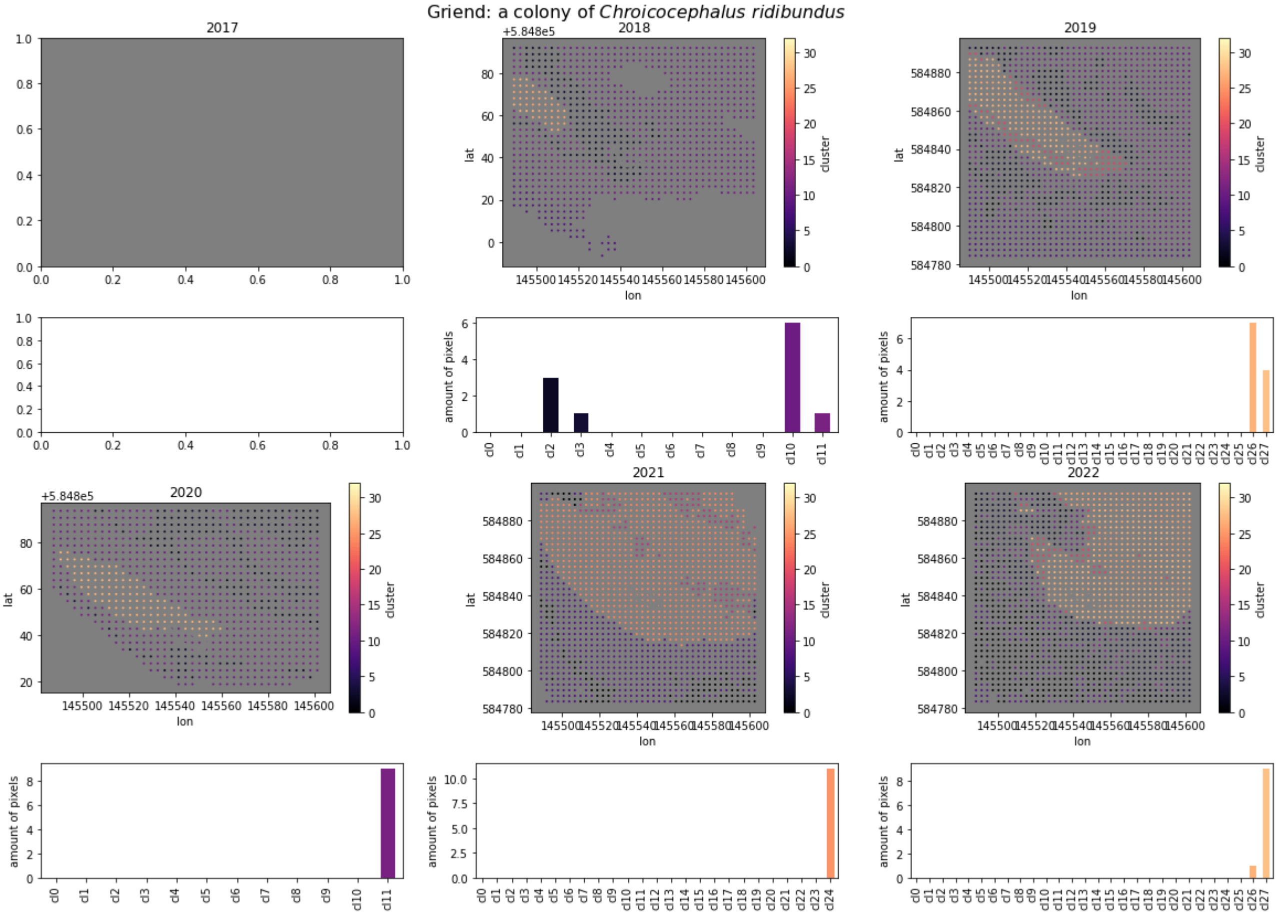


Griend: a colony of *Chroicocephalus ridibundus*

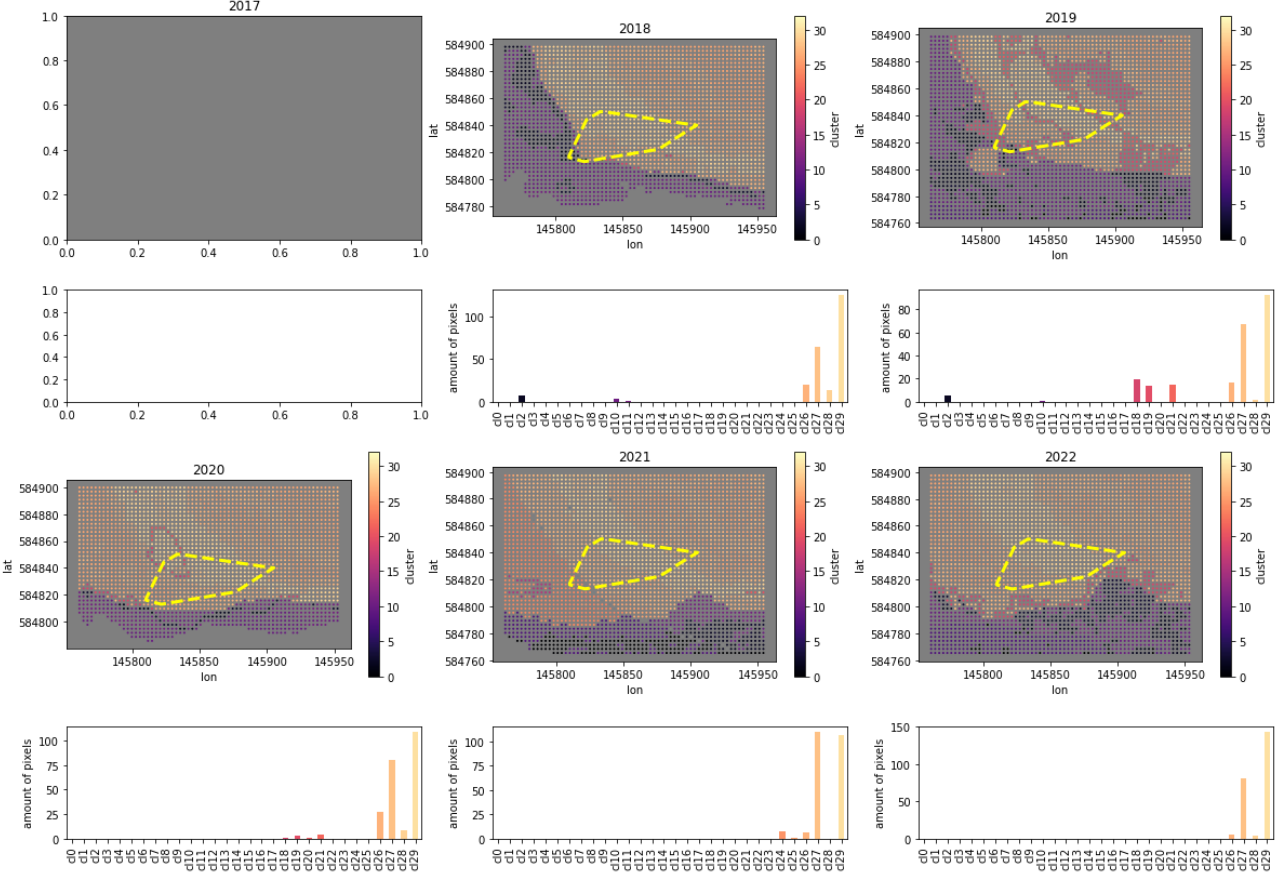

Griend: a colony of *Chroicocephalus ridibundus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
+5.848e5
584880
584860
584840
584820
584800
584780
145960
145980
146000
146020
146040
146060
146080
146100
d0 d1 d2 d3 d4 d5 d6 d7 d8 d9 d10 d11 d12 d13 d14 d15 d16 d17 d18 d19 d20 d21 d22 d23 d24 d25 d26 d27
0 5 10 15 20 25 30


Griend: a colony of *Chroicocephalus ridibundus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
585320
585300
585280
585260
585240
585220
146220
146240
146260
146280
146300
146320
146340
146360
d0 d1 d2 d3 d4 d5 d6 d7 d8 d9 d10 d11 d12 d13 d14 d15 d16 d17 d18 d19 d20 d21 d22 d23 d24 d25 d26 d27 d28 d29
0 5 10 15 20 25 30

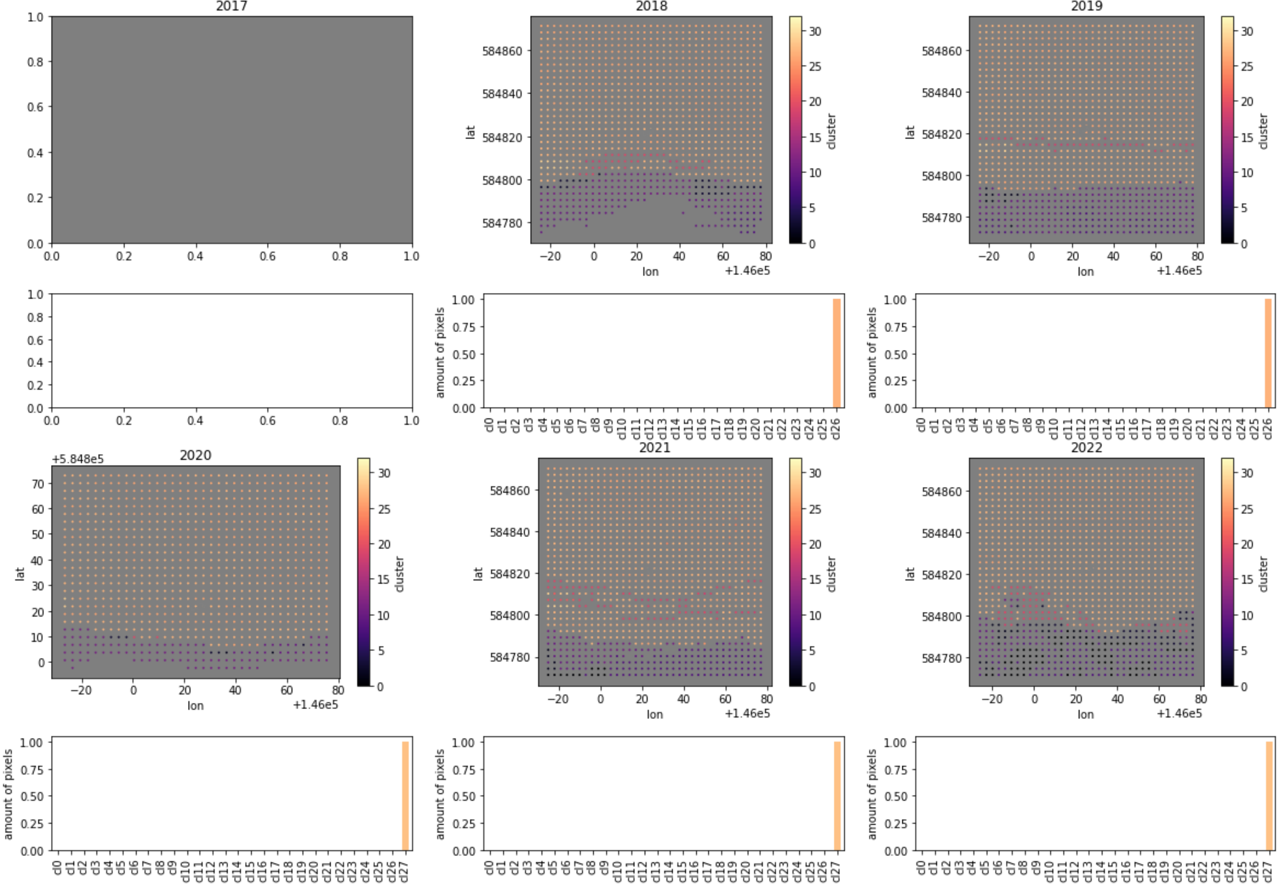

Griend: a colony of *Chroicocephalus ridibundus*
2017
2018
2019
2020
2021
2022
lat
lon
cluster
amount of pixels
146375 146400 146425 146450 146475 146500
585060 585080 585100 585120 585140 585160
d0 … d29

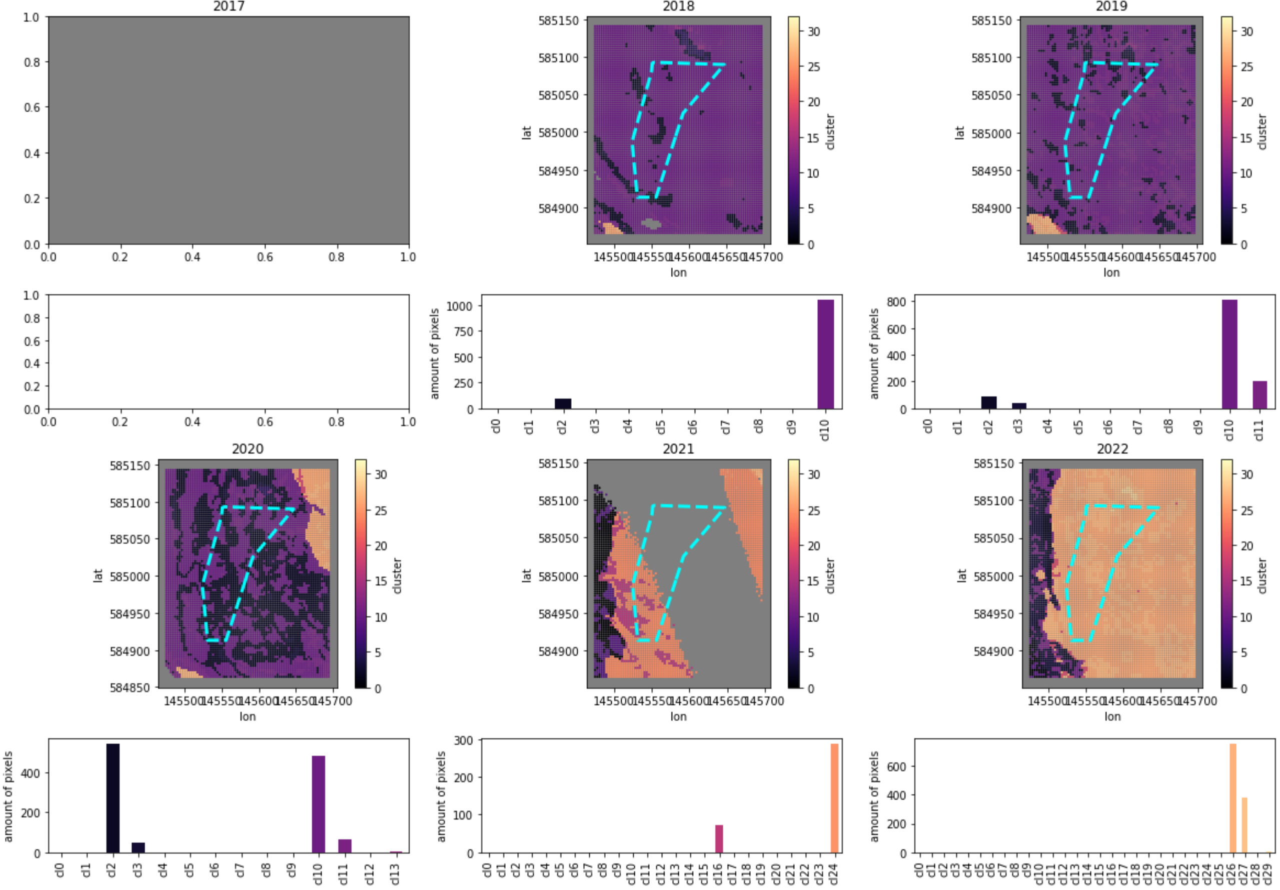

Griend: a colony of *Chroicocephalus ridibundus*
2017
2018
2019
2020
2021
2022
+5.848e5
lat
lon
cluster
amount of pixels
145500 145520 145540 145560 145580 145600
584780 584800 584820 584840 584860 584880
d0 … d27

Griend: a colony of *Thalasseus sandvicensis*

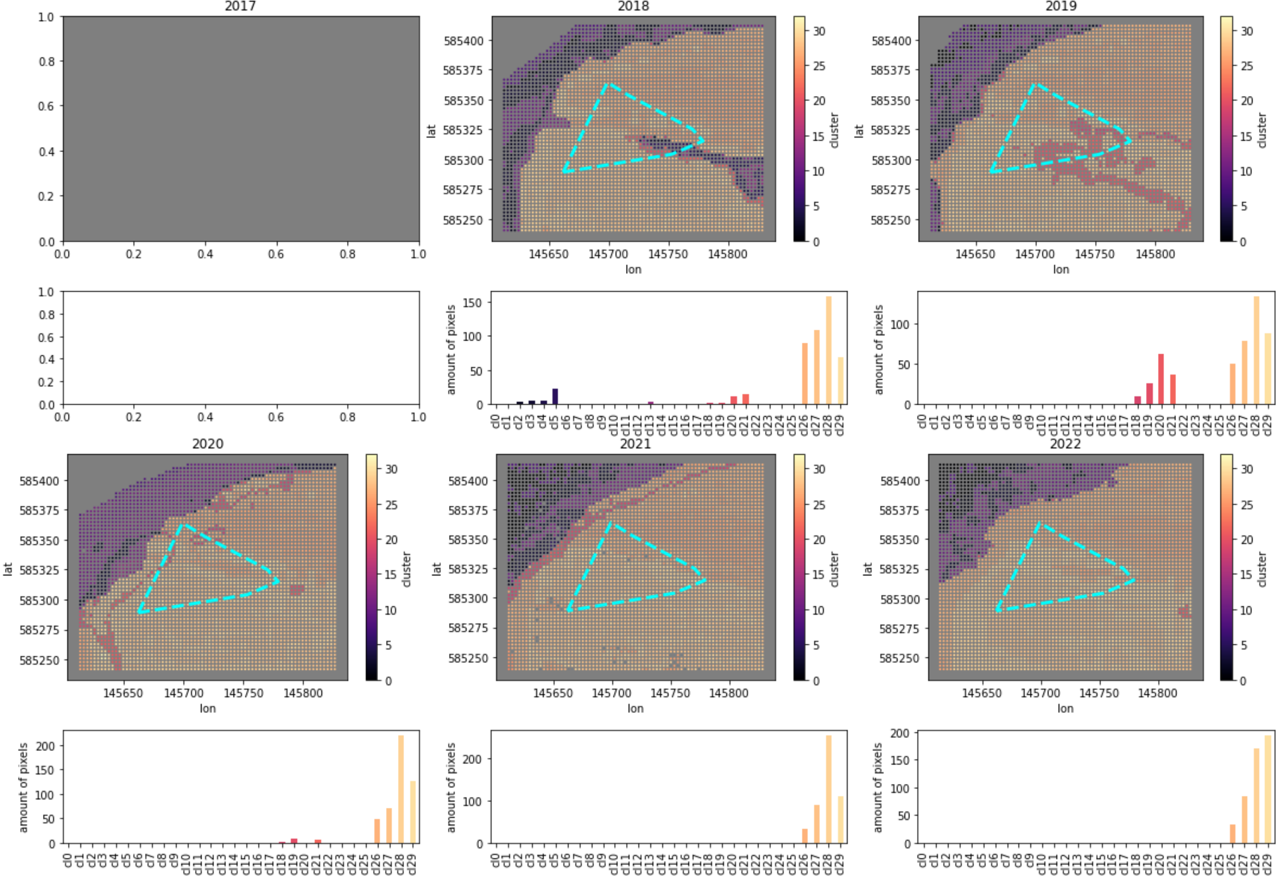


Griend: a colony of *Chroicocephalus ridibundus*

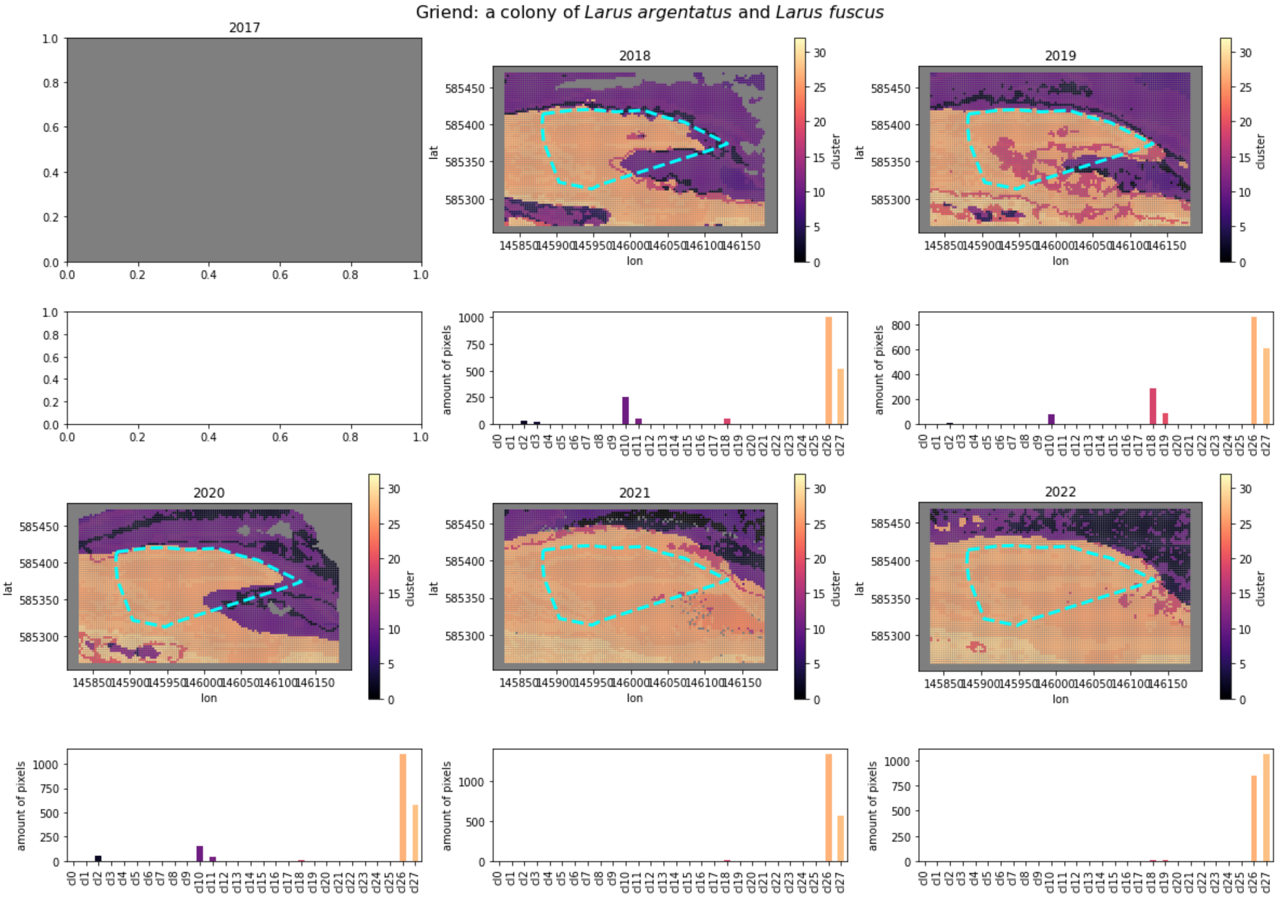


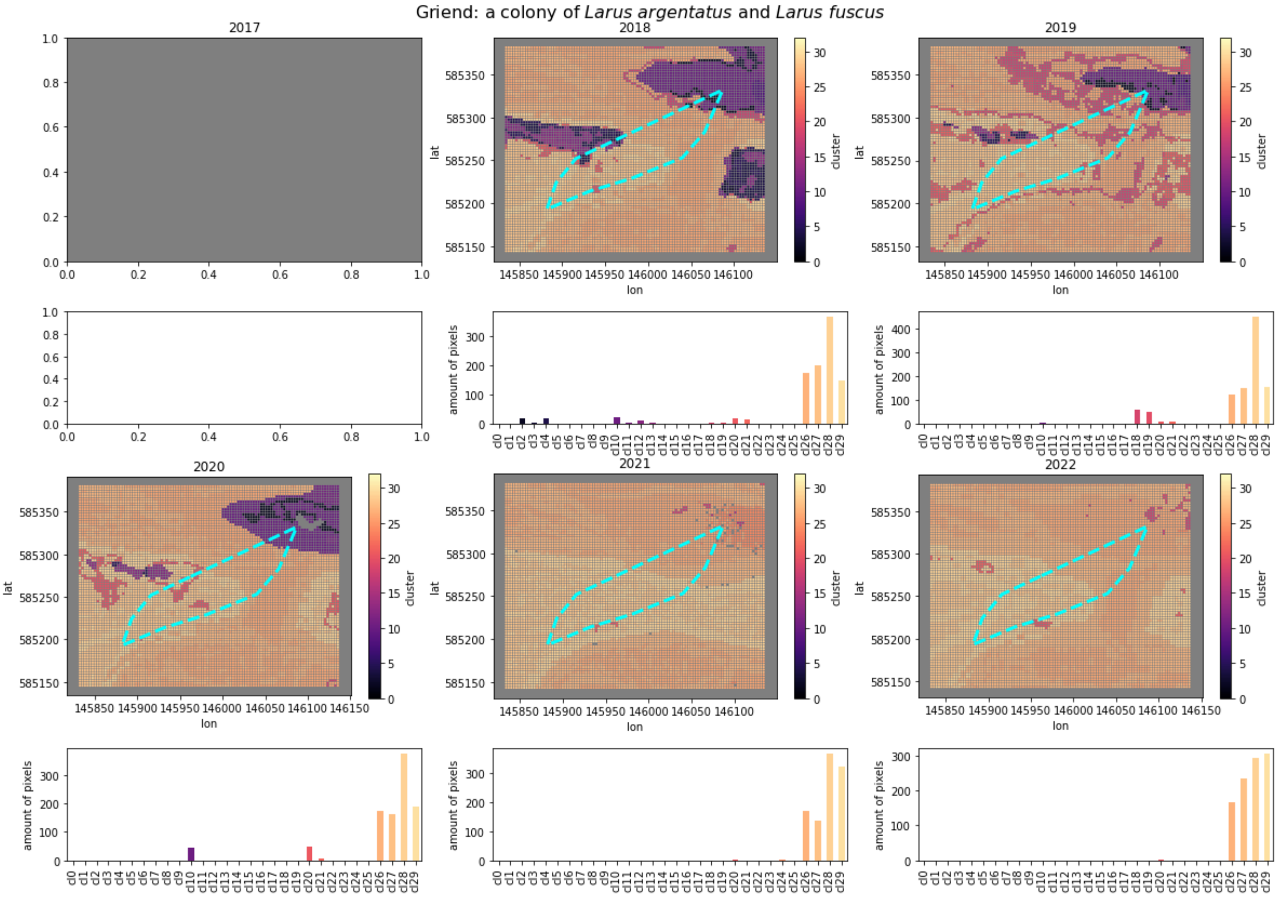


Griend: a colony of *Larus argentatus* and *Larus fuscus*

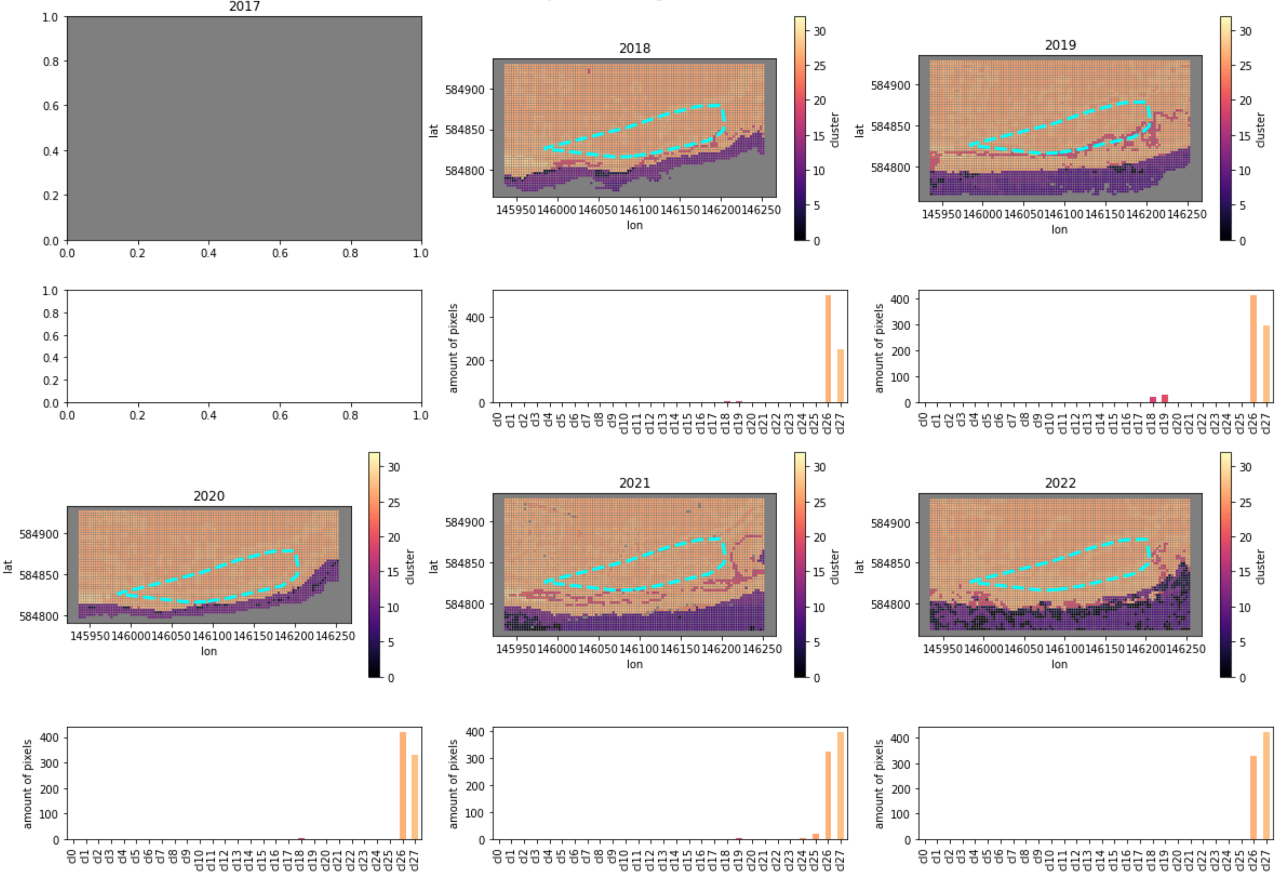


Griend: a colony of *Larus argentatus* and *Larus fuscus*

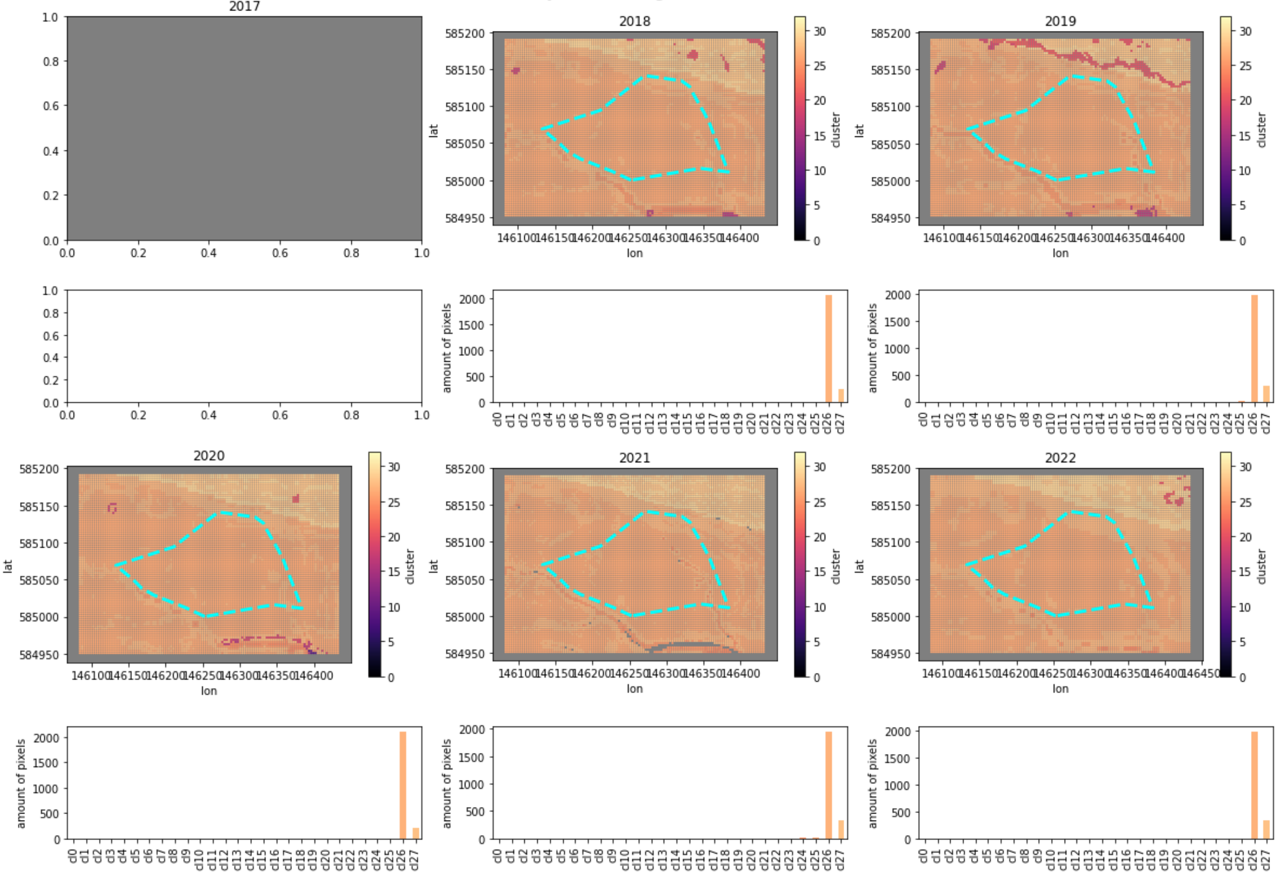

Griend: a colony of *Larus argentatus* and *Larus fuscus*

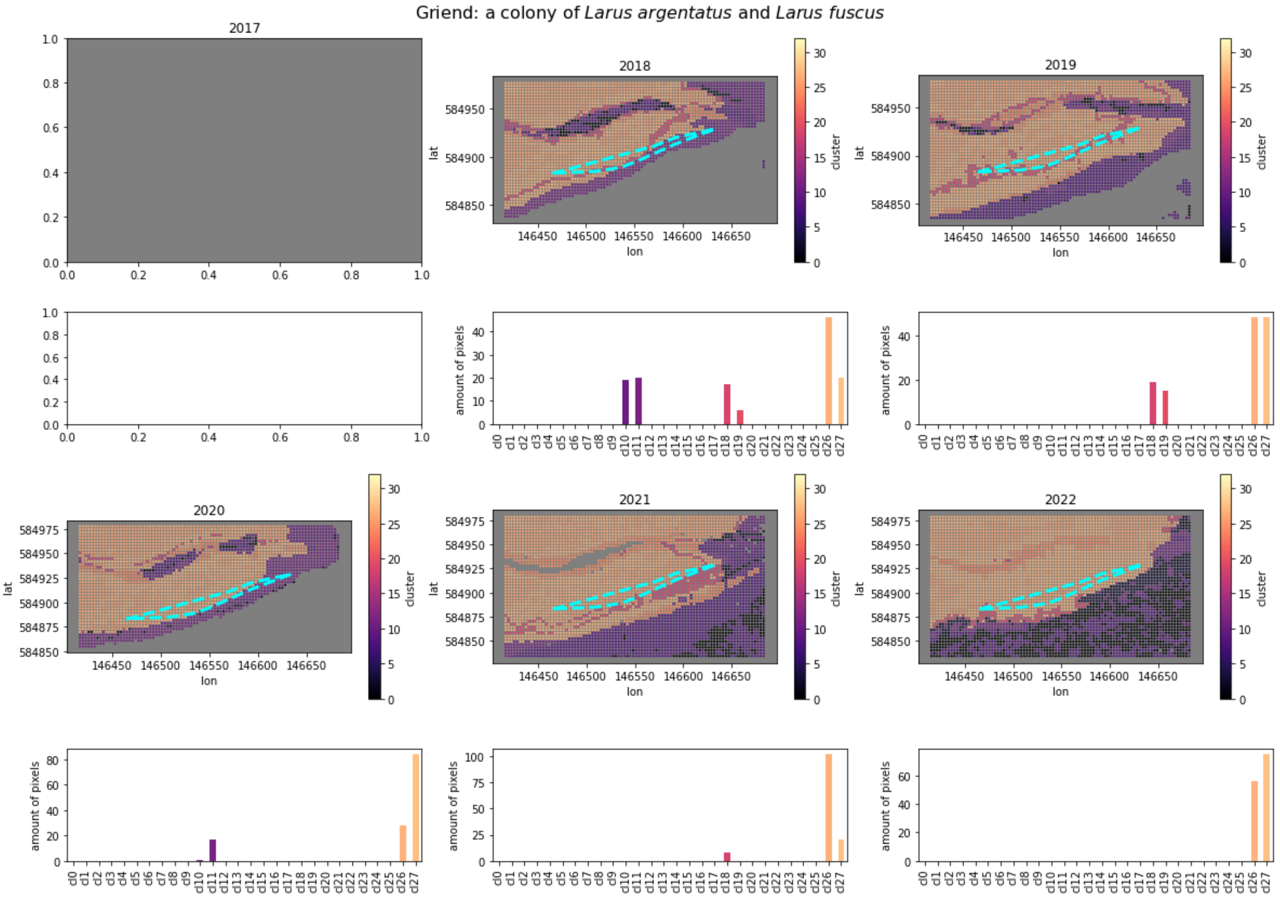

Griend: a colony of *Larus argentatus* and *Larus fuscus*

Griend: a colony of *Larus argentatus* and *Larus fuscus*



Griend: a colony of *Larus argentatus* and *Larus fuscus*





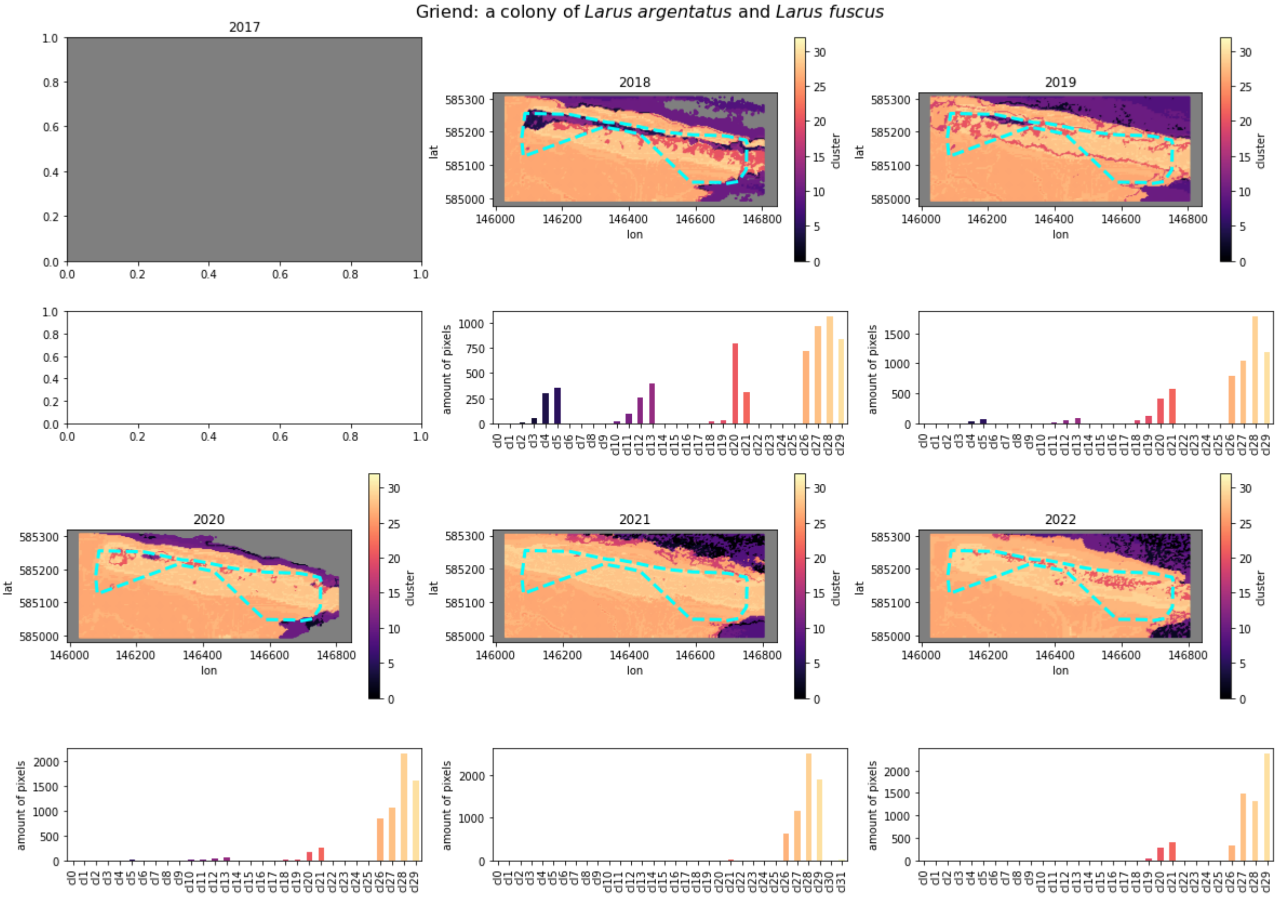
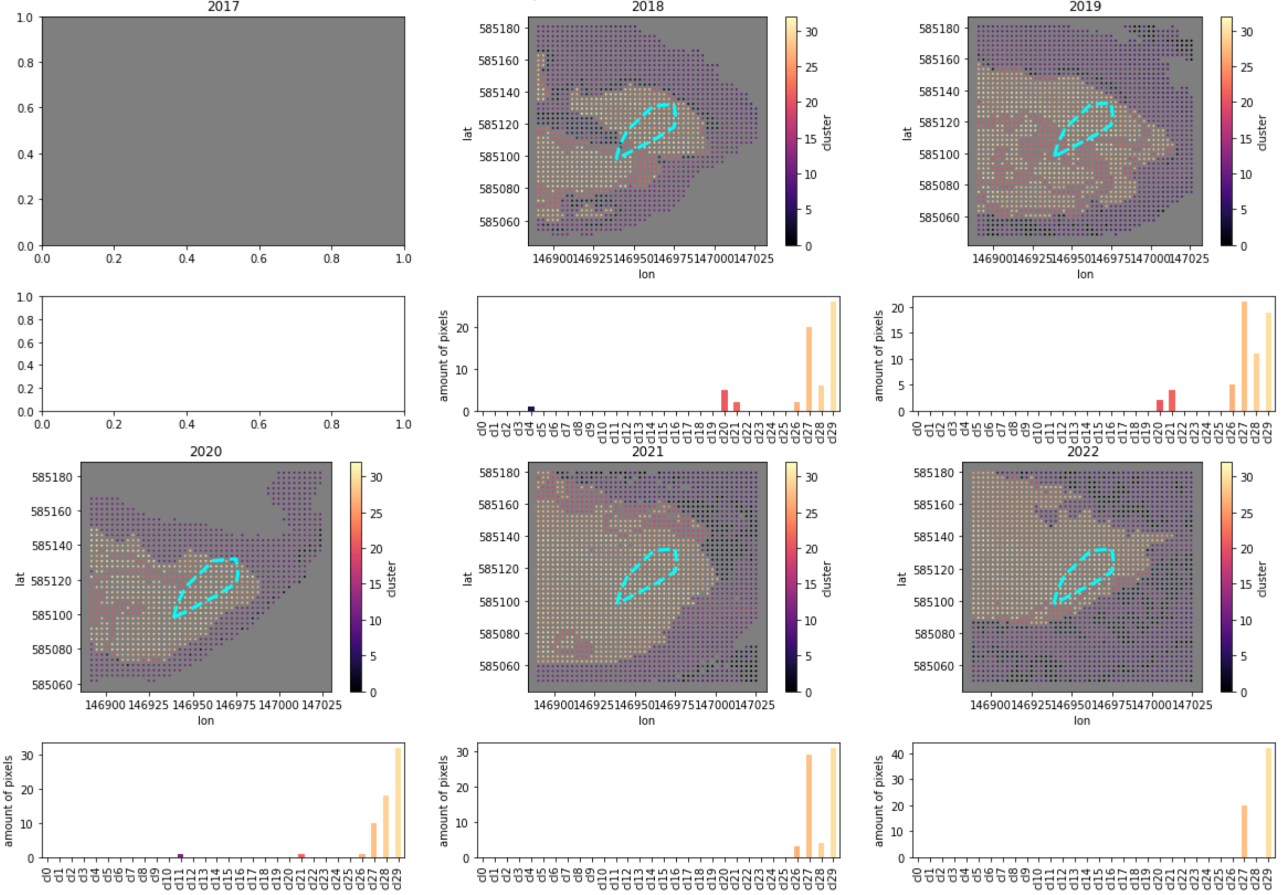
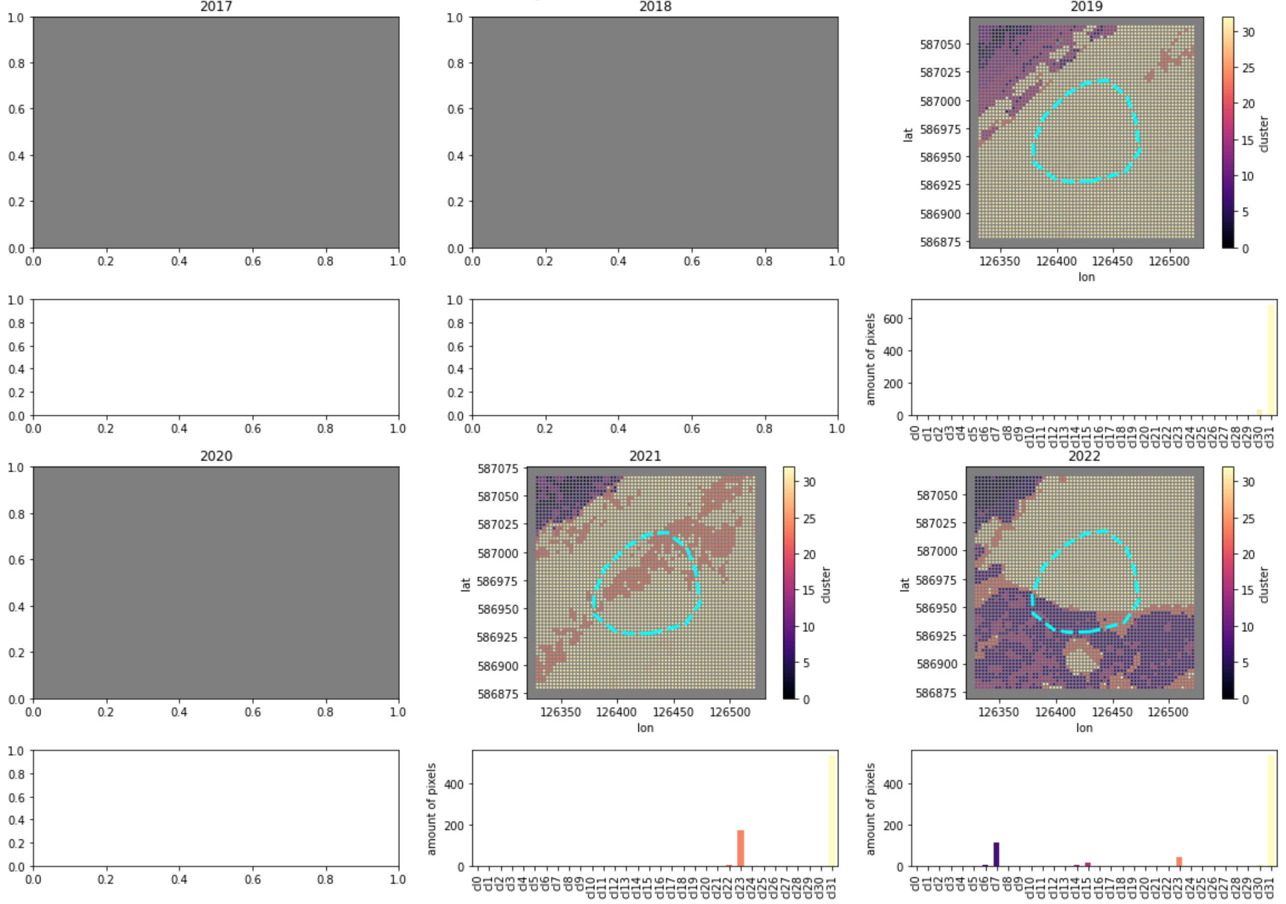


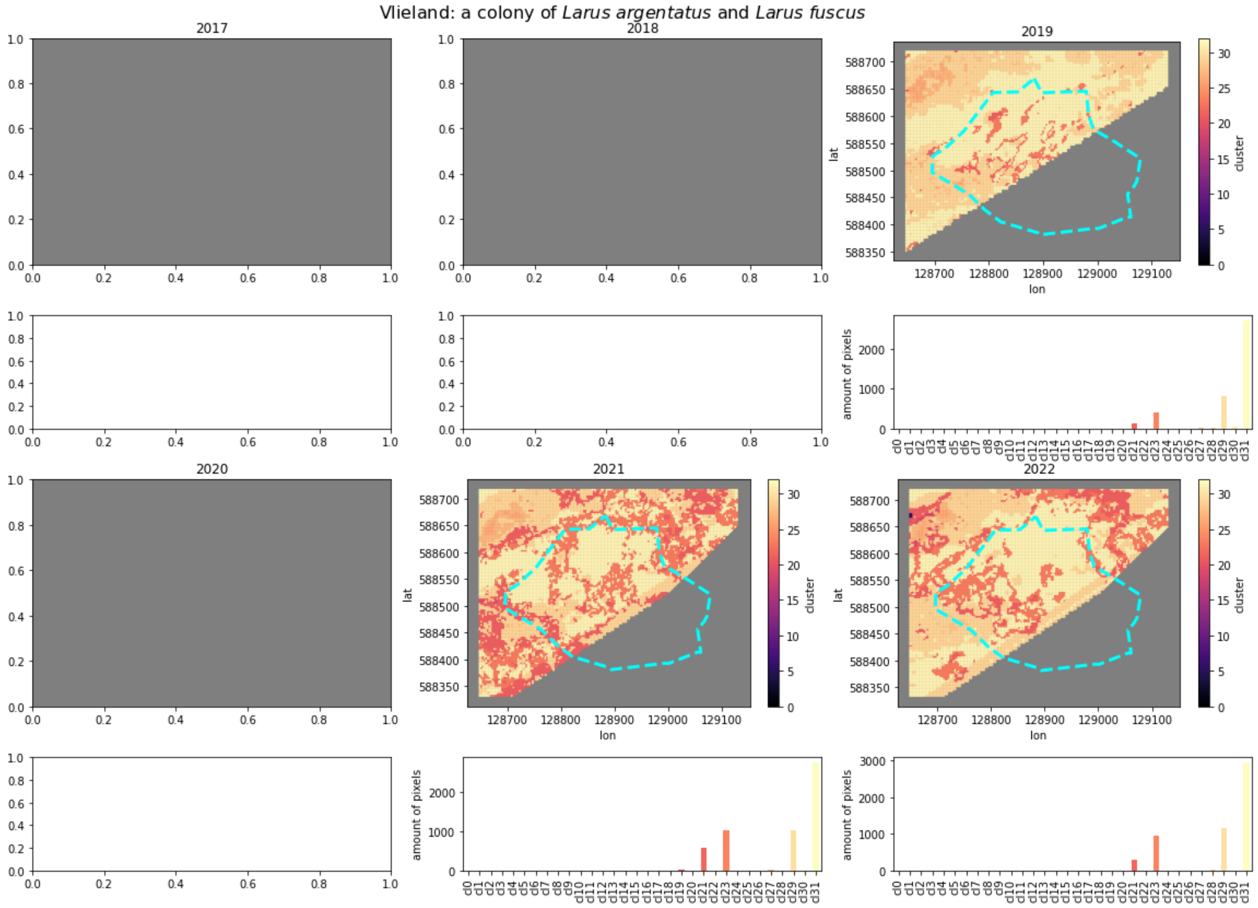
Figure E.9: Distribution of clusters per colony in Griend

Griend: a colony of *Larus argentatus* and *Larus fuscus*



Vlieland: a colony of *Larus argentatus* and *Larus fuscus*





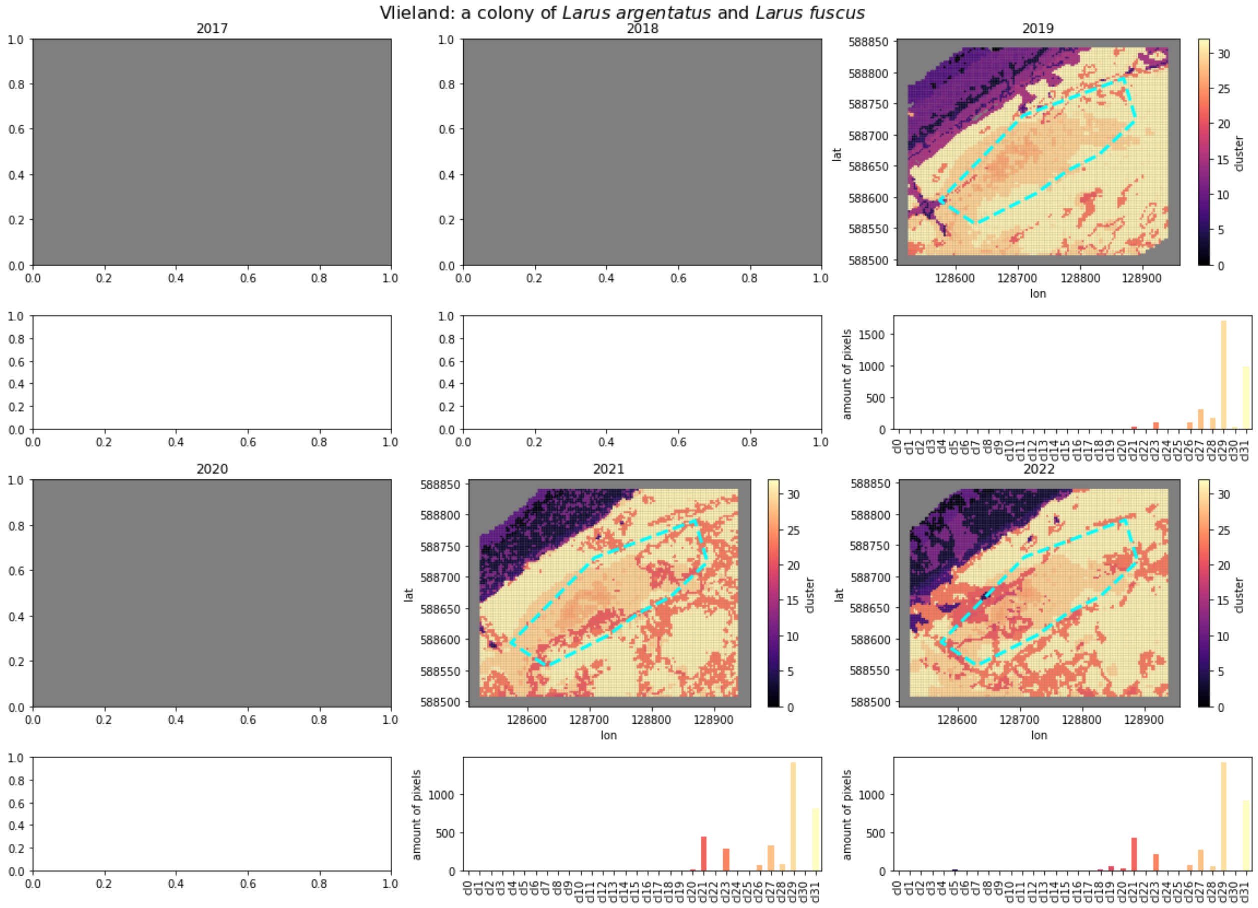
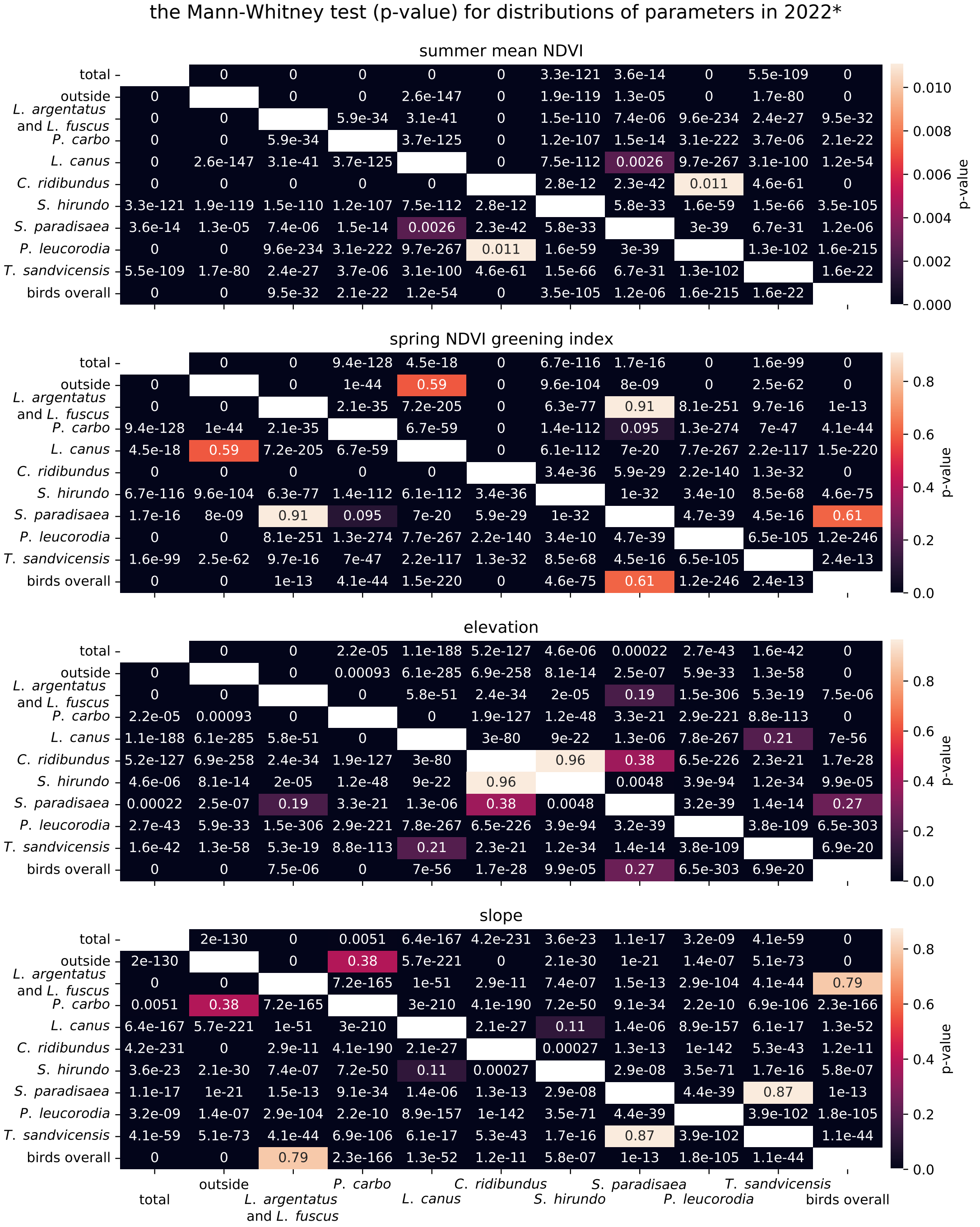


Figure E.10: Distribution of clusters per colony in Vlieland

Appendix F

Full maps with p-values of the Mann-Whitney tests



the Mann-Whitney test (p-value) for distributions of parameters in 2022*

summer mean NDVI

	total	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds overall
total		0	0	0	0	0	3.3e-121	3.6e-14	0	5.5e-109	0
outside	0		0	0	2.6e-147	0	1.9e-119	1.3e-05	0	1.7e-80	0
L. argentatus and *L. fuscus*	0	0		5.9e-34	3.1e-41	0	1.5e-110	7.4e-06	9.6e-234	2.4e-27	9.5e-32
P. carbo	0	0	5.9e-34		3.7e-125	0	1.2e-107	1.5e-14	3.1e-222	3.7e-06	2.1e-22
L. canus	0	2.6e-147	3.1e-41	3.7e-125		0	7.5e-112	0.0026	9.7e-267	3.1e-100	1.2e-54
C. ridibundus	0	0	0	0	0		2.8e-12	2.3e-42	0.011	4.6e-61	0
S. hirundo	3.3e-121	1.9e-119	1.5e-110	1.2e-107	7.5e-112	2.8e-12		5.8e-33	1.6e-59	1.5e-66	3.5e-105
S. paradisaea	3.6e-14	1.3e-05	7.4e-06	1.5e-14	0.0026	2.3e-42	5.8e-33		3e-39	6.7e-31	1.2e-06
P. leucorodia	0	0	9.6e-234	3.1e-222	9.7e-267	0.011	1.6e-59	3e-39		1.3e-102	1.6e-215
T. sandvicensis	5.5e-109	1.7e-80	2.4e-27	3.7e-06	3.1e-100	4.6e-61	1.5e-66	6.7e-31	1.3e-102		1.6e-22
birds overall	0	0	9.5e-32	2.1e-22	1.2e-54	0	3.5e-105	1.2e-06	1.6e-215	1.6e-22	

spring NDVI greening index

	total	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds overall
total		0	0	9.4e-128	4.5e-18	0	6.7e-116	1.7e-16	0	1.6e-99	0
outside	0		0	1e-44	0.59	0	9.6e-104	8e-09	0	2.5e-62	0
L. argentatus and *L. fuscus*	0	0		2.1e-35	7.2e-205	0	6.3e-77	0.91	8.1e-251	9.7e-16	1e-13
P. carbo	9.4e-128	1e-44	2.1e-35		6.7e-59	0	1.4e-112	0.095	1.3e-274	7e-47	4.1e-44
L. canus	4.5e-18	0.59	7.2e-205	6.7e-59		0	6.1e-112	7e-20	7.7e-267	2.2e-117	1.5e-220
C. ridibundus	0	0	0	0	0		3.4e-36	5.9e-29	2.2e-140	1.3e-32	0
S. hirundo	6.7e-116	9.6e-104	6.3e-77	1.4e-112	6.1e-112	3.4e-36		1e-32	3.4e-10	8.5e-68	4.6e-75
S. paradisaea	1.7e-16	8e-09	0.91	0.095	7e-20	5.9e-29	1e-32		4.7e-39	4.5e-16	0.61
P. leucorodia	0	0	8.1e-251	1.3e-274	7.7e-267	2.2e-140	3.4e-10	4.7e-39		6.5e-105	1.2e-246
T. sandvicensis	1.6e-99	2.5e-62	9.7e-16	7e-47	2.2e-117	1.3e-32	8.5e-68	4.5e-16	6.5e-105		2.4e-13
birds overall	0	0	1e-13	4.1e-44	1.5e-220	0	4.6e-75	0.61	1.2e-246	2.4e-13	

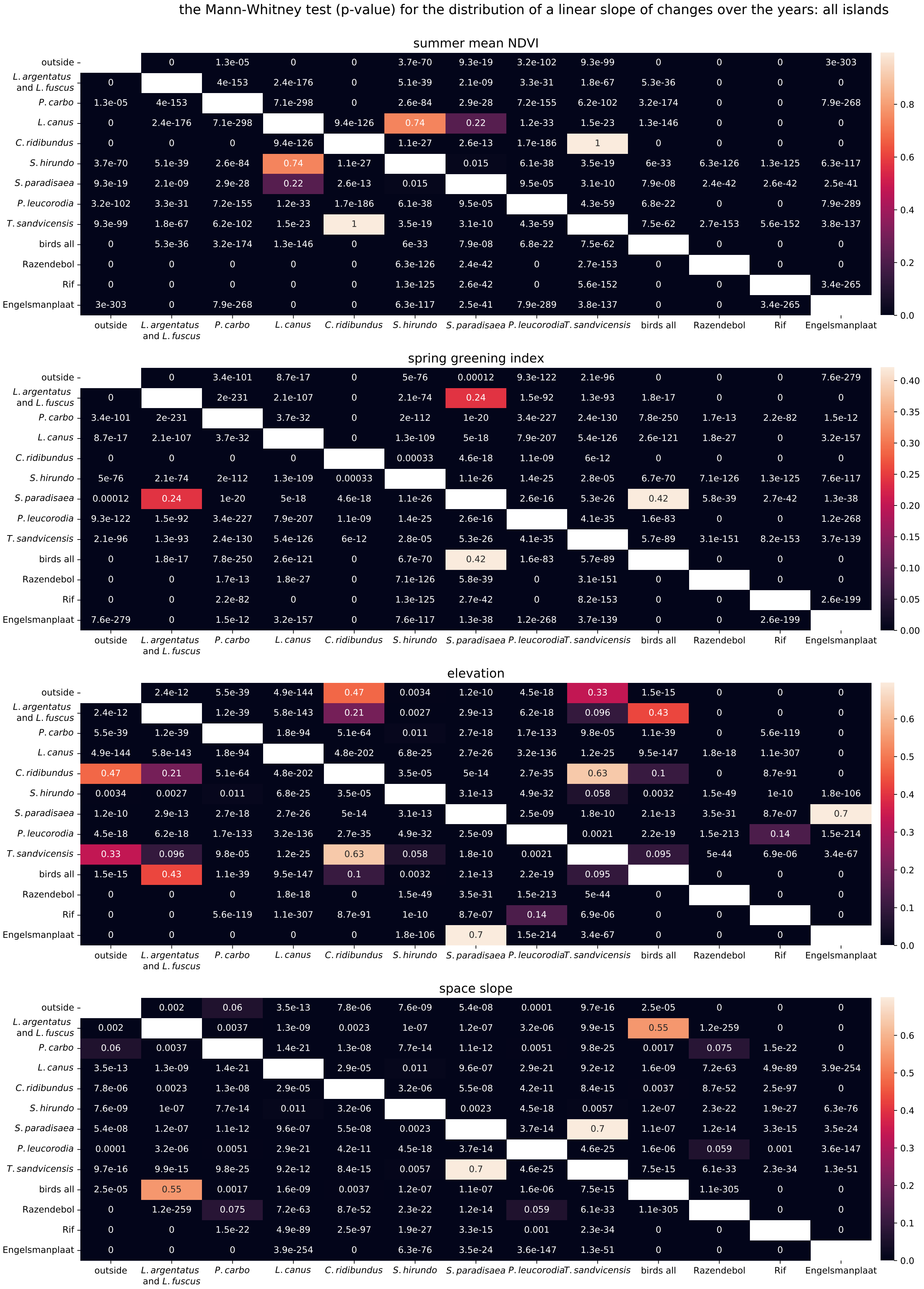
elevation

	total	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds overall
total		0	0	2.2e-05	1.1e-188	5.2e-127	4.6e-06	0.00022	2.7e-43	1.6e-42	0
outside	0		0	0.00093	6.1e-285	6.9e-258	8.1e-14	2.5e-07	5.9e-33	1.3e-58	0
L. argentatus and *L. fuscus*	0	0		0	5.8e-51	2.4e-34	2e-05	0.19	1.5e-306	5.3e-19	7.5e-06
P. carbo	2.2e-05	0.00093	0		0	1.9e-127	1.2e-48	3.3e-21	2.9e-221	8.8e-113	0
L. canus	1.1e-188	6.1e-285	5.8e-51	0		3e-80	9e-22	1.3e-06	7.8e-267	0.21	7e-56
C. ridibundus	5.2e-127	6.9e-258	2.4e-34	1.9e-127	3e-80		0.96	0.38	6.5e-226	2.3e-21	1.7e-28
S. hirundo	4.6e-06	8.1e-14	2e-05	1.2e-48	9e-22	0.96		0.0048	3.9e-94	1.2e-34	9.9e-05
S. paradisaea	0.00022	2.5e-07	0.19	3.3e-21	1.3e-06	0.38	0.0048		3.2e-39	1.4e-14	0.27
P. leucorodia	2.7e-43	5.9e-33	1.5e-306	2.9e-221	7.8e-267	6.5e-226	3.9e-94	3.2e-39		3.8e-109	6.5e-303
T. sandvicensis	1.6e-42	1.3e-58	5.3e-19	8.8e-113	0.21	2.3e-21	1.2e-34	1.4e-14	3.8e-109		6.9e-20
birds overall	0	0	7.5e-06	0	7e-56	1.7e-28	9.9e-05	0.27	6.5e-303	6.9e-20	

slope

	total	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds overall
total		2e-130	0	0.0051	6.4e-167	4.2e-231	3.6e-23	1.1e-17	3.2e-09	4.1e-59	0
outside	2e-130		0	0.38	5.7e-221	0	2.1e-30	1e-21	1.4e-07	5.1e-73	0
L. argentatus and *L. fuscus*	0	0		7.2e-165	1e-51	2.9e-11	7.4e-07	1.5e-13	2.9e-104	4.1e-44	0.79
P. carbo	0.0051	0.38	7.2e-165		3e-210	4.1e-190	7.2e-50	9.1e-34	2.2e-10	6.9e-106	2.3e-166
L. canus	6.4e-167	5.7e-221	1e-51	3e-210		2.1e-27	0.11	1.4e-06	8.9e-157	6.1e-17	1.3e-52
C. ridibundus	4.2e-231	0	2.9e-11	4.1e-190	2.1e-27		0.00027	1.3e-13	1e-142	5.3e-43	1.2e-11
S. hirundo	3.6e-23	2.1e-30	7.4e-07	7.2e-50	0.11	0.00027		2.9e-08	3.5e-71	1.7e-16	5.8e-07
S. paradisaea	1.1e-17	1e-21	1.5e-13	9.1e-34	1.4e-06	1.3e-13	2.9e-08		4.4e-39	0.87	1e-13
P. leucorodia	3.2e-09	1.4e-07	2.9e-104	2.2e-10	8.9e-157	1e-142	3.5e-71	4.4e-39		3.9e-102	1.8e-105
T. sandvicensis	4.1e-59	5.1e-73	4.1e-44	6.9e-106	6.1e-17	5.3e-43	1.7e-16	0.87	3.9e-102		1.1e-44
birds overall	0	0	0.79	2.3e-166	1.3e-52	1.2e-11	5.8e-07	1e-13	1.8e-105	1.1e-44	

Figure F.1: P-values from the Mann-Whitney tests for all four environmental features in 2022 within and outside of bird colonies as well as per species



the Mann-Whitney test (p-value) for the distribution of a linear slope of changes over the years: all islands

summer mean NDVI

	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds all	Razendebol	Rif	Engelsmanplaat
outside		0	1.3e-05	0	0	3.7e-70	9.3e-19	3.2e-102	9.3e-99	0	0	0	3e-303
L. argentatus and *L. fuscus*	0		4e-153	2.4e-176	0	5.1e-39	2.1e-09	3.3e-31	1.8e-67	5.3e-36	0	0	0
P. carbo	1.3e-05	4e-153		7.1e-298	0	2.6e-84	2.9e-28	7.2e-155	6.2e-102	3.2e-174	0	0	7.9e-268
L. canus	0	2.4e-176	7.1e-298		9.4e-126	0.74	0.22	1.2e-33	1.5e-23	1.3e-146	0	0	0
C. ridibundus	0	0	0	9.4e-126		1.1e-27	2.6e-13	1.7e-186	1	0	0	0	0
S. hirundo	3.7e-70	5.1e-39	2.6e-84	0.74	1.1e-27		0.015	6.1e-38	3.5e-19	6e-33	6.3e-126	1.3e-125	6.3e-117
S. paradisaea	9.3e-19	2.1e-09	2.9e-28	0.22	2.6e-13	0.015		9.5e-05	3.1e-10	7.9e-08	2.4e-42	2.6e-42	2.5e-41
P. leucorodia	3.2e-102	3.3e-31	7.2e-155	1.2e-33	1.7e-186	6.1e-38	9.5e-05		4.3e-59	6.8e-22	0	0	7.9e-289
T. sandvicensis	9.3e-99	1.8e-67	6.2e-102	1.5e-23	1	3.5e-19	3.1e-10	4.3e-59		7.5e-62	2.7e-153	5.6e-152	3.8e-137
birds all	0	5.3e-36	3.2e-174	1.3e-146	0	6e-33	7.9e-08	6.8e-22	7.5e-62		0	0	0
Razendebol	0	0	0	0	0	6.3e-126	2.4e-42	0	2.7e-153	0		0	0
Rif	0	0	0	0	0	1.3e-125	2.6e-42	0	5.6e-152	0	0		3.4e-265
Engelsmanplaat	3e-303	0	7.9e-268	0	0	6.3e-117	2.5e-41	7.9e-289	3.8e-137	0	0	3.4e-265	

spring greening index

	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds all	Razendebol	Rif	Engelsmanplaat
outside		0	3.4e-101	8.7e-17	0	5e-76	0.00012	9.3e-122	2.1e-96	0	0	0	7.6e-279
L. argentatus and *L. fuscus*	0		2e-231	2.1e-107	0	2.1e-74	0.24	1.5e-92	1.3e-93	1.8e-17	0	0	0
P. carbo	3.4e-101	2e-231		3.7e-32	0	2e-112	1e-20	3.4e-227	2.4e-130	7.8e-250	1.7e-13	2.2e-82	1.5e-12
L. canus	8.7e-17	2.1e-107	3.7e-32		0	1.3e-109	5e-18	7.9e-207	5.4e-126	2.6e-121	1.8e-27	0	3.2e-157
C. ridibundus	0	0	0	0		0.00033	4.6e-18	1.1e-09	6e-12	0	0	0	0
S. hirundo	5e-76	2.1e-74	2e-112	1.3e-109	0.00033		1.1e-26	1.4e-25	2.8e-05	6.7e-70	7.1e-126	1.3e-125	7.6e-117
S. paradisaea	0.00012	0.24	1e-20	5e-18	4.6e-18	1.1e-26		2.6e-16	5.3e-26	0.42	5.8e-39	2.7e-42	1.3e-38
P. leucorodia	9.3e-122	1.5e-92	3.4e-227	7.9e-207	1.1e-09	1.4e-25	2.6e-16		4.1e-35	1.6e-83	0	0	1.2e-268
T. sandvicensis	2.1e-96	1.3e-93	2.4e-130	5.4e-126	6e-12	2.8e-05	5.3e-26	4.1e-35		5.7e-89	3.1e-151	8.2e-153	3.7e-139
birds all	0	1.8e-17	7.8e-250	2.6e-121	0	6.7e-70	0.42	1.6e-83	5.7e-89		0	0	0
Razendebol	0	0	1.7e-13	1.8e-27	0	7.1e-126	5.8e-39	0	3.1e-151	0		0	0
Rif	0	0	2.2e-82	0	0	1.3e-125	2.7e-42	0	8.2e-153	0	0		2.6e-199
Engelsmanplaat	7.6e-279	0	1.5e-12	3.2e-157	0	7.6e-117	1.3e-38	1.2e-268	3.7e-139	0	0	2.6e-199	

elevation

	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds all	Razendebol	Rif	Engelsmanplaat
outside		2.4e-12	5.5e-39	4.9e-144	0.47	0.0034	1.2e-10	4.5e-18	0.33	1.5e-15	0	0	0
L. argentatus and *L. fuscus*	2.4e-12		1.2e-39	5.8e-143	0.21	0.0027	2.9e-13	6.2e-18	0.096	0.43	0	0	0
P. carbo	5.5e-39	1.2e-39		1.8e-94	5.1e-64	0.011	2.7e-18	1.7e-133	9.8e-05	1.1e-39	0	5.6e-119	0
L. canus	4.9e-144	5.8e-143	1.8e-94		4.8e-202	6.8e-25	2.7e-26	3.2e-136	1.2e-25	9.5e-147	1.8e-18	1.1e-307	0
C. ridibundus	0.47	0.21	5.1e-64	4.8e-202		3.5e-05	5e-14	2.7e-35	0.63	0.1	0	8.7e-91	0
S. hirundo	0.0034	0.0027	0.011	6.8e-25	3.5e-05		3.1e-13	4.9e-32	0.058	0.0032	1.5e-49	1e-10	1.8e-106
S. paradisaea	1.2e-10	2.9e-13	2.7e-18	2.7e-26	5e-14	3.1e-13		2.5e-09	1.8e-10	2.1e-13	3.5e-31	8.7e-07	0.7
P. leucorodia	4.5e-18	6.2e-18	1.7e-133	3.2e-136	2.7e-35	4.9e-32	2.5e-09		0.0021	2.2e-19	1.5e-213	0.14	1.5e-214
T. sandvicensis	0.33	0.096	9.8e-05	1.2e-25	0.63	0.058	1.8e-10	0.0021		0.095	5e-44	6.9e-06	3.4e-67
birds all	1.5e-15	0.43	1.1e-39	9.5e-147	0.1	0.0032	2.1e-13	2.2e-19	0.095		0	0	0
Razendebol	0	0	0	1.8e-18	0	1.5e-49	3.5e-31	1.5e-213	5e-44	0		0	0
Rif	0	0	5.6e-119	1.1e-307	8.7e-91	1e-10	8.7e-07	0.14	6.9e-06	0	0		0
Engelsmanplaat	0	0	0	0	0	1.8e-106	0.7	1.5e-214	3.4e-67	0	0	0	

space slope

	outside	*L. argentatus* and *L. fuscus*	*P. carbo*	*L. canus*	*C. ridibundus*	*S. hirundo*	*S. paradisaea*	*P. leucorodia*	*T. sandvicensis*	birds all	Razendebol	Rif	Engelsmanplaat
outside		0.002	0.06	3.5e-13	7.8e-06	7.6e-09	5.4e-08	0.0001	9.7e-16	2.5e-05	0	0	0
L. argentatus and *L. fuscus*	0.002		0.0037	1.3e-09	0.0023	1e-07	1.2e-07	3.2e-06	9.9e-15	0.55	1.2e-259	0	0
P. carbo	0.06	0.0037		1.4e-21	1.3e-08	7.7e-14	1.1e-12	0.0051	9.8e-25	0.0017	0.075	1.5e-22	0
L. canus	3.5e-13	1.3e-09	1.4e-21		2.9e-05	0.011	9.6e-07	2.9e-21	9.2e-12	1.6e-09	7.2e-63	4.9e-89	3.9e-254
C. ridibundus	7.8e-06	0.0023	1.3e-08	2.9e-05		3.2e-06	5.5e-08	4.2e-11	8.4e-15	0.0037	8.7e-52	2.5e-97	0
S. hirundo	7.6e-09	1e-07	7.7e-14	0.011	3.2e-06		0.0023	4.5e-18	0.0057	1.2e-07	2.3e-22	1.9e-27	6.3e-76
S. paradisaea	5.4e-08	1.2e-07	1.1e-12	9.6e-07	5.5e-08	0.0023		3.7e-14	0.7	1.1e-07	1.2e-14	3.3e-15	3.5e-24
P. leucorodia	0.0001	3.2e-06	0.0051	2.9e-21	4.2e-11	4.5e-18	3.7e-14		4.6e-25	1.6e-06	0.059	0.001	3.6e-147
T. sandvicensis	9.7e-16	9.9e-15	9.8e-25	9.2e-12	8.4e-15	0.0057	0.7	4.6e-25		7.5e-15	6.1e-33	2.3e-34	1.3e-51
birds all	2.5e-05	0.55	0.0017	1.6e-09	0.0037	1.2e-07	1.1e-07	1.6e-06	7.5e-15		1.1e-305	0	0
Razendebol	0	1.2e-259	0.075	7.2e-63	8.7e-52	2.3e-22	1.2e-14	0.059	6.1e-33	1.1e-305		0	0
Rif	0	0	1.5e-22	4.9e-89	2.5e-97	1.9e-27	3.3e-15	0.001	2.3e-34	0	0		0
Engelsmanplaat	0	0	0	3.9e-254	0	6.3e-76	3.5e-24	3.6e-147	1.3e-51	0	0	0	

Figure F.2: P-values from the Mann-Whitney tests or a linear annual time coefficient within and outside of bird colonies as well as per species in 2017-2022

Appendix G

Distribution of parameters in the year of observation

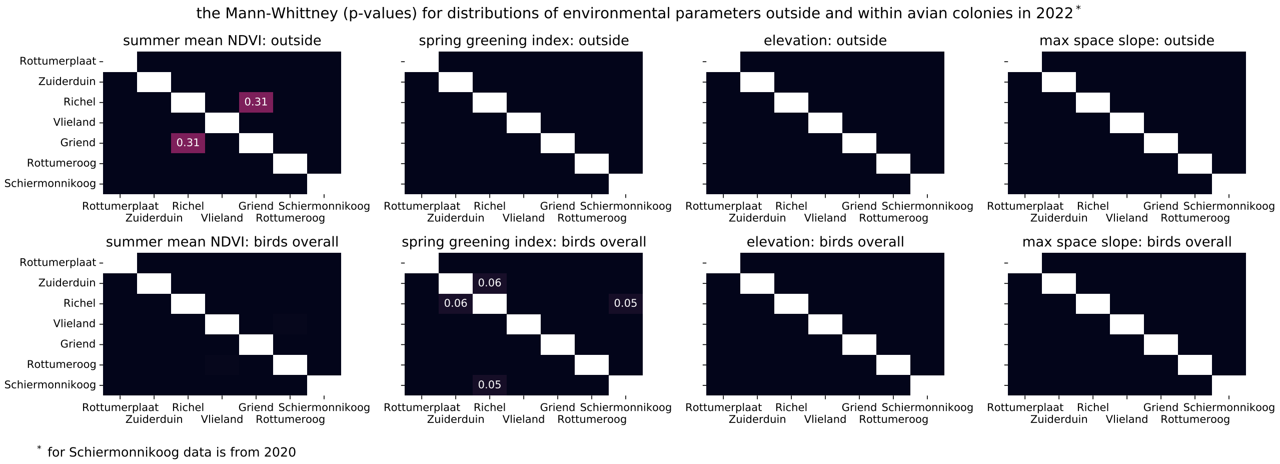


Figure G.1: The full p-value maps for within and outside of avian colonies in the year of observation

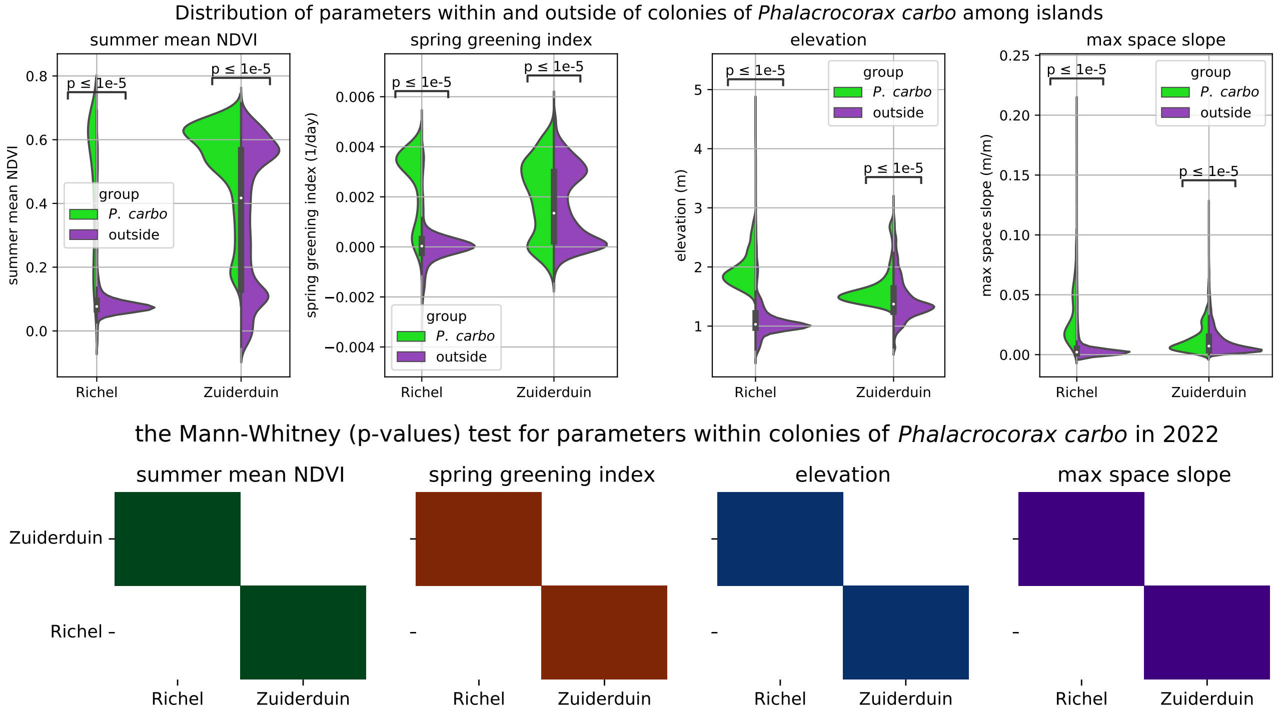
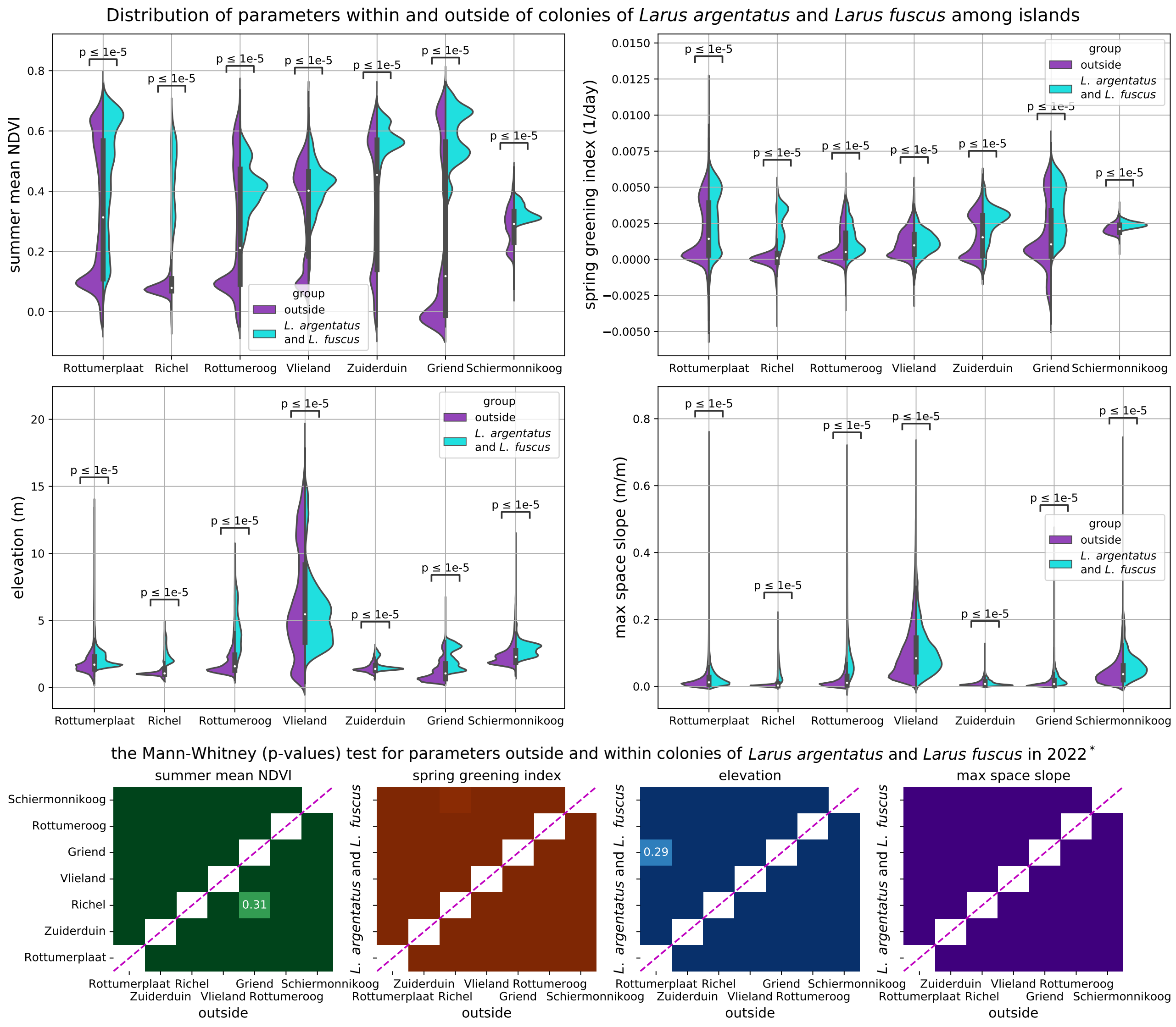


Figure G.2: Distributions of environmental parameter per island for outside areas and places with birds in the year of observation for *Phalacrocorax carbo* as well as the Mann-Whitney test between different islands. All p-values are marked if they are higher than 0.05



* for Schiermonnikoog data is from 2020

Figure G.3: Parameter per island for outside and within colonies of *L. argentatus* and *L. fuscus* in the year of observation and p-value maps within two groups. All p-values are marked if they are higher than 0.05

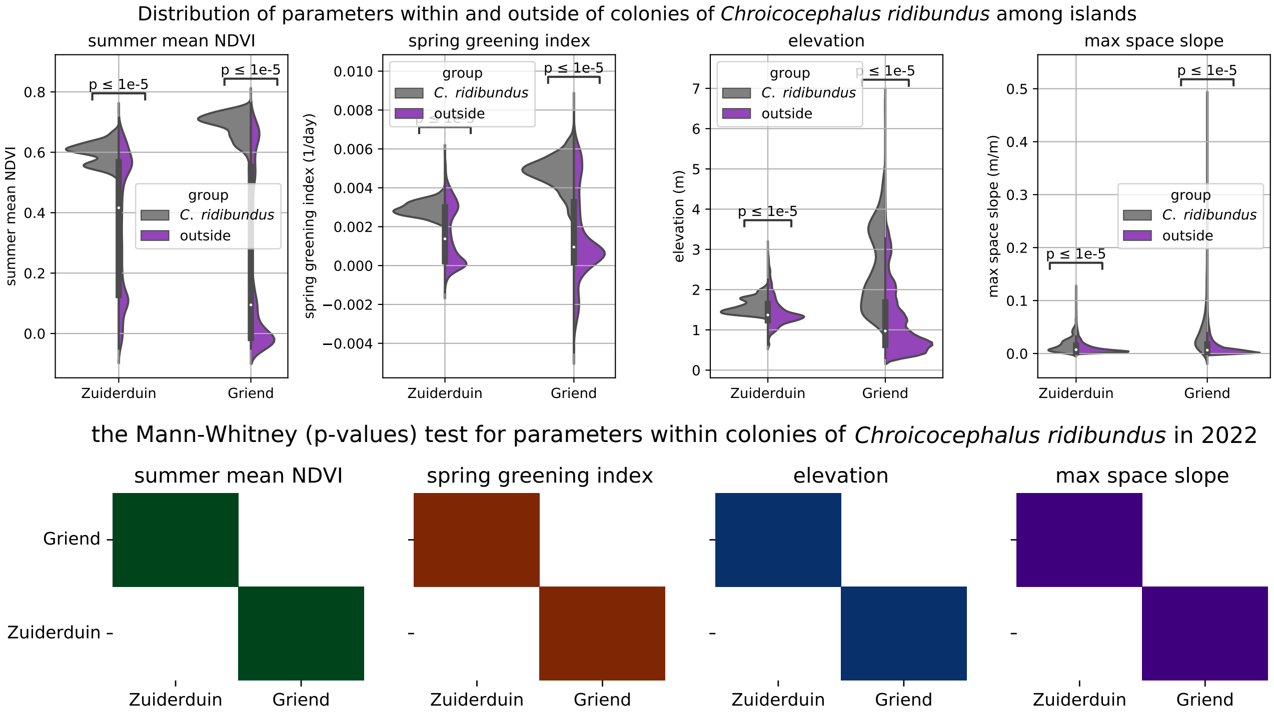


Figure G.4: Distributions of environmental parameter per island for outside areas and places with birds in the year of observation for *Chroicocephalus ridibundus* as well as the Mann-Whitney test between different islands. All p-values are marked if they are higher than 0.05

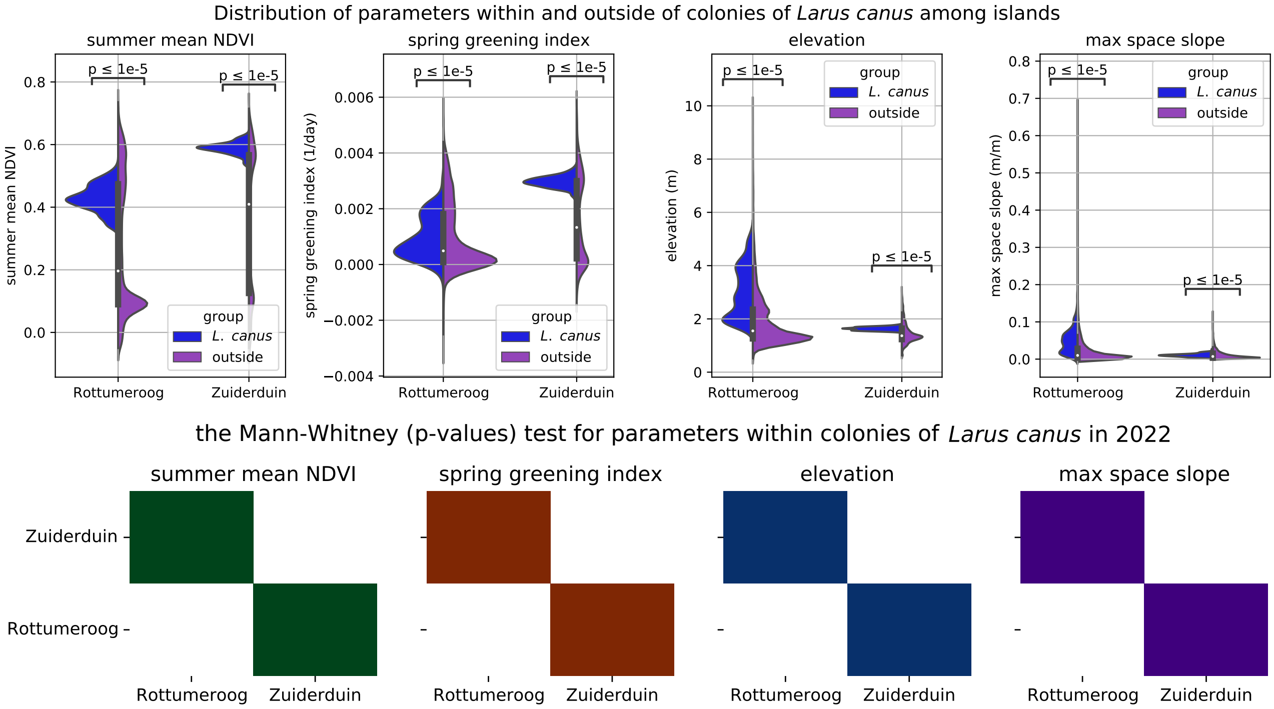


Figure G.5: Distributions of environmental parameter per island for outside areas and places with birds in the year of observation for *Larus canus* as well as the Mann-Whitney test between different islands. All p-values are marked if they are higher than 0.05

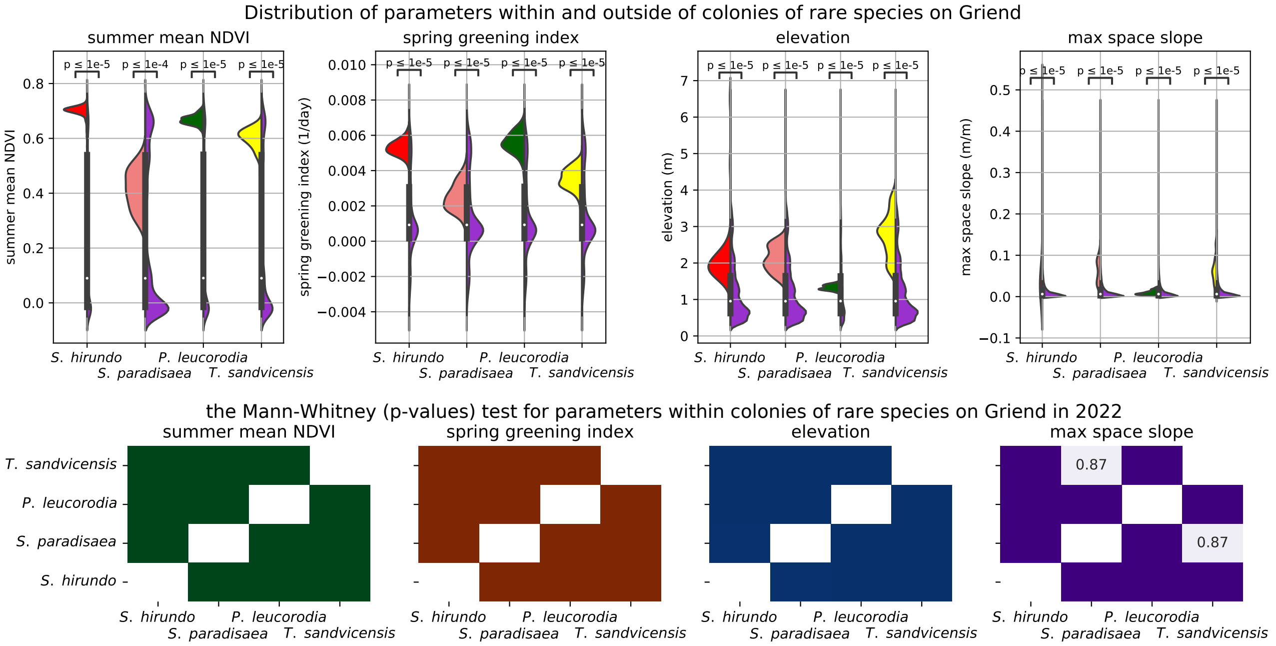
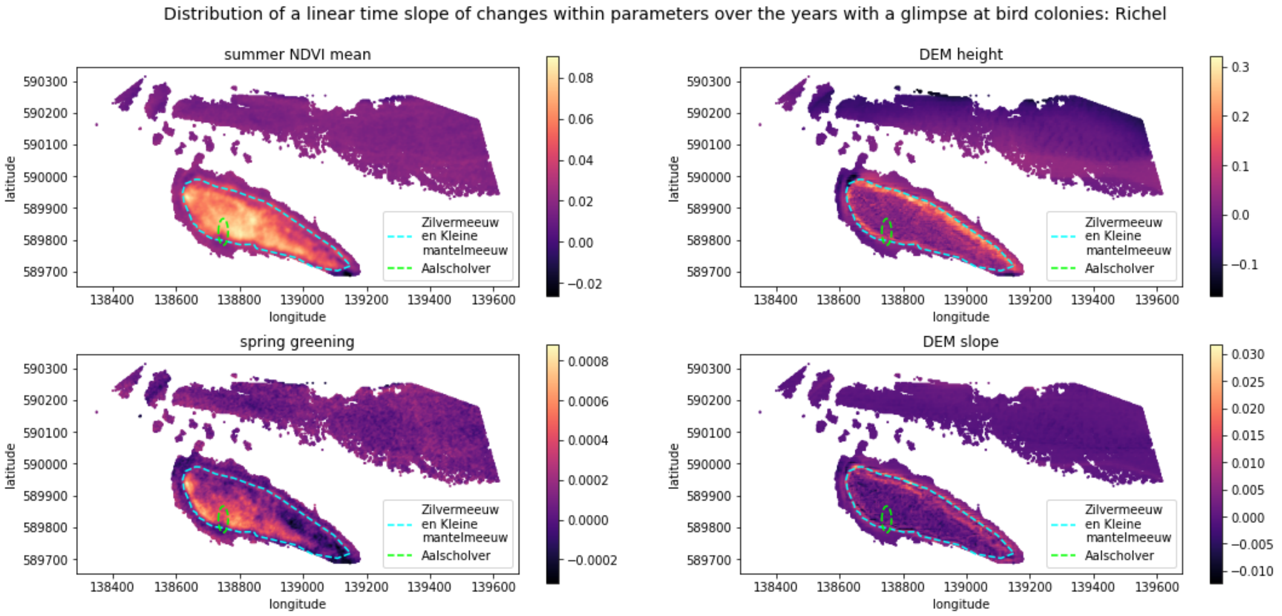


Figure G.6: Distributions of environmental parameter per island for outside areas and places with birds in the year of observation for rare species on Griend as well as the Mann-Whitney test between different species. All p-values are marked if they are higher than 0.05

Appendix H

Distribution of a linear time coefficient

H.1 Linear time coefficients: maps



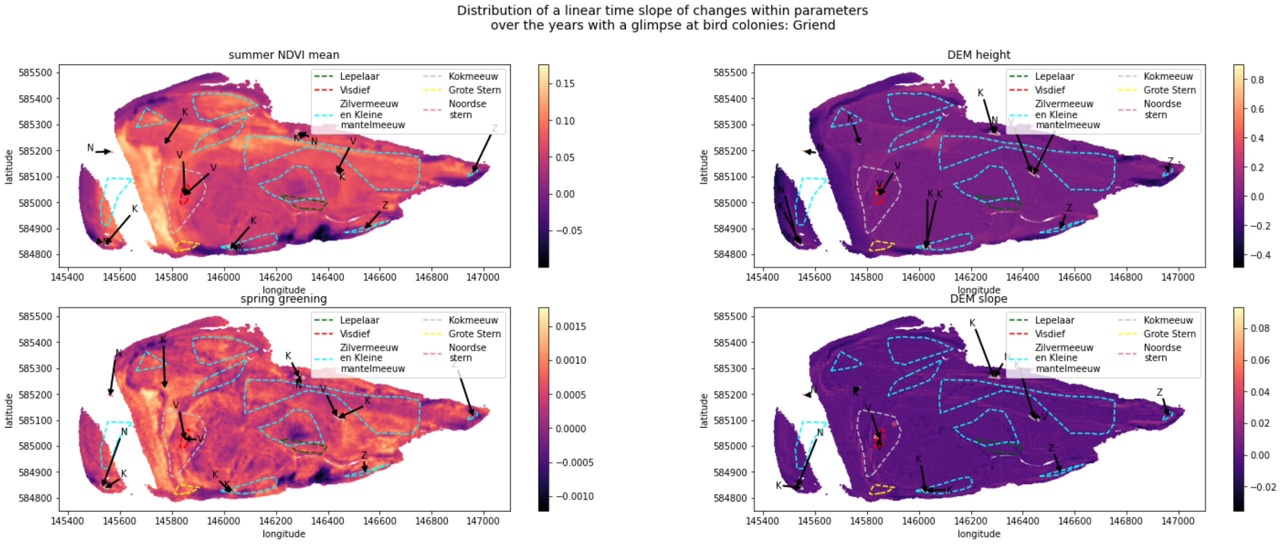
Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Richel

summer NDVI mean

DEM height

spring greening

DEM slope



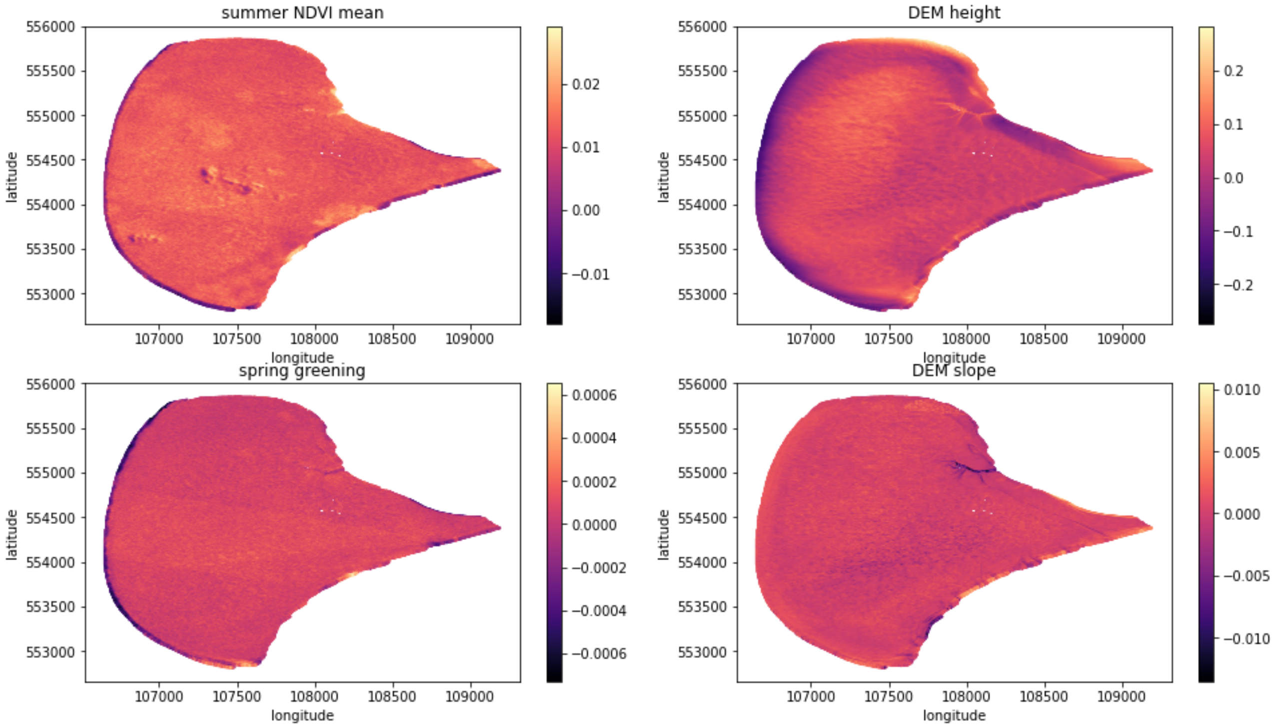
Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Griend

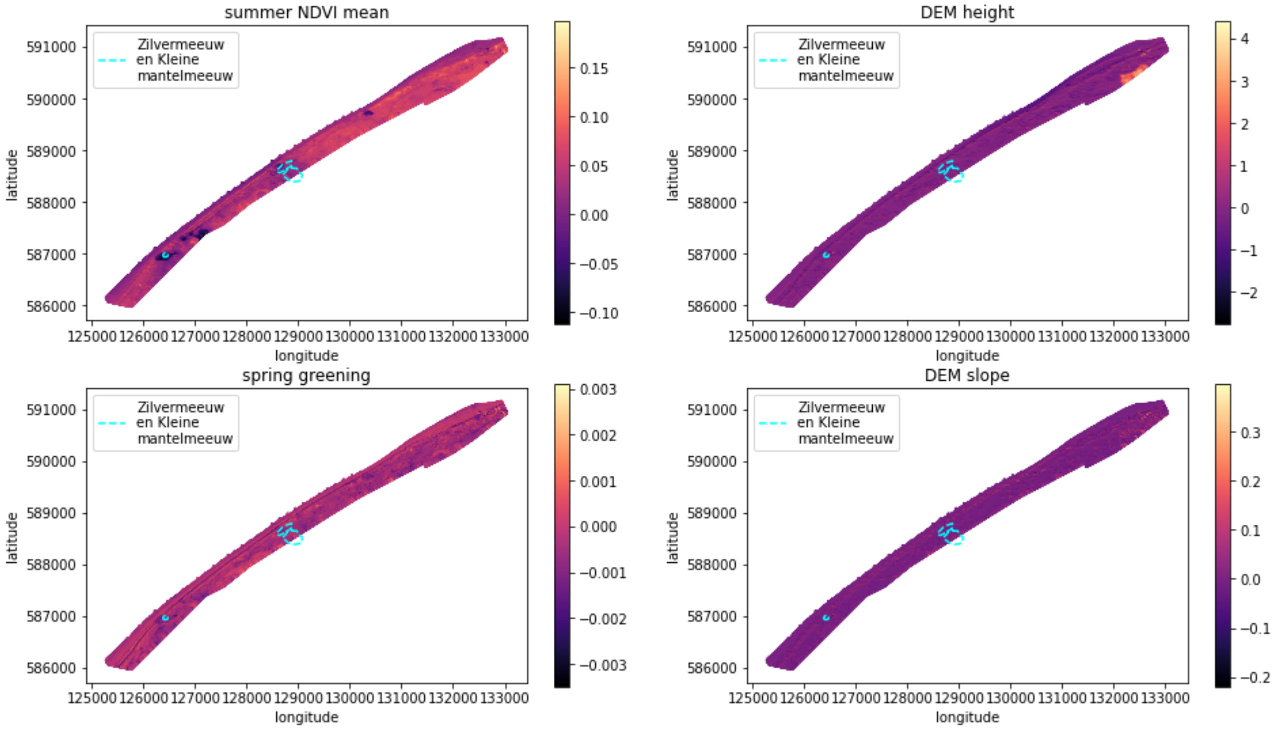
summer NDVI mean

DEM height

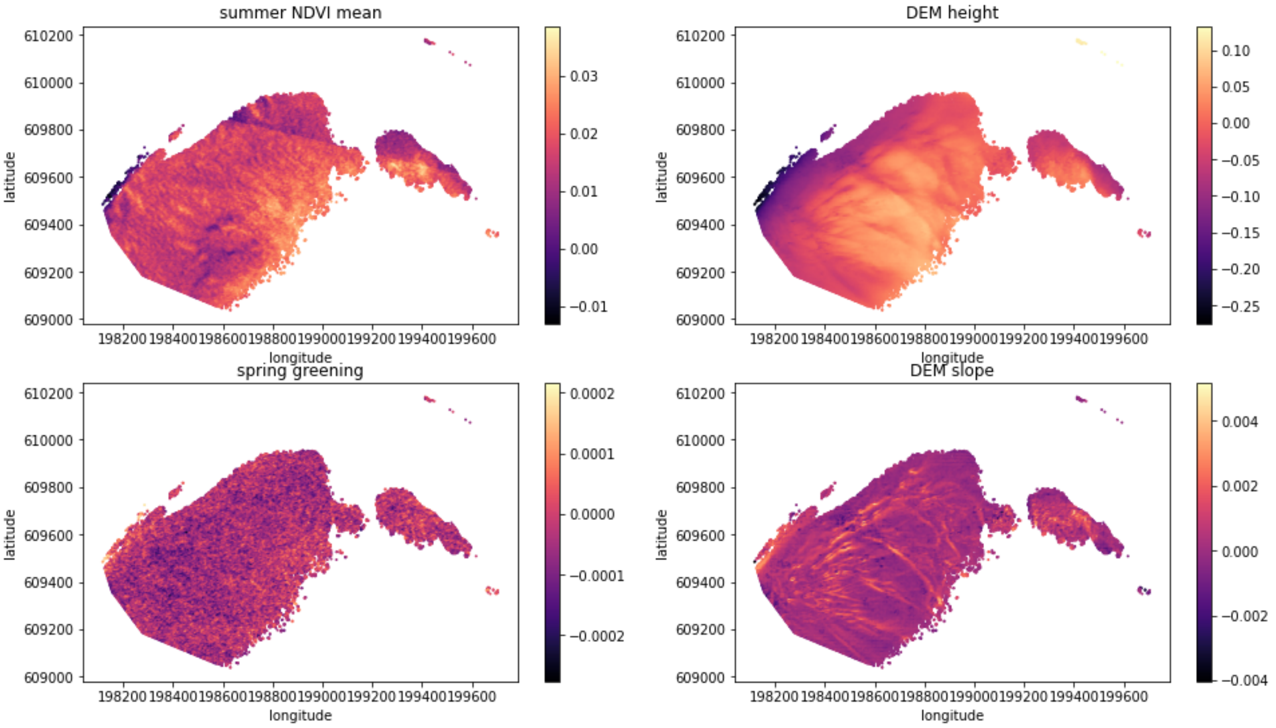
spring greening

DEM slope

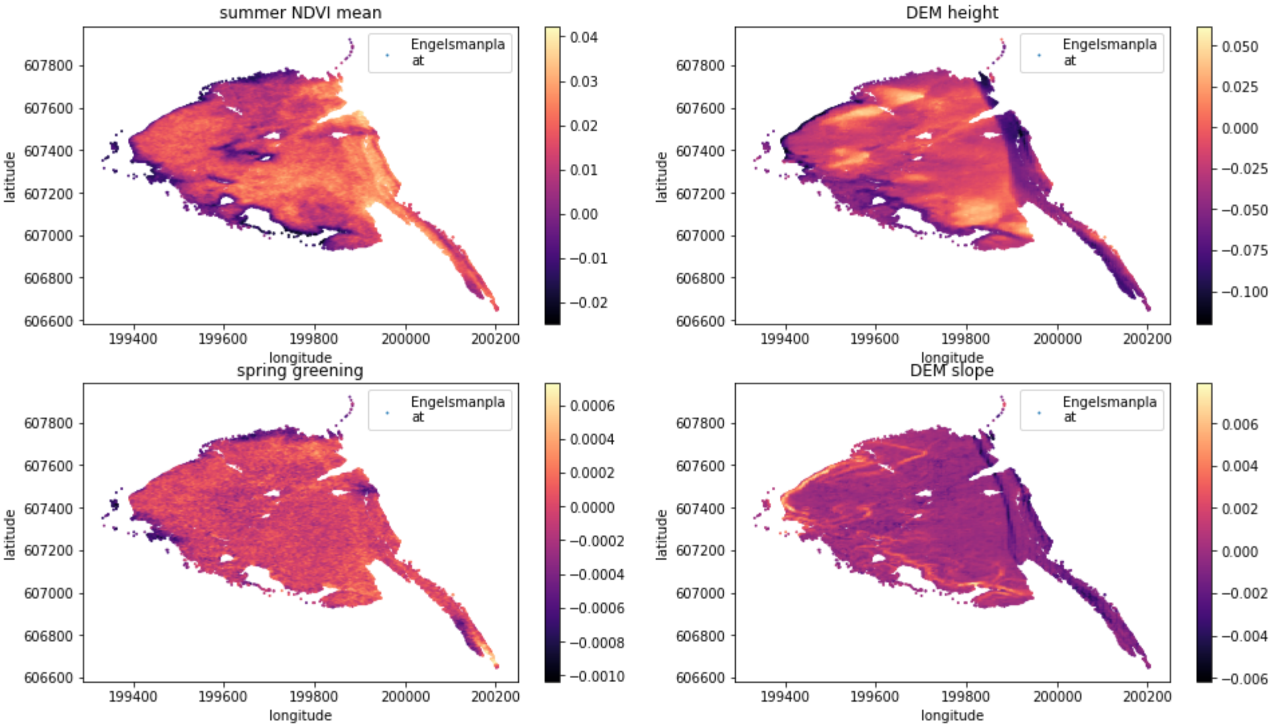

Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Razendebol


Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Vlieland

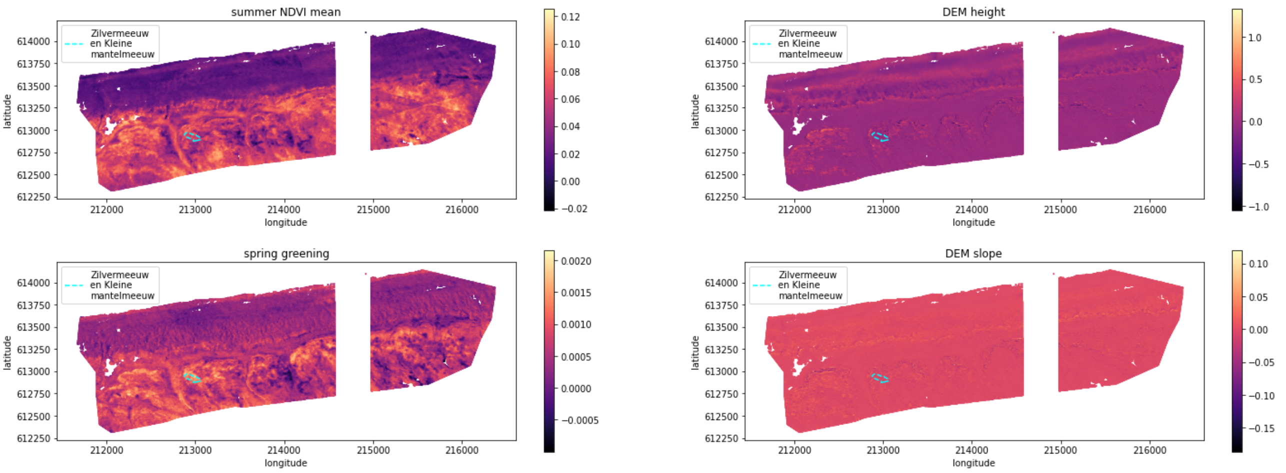
Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Rif



Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Engelsmanplaat



Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Schiermonnikoog

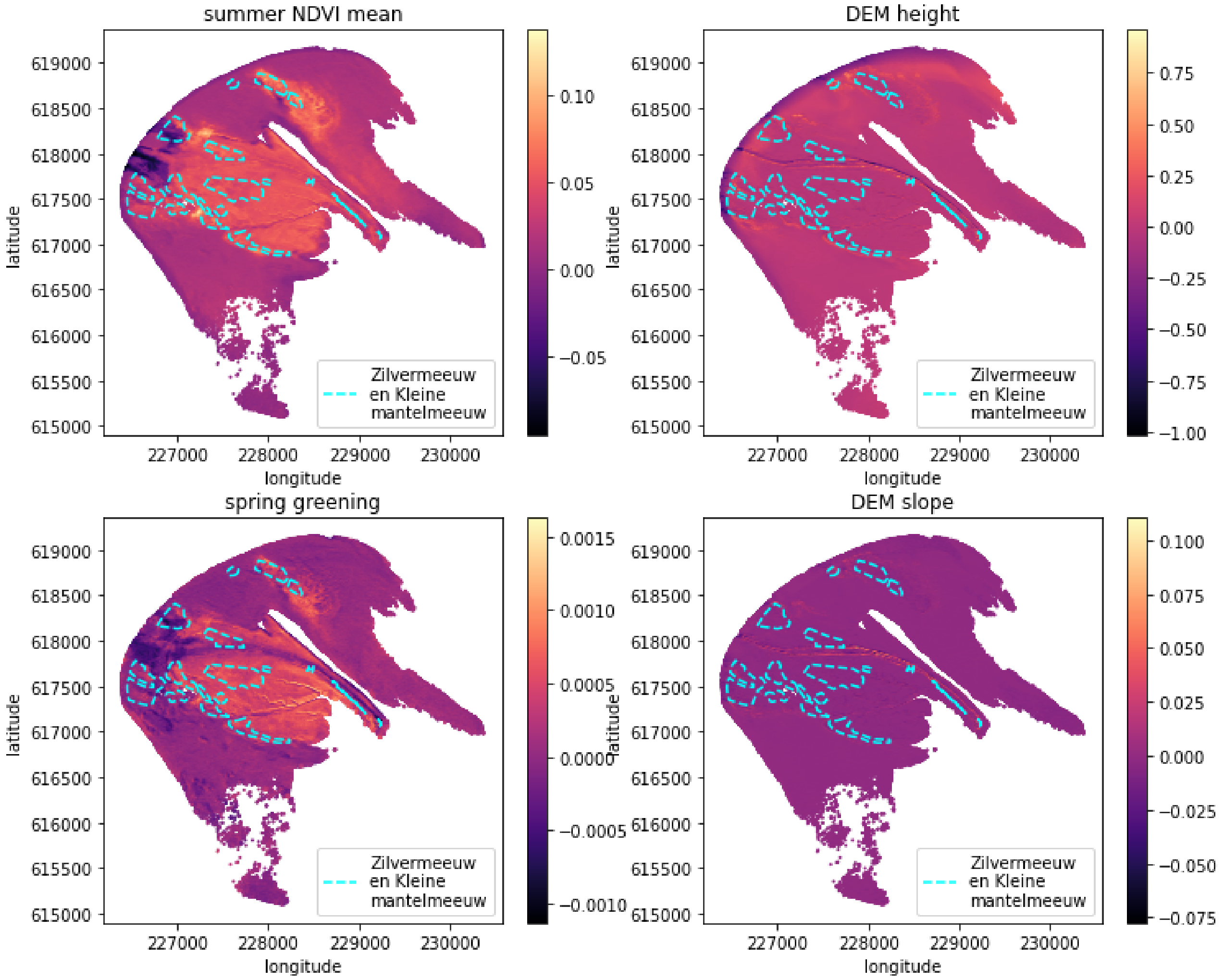

summer NDVI mean

DEM height

spring greening

DEM slope

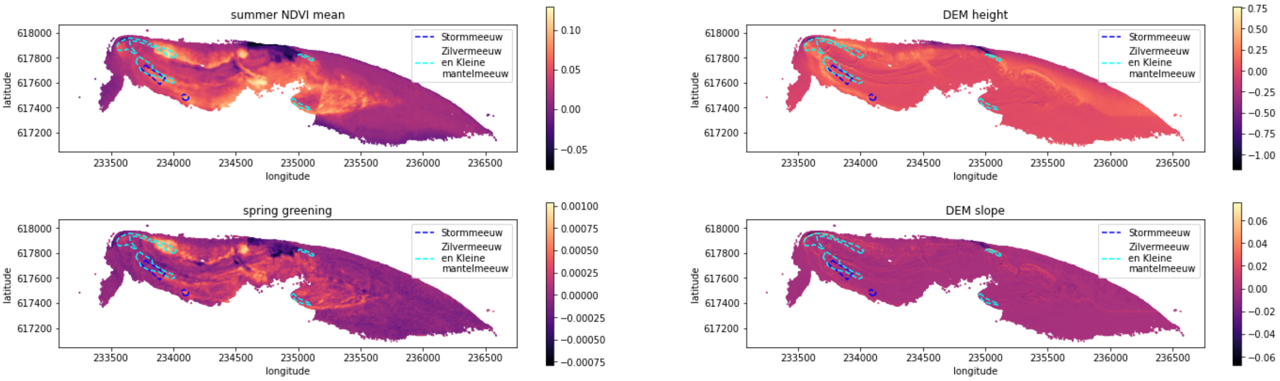
Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Rottumerplaat


summer NDVI mean

DEM height

spring greening

DEM slope


Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Rottumeroog

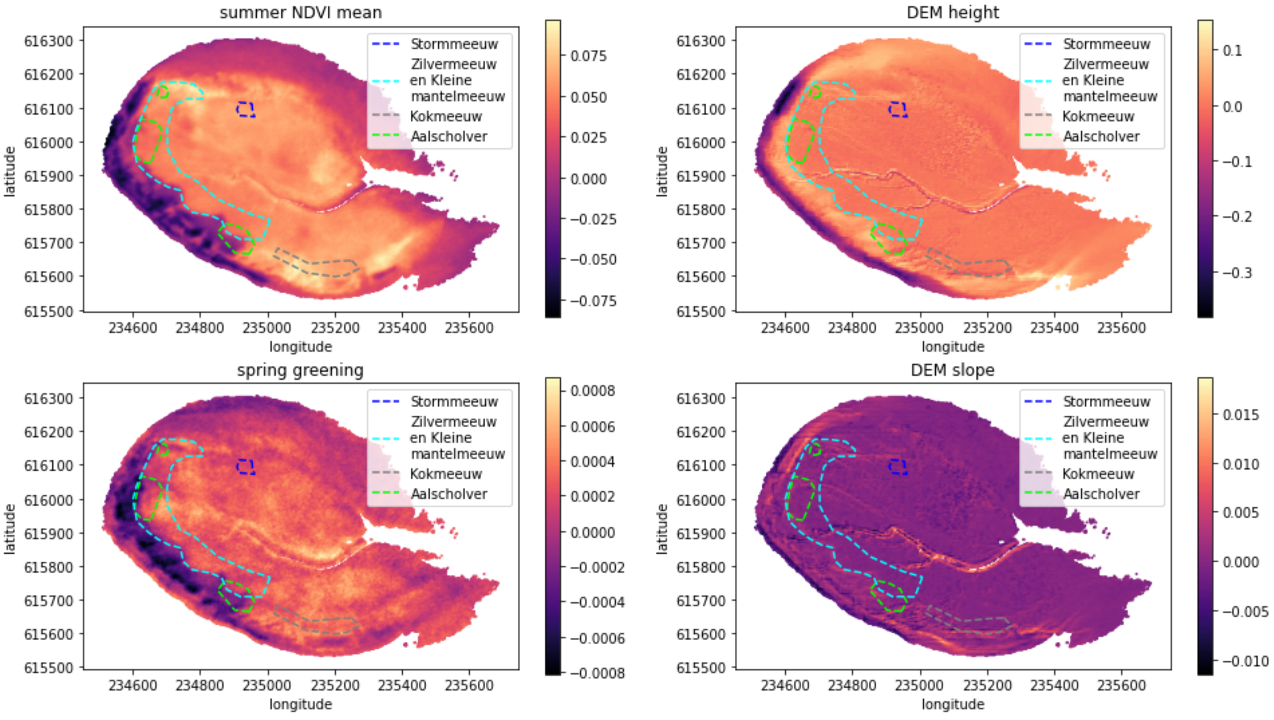

Distribution of a linear time slope of changes within parameters over the years with a glimpse at bird colonies: Zuiderduin

Figure H.1: Maps with a linear time coefficient of a parameter development per annum

H.2 Linear time coefficients: per species per island

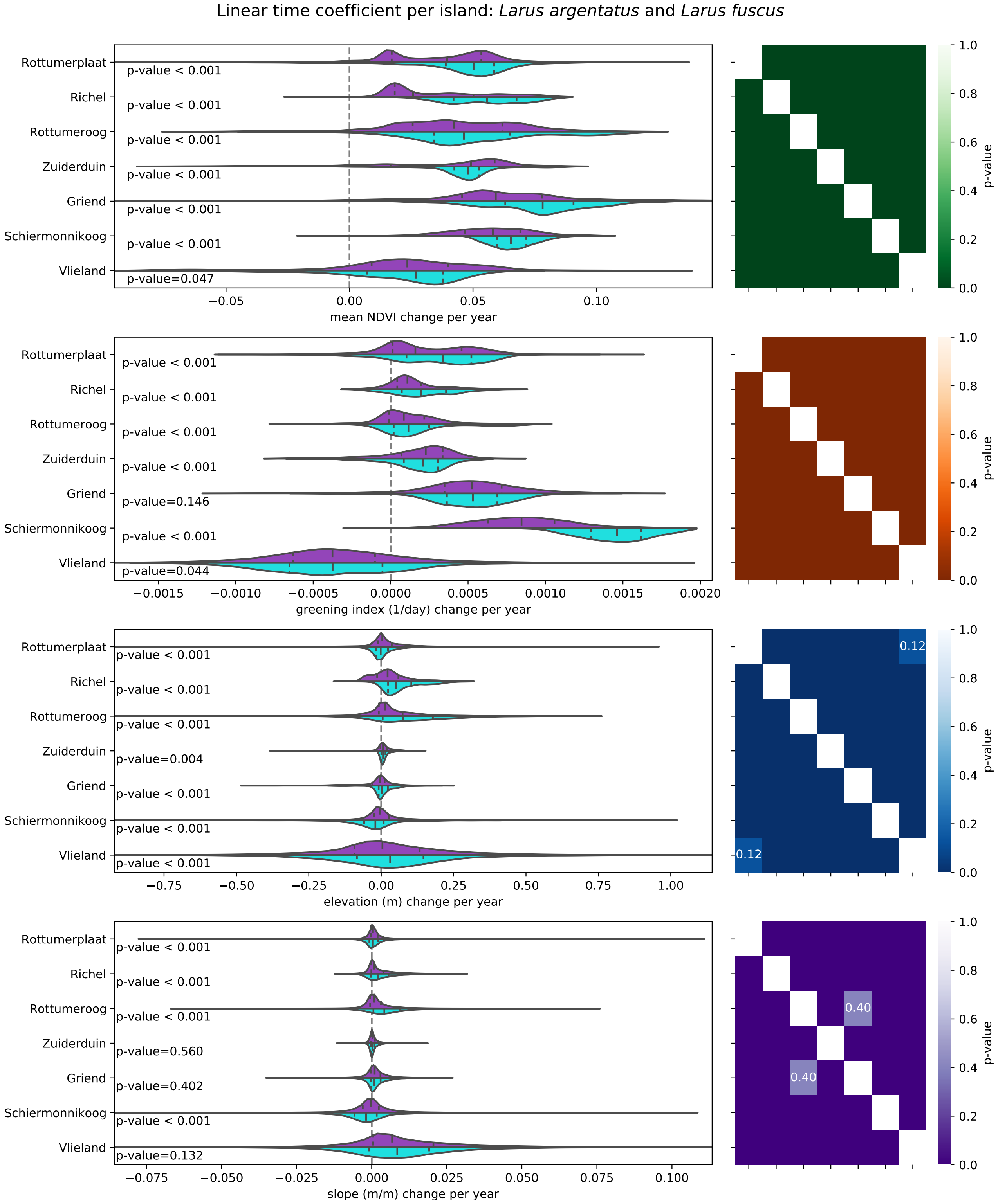


Figure H.2: Distribution of a linear time coefficient per island for within and outside of colonies of *Larus argentatus* and *Larus fuscus* in 2017-2022 for bird-containing islands only. The Mann-Whitney test is used to compare distributions between one another for different islands as well as within colonies and outside. All p-values are marked if they are higher than 0.05

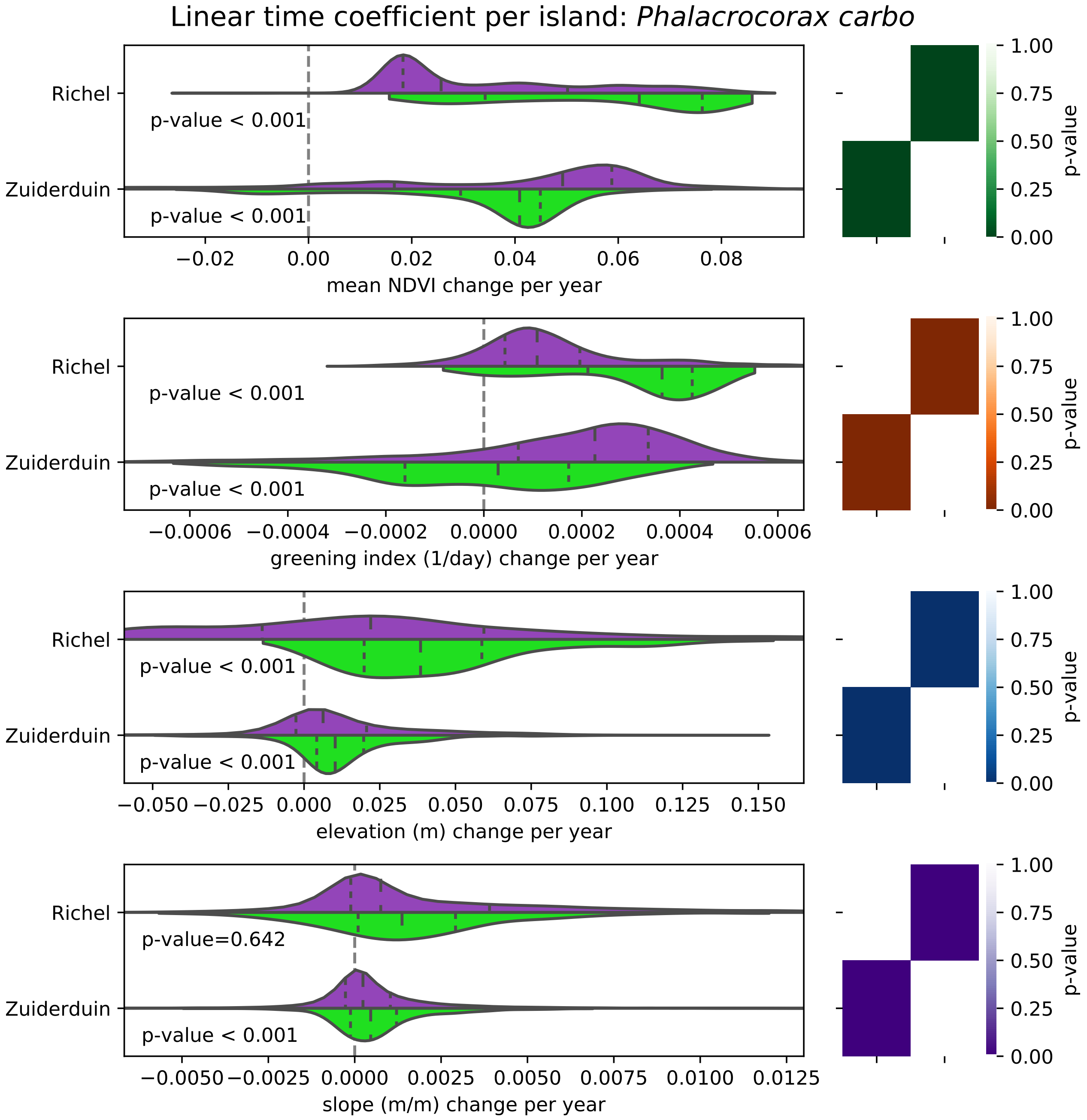


Figure H.3: Distribution of a linear time coefficient per island for within and outside of colonies of *Phalacrocorax carbo* in 2017-2022 for bird-containing islands only. All p-values are marked if they are higher than 0.05

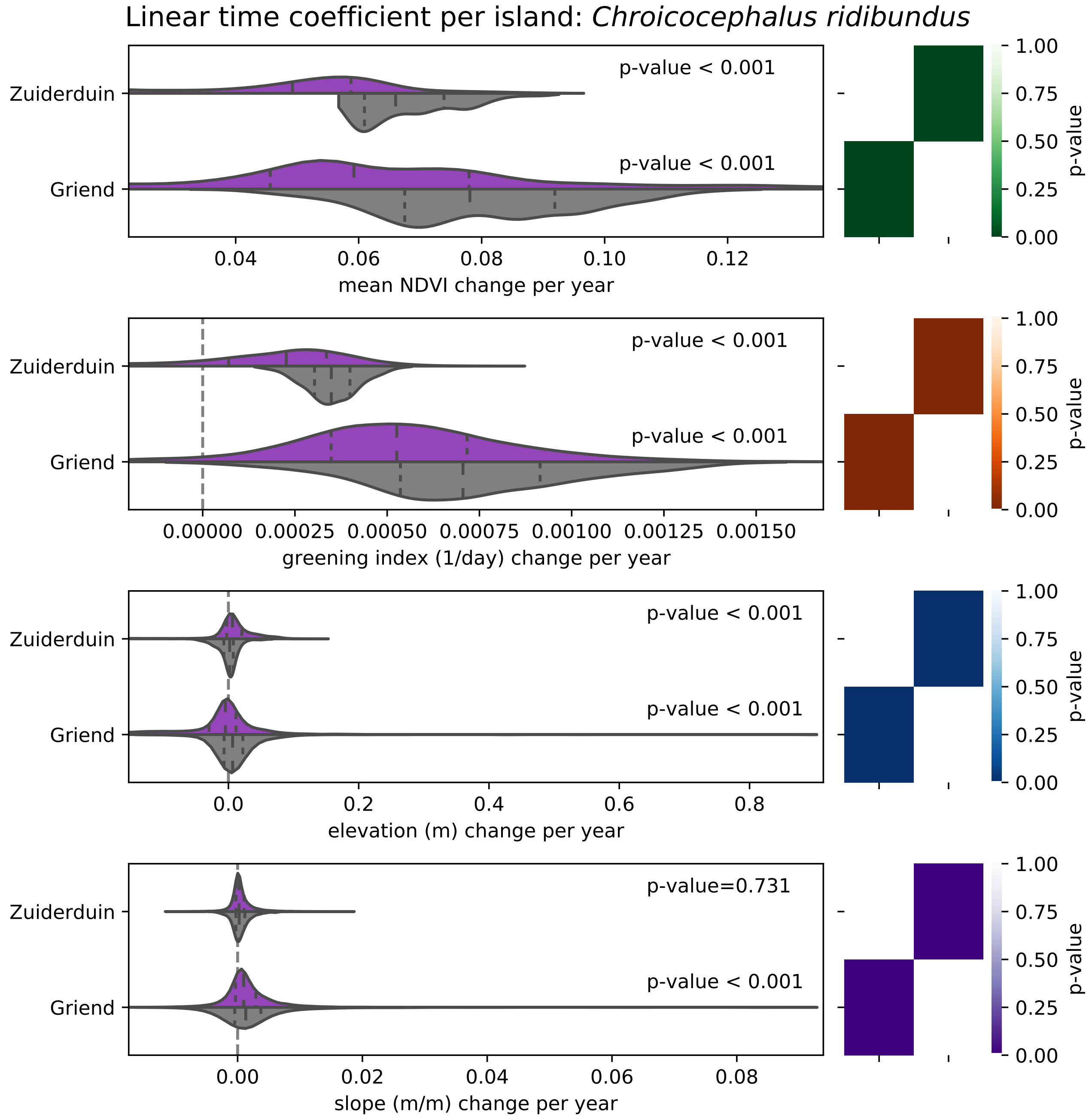


Figure H.4: Distribution of a linear time coefficient per island for within and outside of colonies of *Chroicocephalus ridibundus* in 2017-2022 for bird-containing islands only. All p-values are marked if they are higher than 0.05

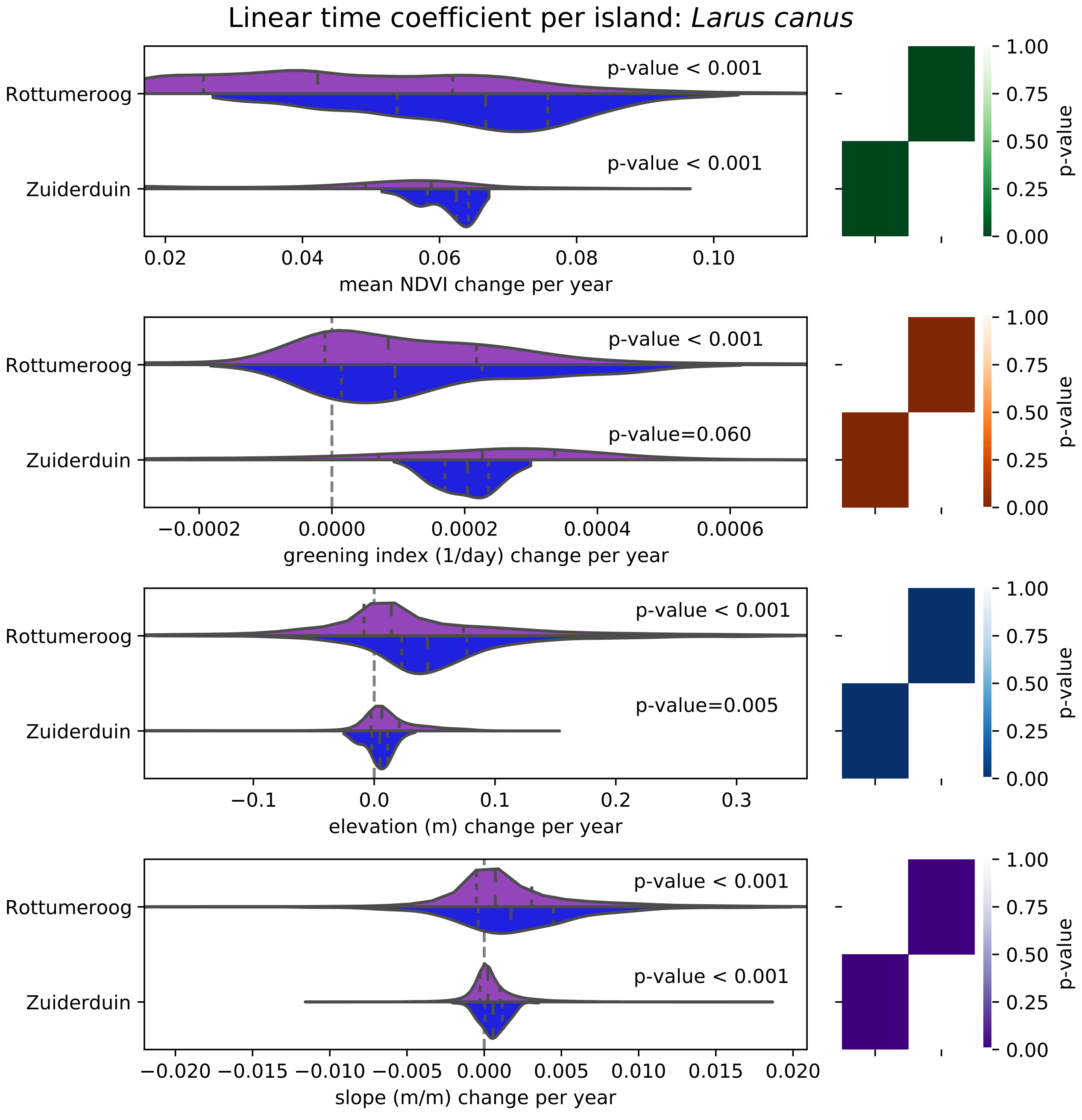


Figure H.5: Distribution of a linear time coefficient per island for within and outside of colonies of *Larus canus* in 2017-2022 for bird-containing islands only. All p-values are marked if they are higher than 0.05

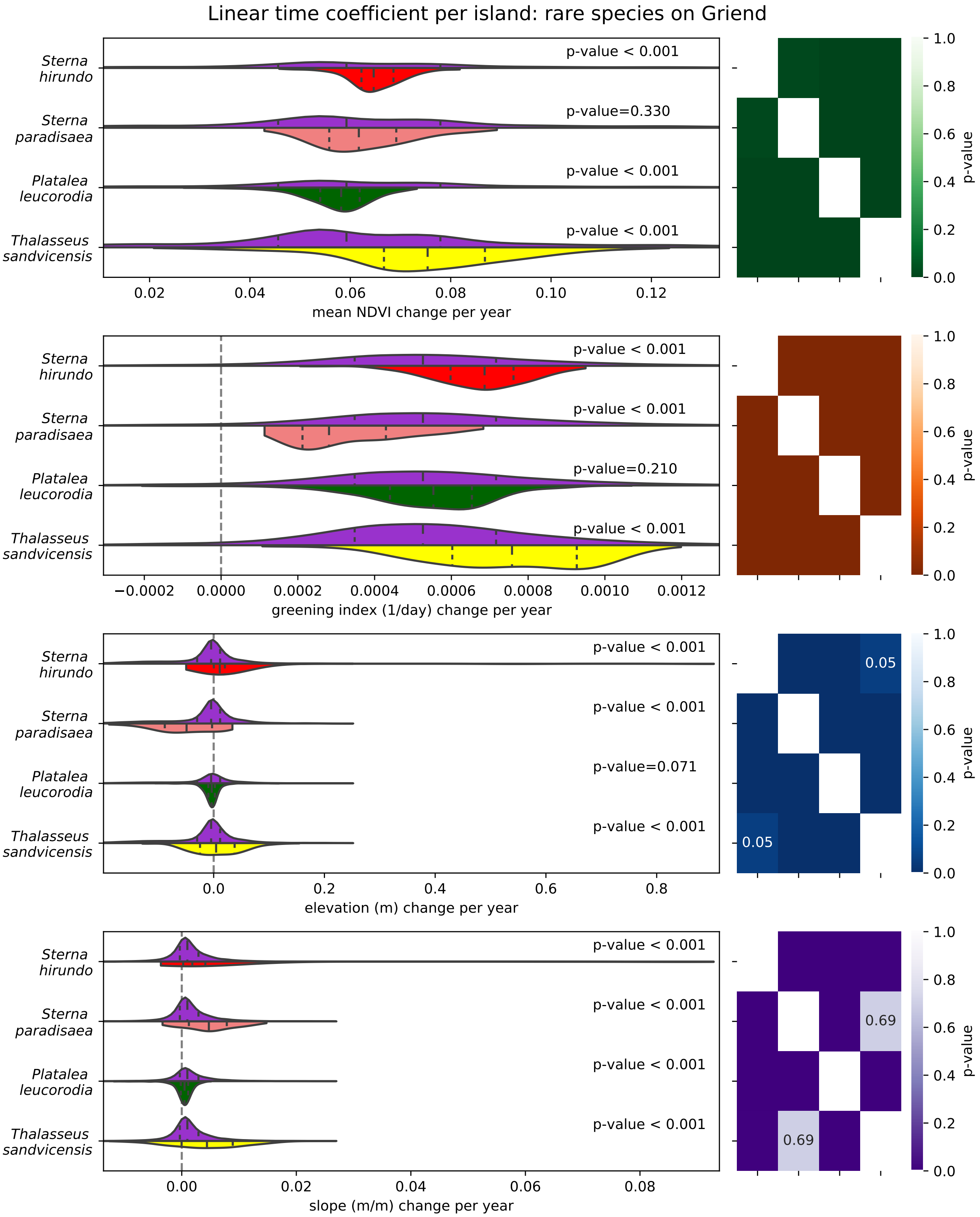


Figure H.6: Distribution of a linear time coefficient within and outside of colonies of rare species on Griend in 2017-2022. All p-values are marked if they are higher than 0.05

Appendix I

Cluster variability per island

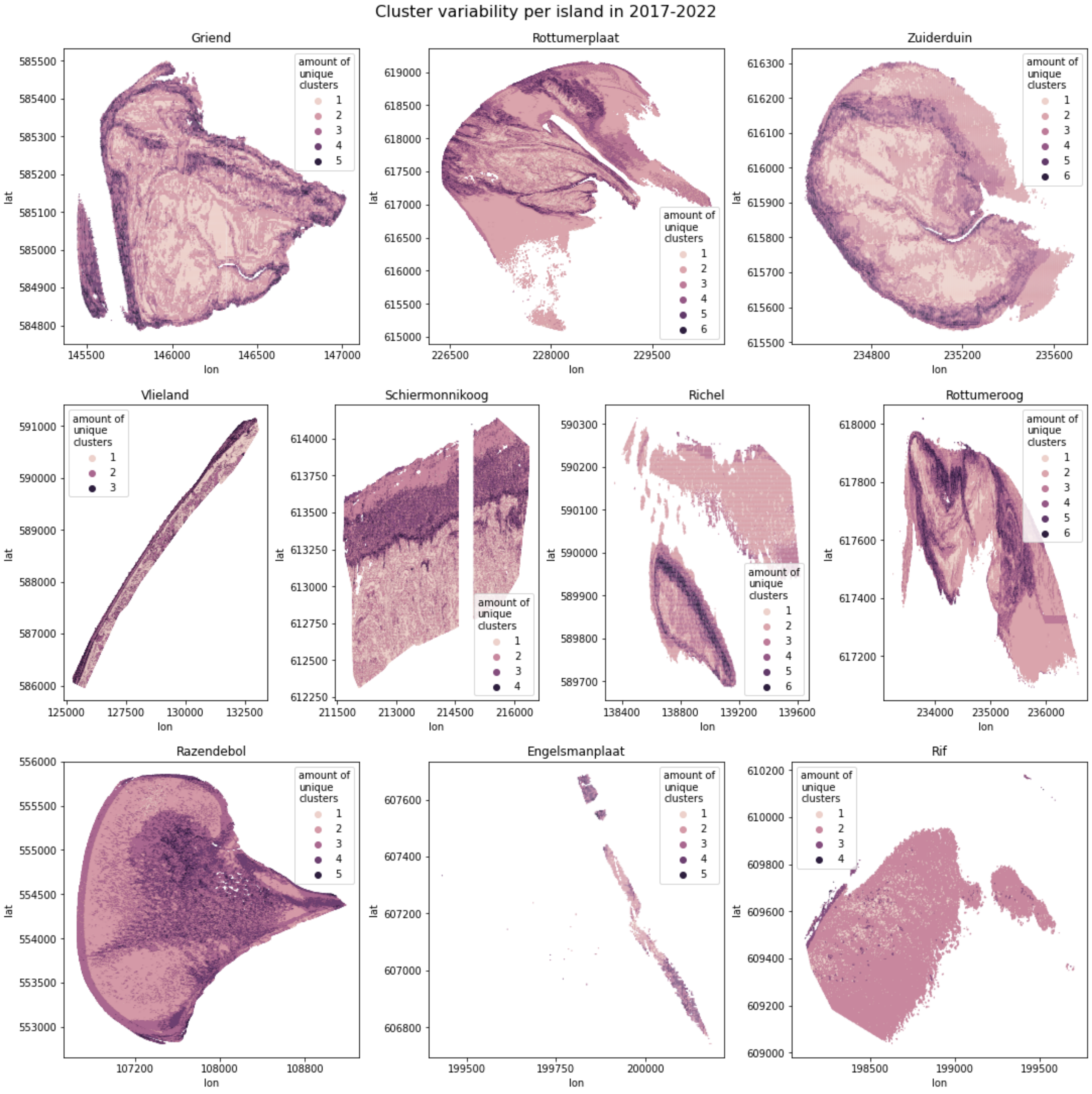


Figure I.1: Amount of unique clusters per island: map

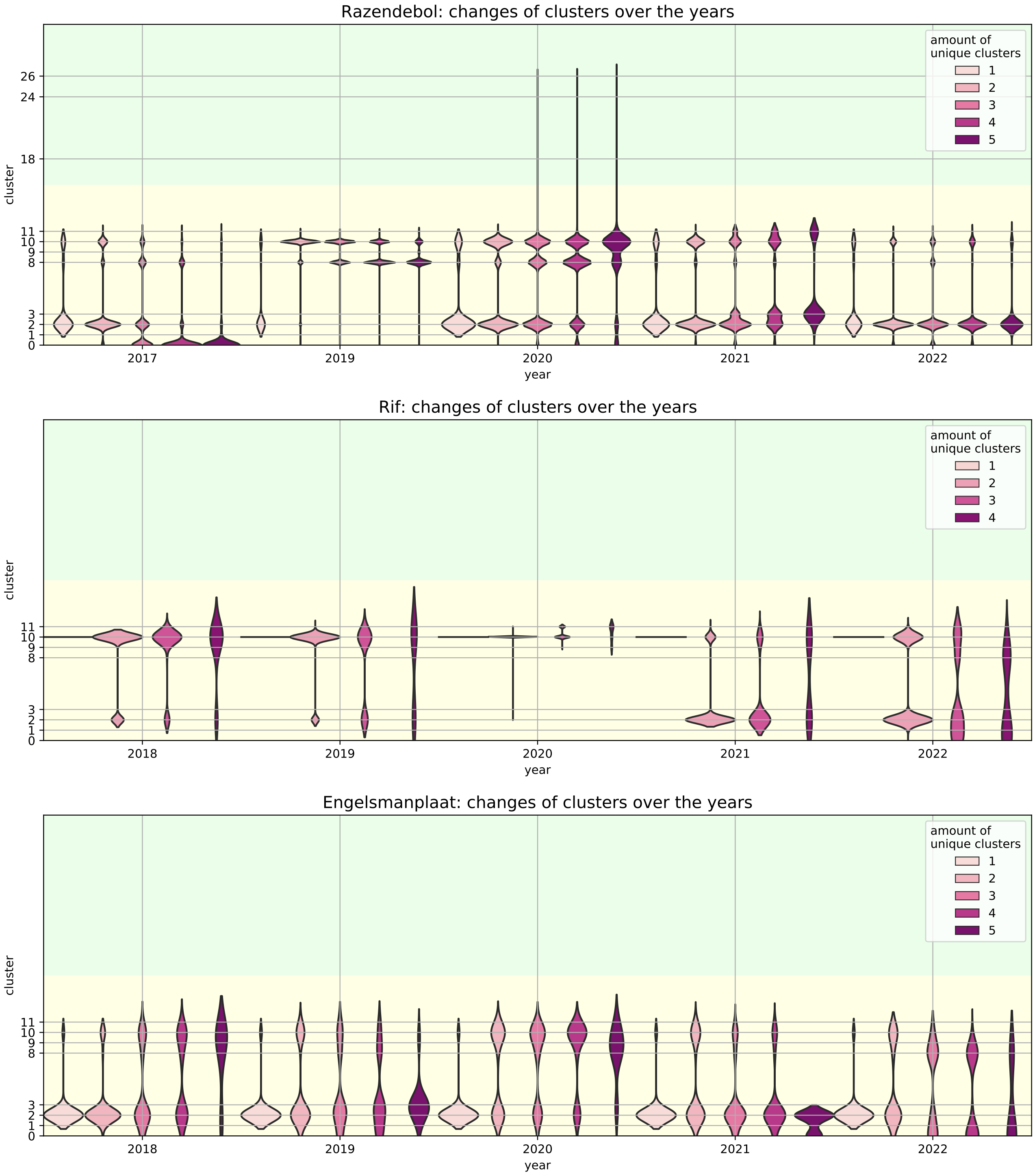
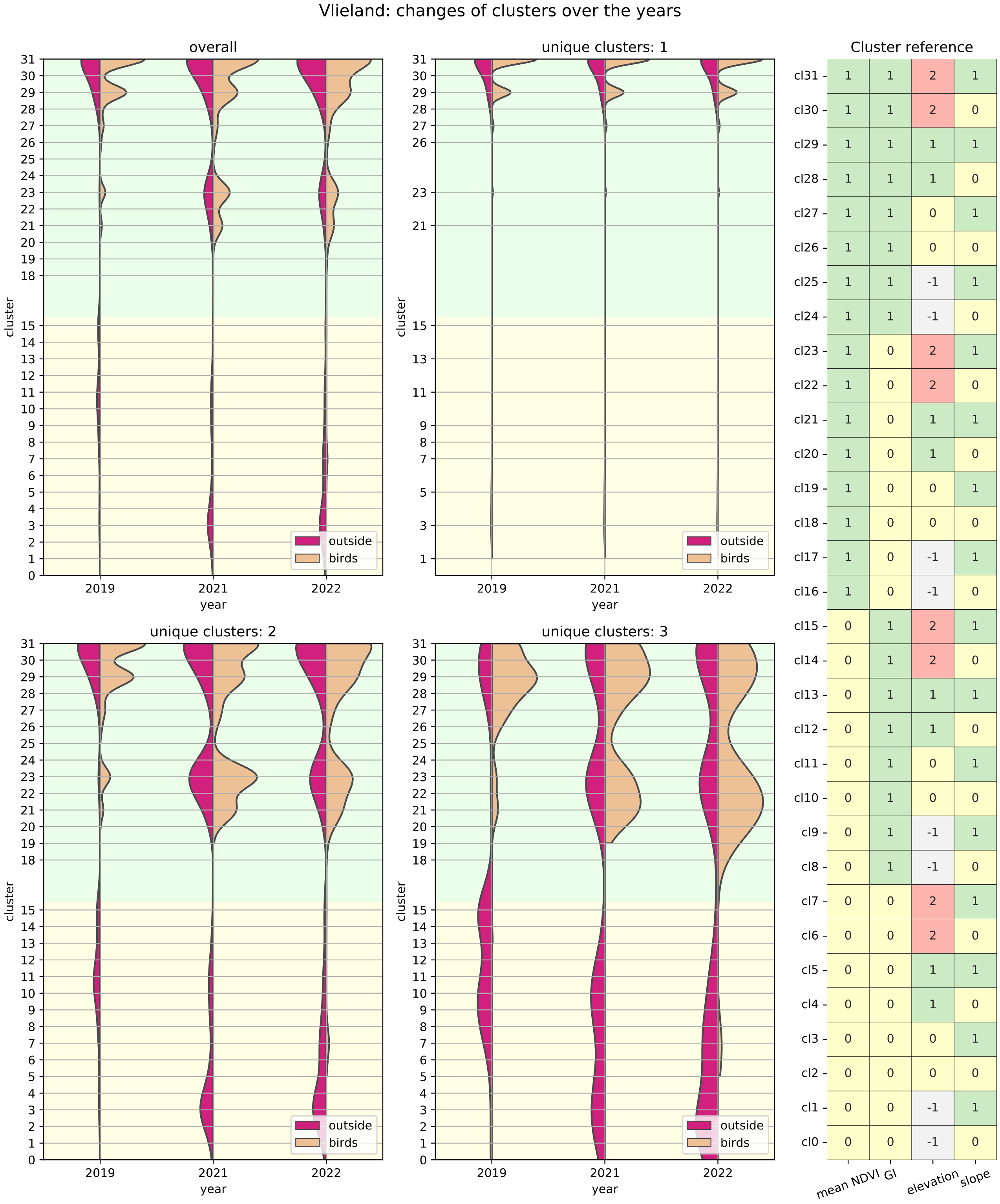
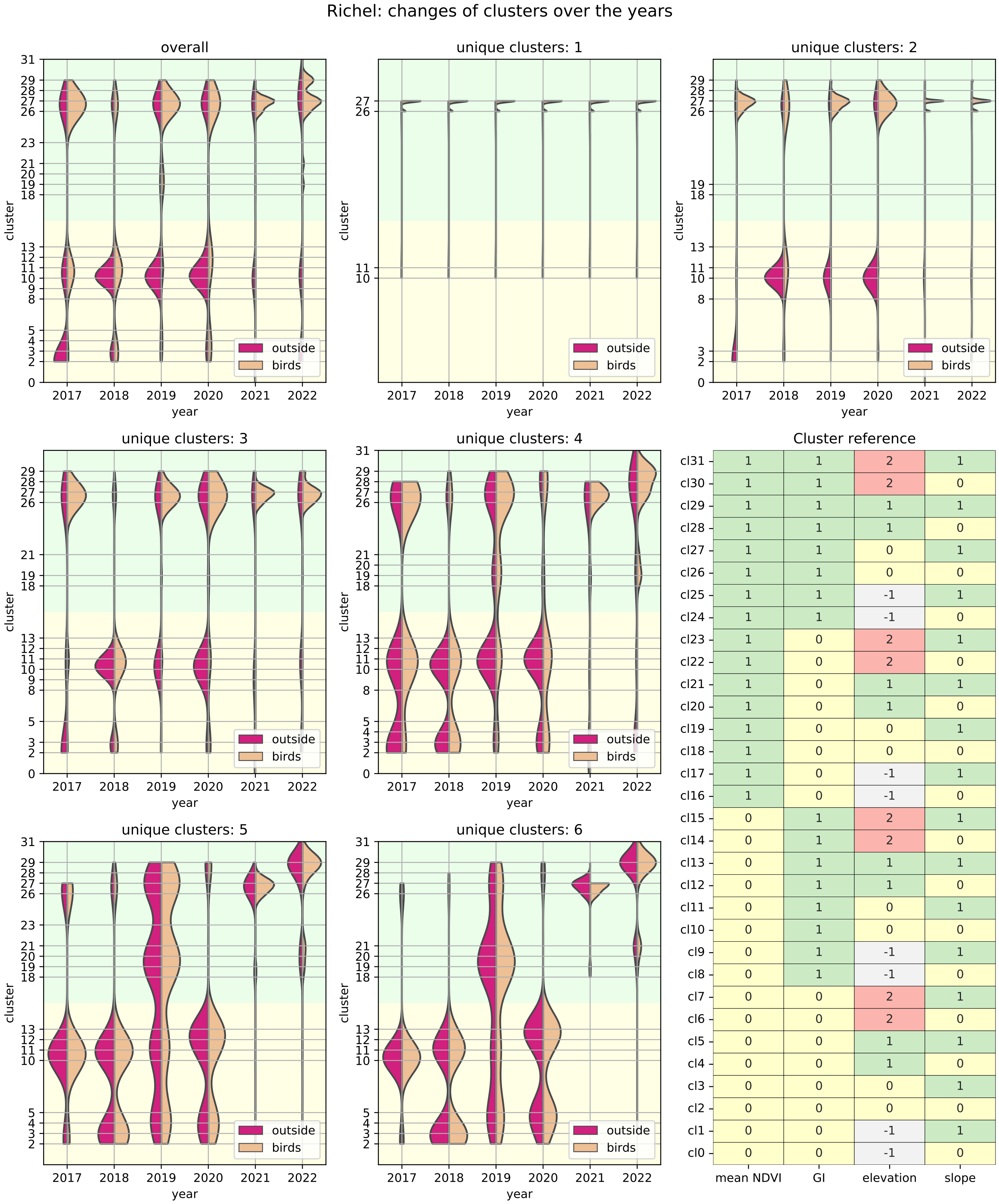


Figure I.2: Distribution of clusters per annum depending on environmental variability: islands without birds



	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.3: Distribution of clusters per annum depending on environmental variability: Vlieland



	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
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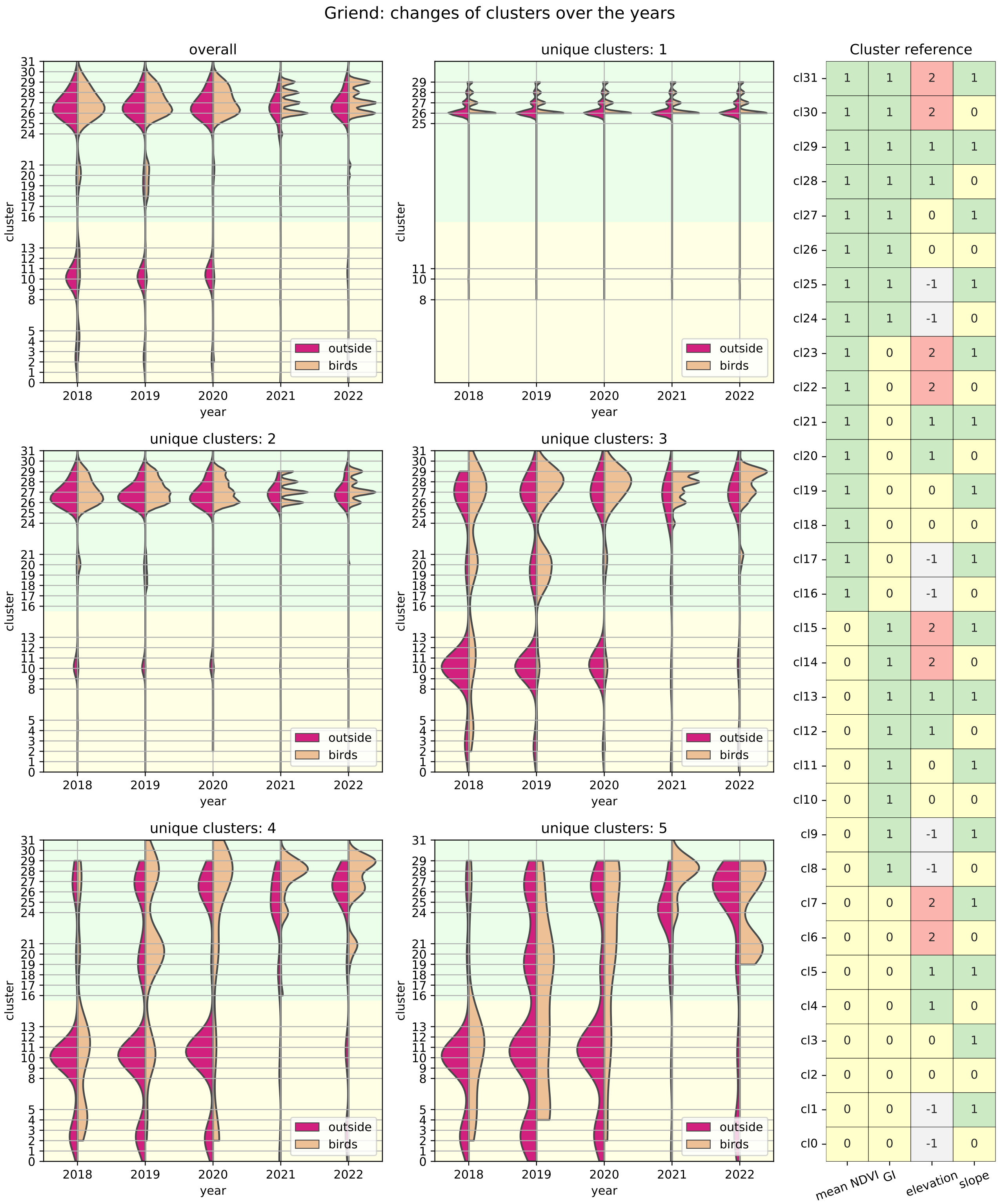
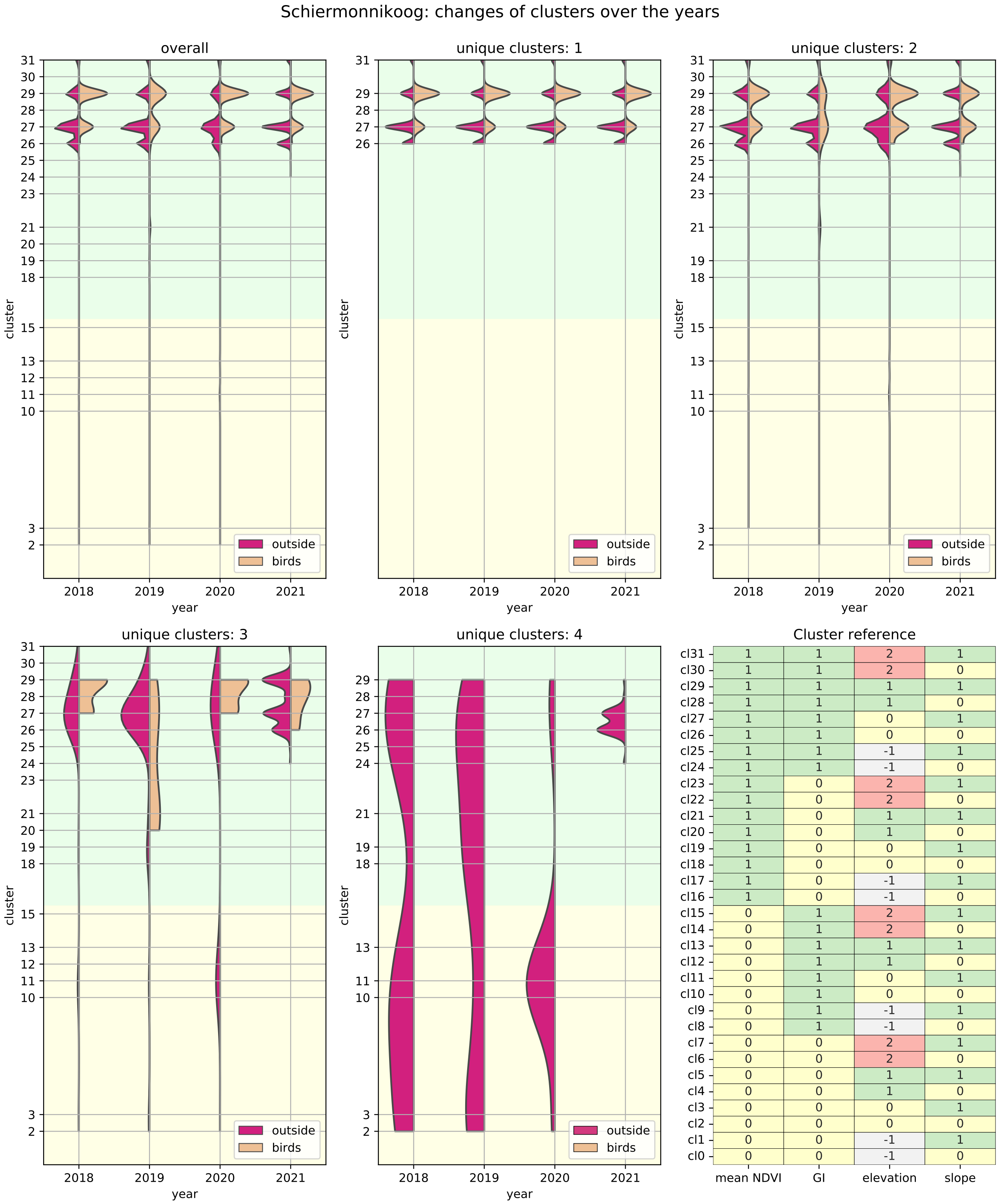
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.4: Distribution of clusters per annum depending on environmental variability: Richel



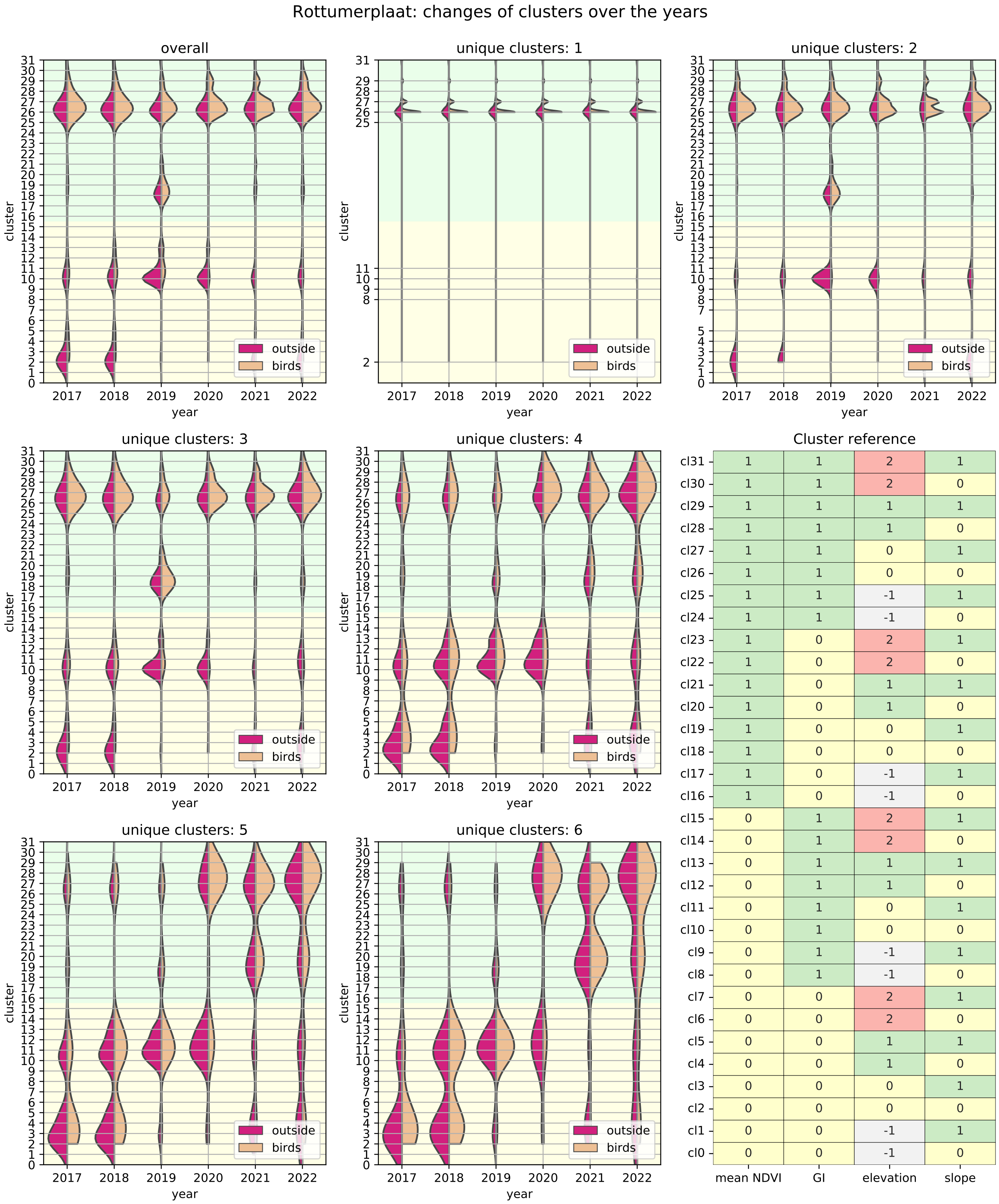
	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.5: Distribution of clusters per annum depending on environmental variability: Griend



	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.6: Distribution of clusters per annum depending on environmental variability: Schiermonnikoog



	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
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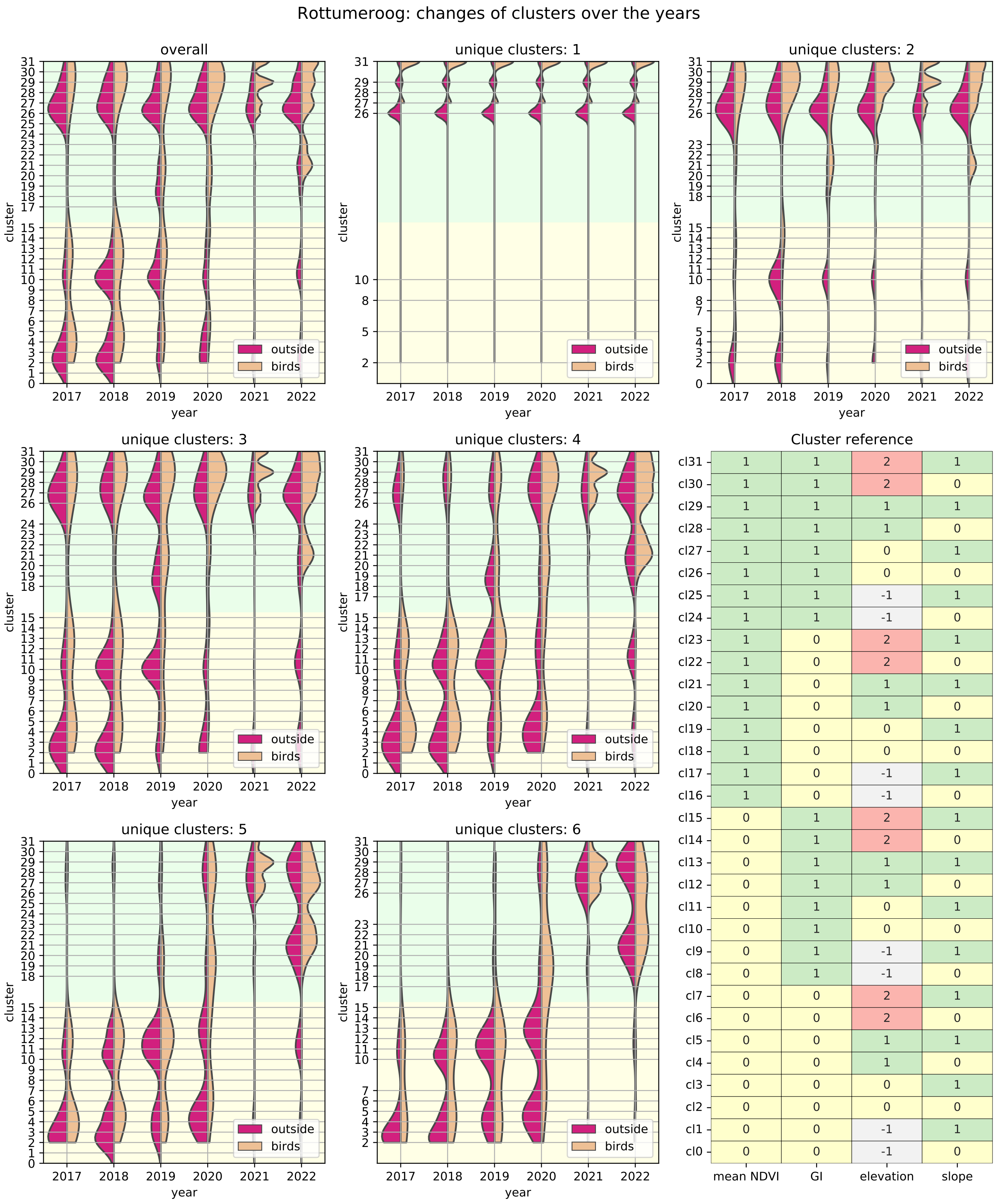
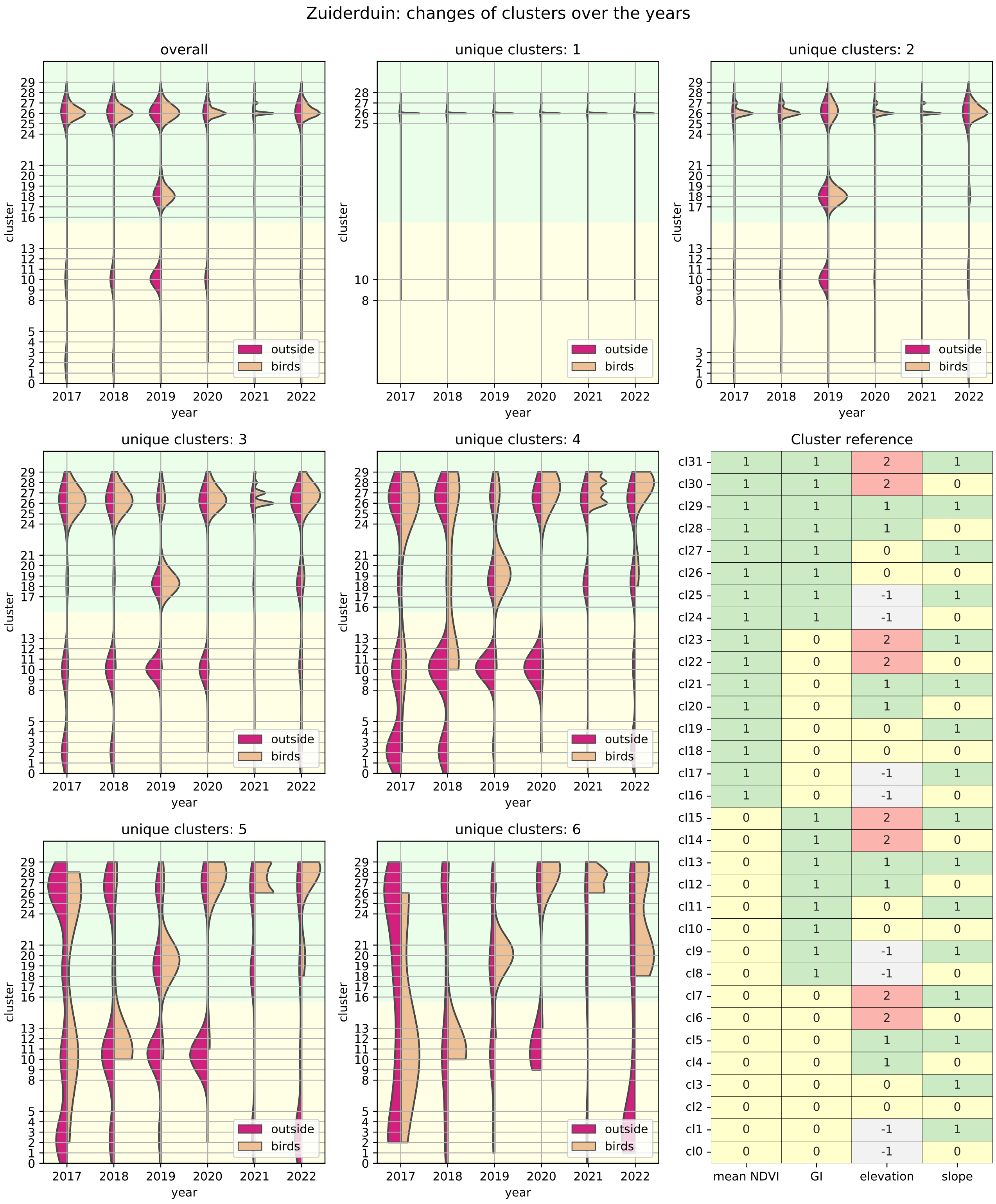
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.7: Distribution of clusters per annum depending on environmental variability: Rottumerplaat


Rottumeroog: changes of clusters over the years

	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.8: Distribution of clusters per annum depending on environmental variability: Rottumeroog

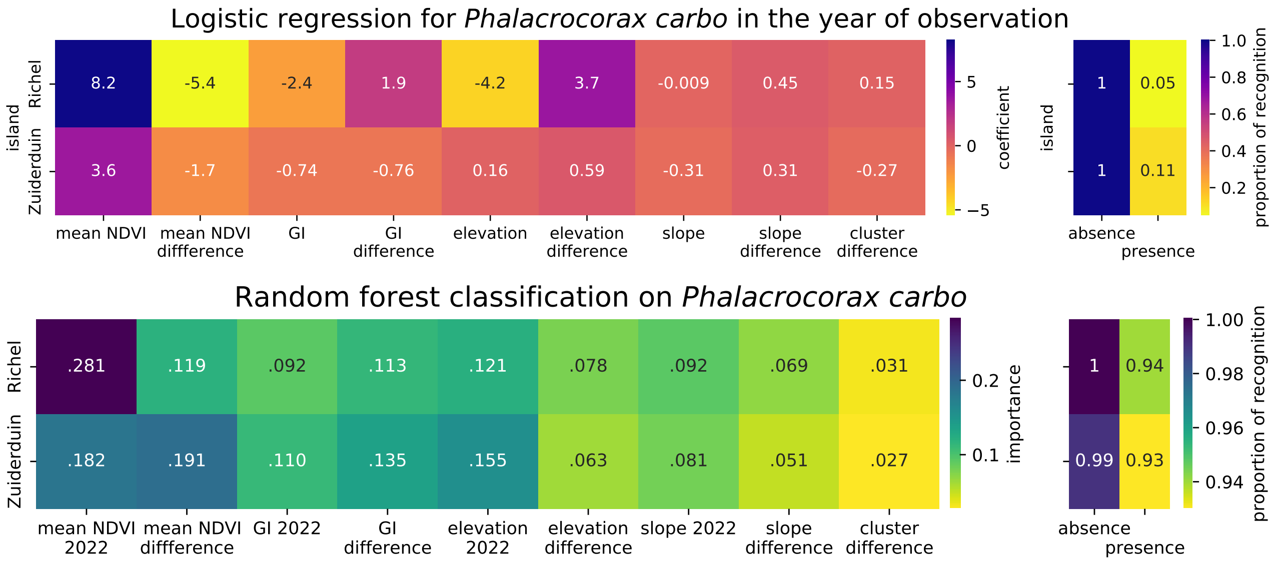


	mean NDVI	GI	elevation	slope
cl31	1	1	2	1
cl30	1	1	2	0
cl29	1	1	1	1
cl28	1	1	1	0
cl27	1	1	0	1
cl26	1	1	0	0
cl25	1	1	-1	1
cl24	1	1	-1	0
cl23	1	0	2	1
cl22	1	0	2	0
cl21	1	0	1	1
cl20	1	0	1	0
cl19	1	0	0	1
cl18	1	0	0	0
cl17	1	0	-1	1
cl16	1	0	-1	0
cl15	0	1	2	1
cl14	0	1	2	0
cl13	0	1	1	1
cl12	0	1	1	0
cl11	0	1	0	1
cl10	0	1	0	0
cl9	0	1	-1	1
cl8	0	1	-1	0
cl7	0	0	2	1
cl6	0	0	2	0
cl5	0	0	1	1
cl4	0	0	1	0
cl3	0	0	0	1
cl2	0	0	0	0
cl1	0	0	-1	1
cl0	0	0	-1	0

Figure I.9: Distribution of clusters per annum depending on environmental variability: Zuiderduin

Appendix J

Logistic regression and Random Forest classification



Logistic regression for *Phalacrocorax carbo* in the year of observation

island	mean NDVI	mean NDVI diffference	GI	GI difference	elevation	elevation difference	slope	slope difference	cluster difference
Richel	8.2	-5.4	-2.4	1.9	-4.2	3.7	-0.009	0.45	0.15
Zuiderduin	3.6	-1.7	-0.74	-0.76	0.16	0.59	-0.31	0.31	-0.27

island	absence	presence
Richel	1	0.05
Zuiderduin	1	0.11

Random forest classification on *Phalacrocorax carbo*

	mean NDVI 2022	mean NDVI diffference	GI 2022	GI difference	elevation 2022	elevation difference	slope 2022	slope difference	cluster difference
Richel	.281	.119	.092	.113	.121	.078	.092	.069	.031
Zuiderduin	.182	.191	.110	.135	.155	.063	.081	.051	.027

	absence	presence
Richel	1	0.94
Zuiderduin	0.99	0.93

Figure J.1: Logistic regression and Random Forest classification to predict the absence or presence of *Phalacrocorax carbo* in the year of observation per island

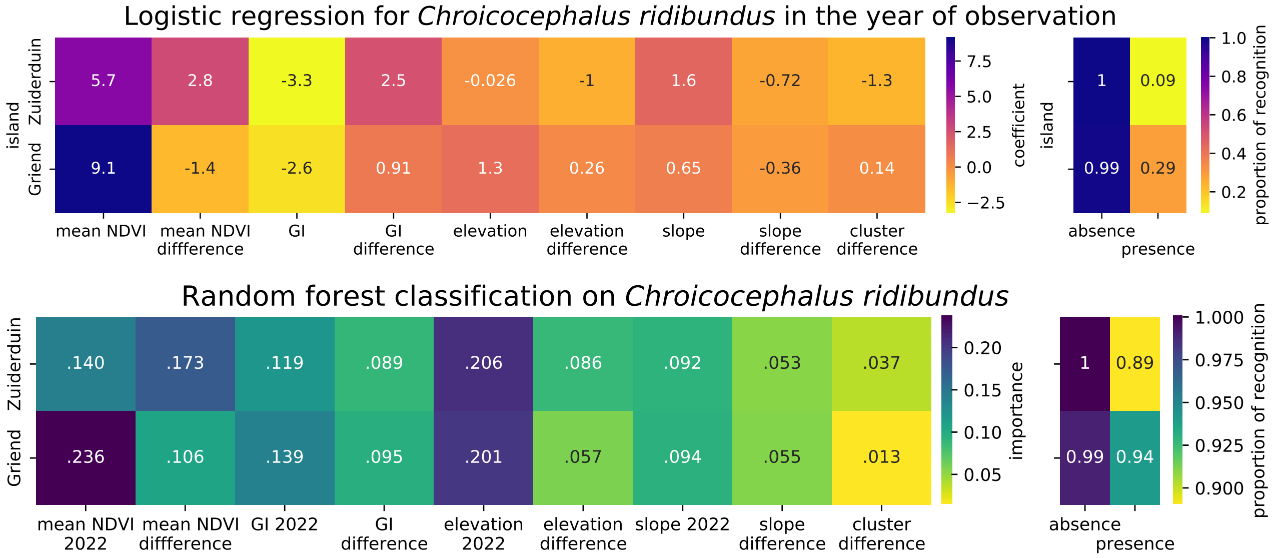


Figure J.2: Logistic regression and Random Forest classification to predict the absence or presence of *Chroicocephalus ridibundus* in the year of observation per island

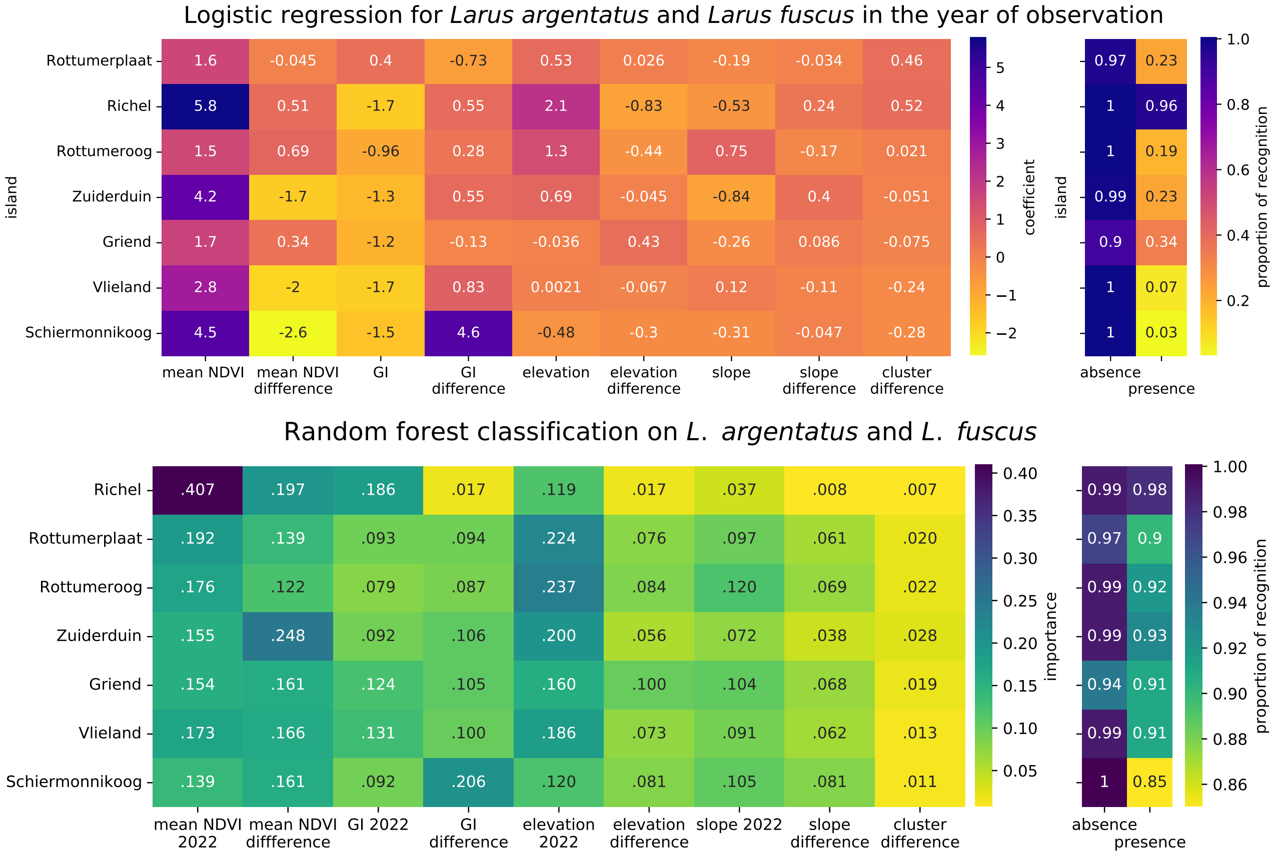


Figure J.3: Logistic regression and Random Forest classification to predict the absence or presence of *L. argentatus* and *L. fuscus* in the year of observation per island

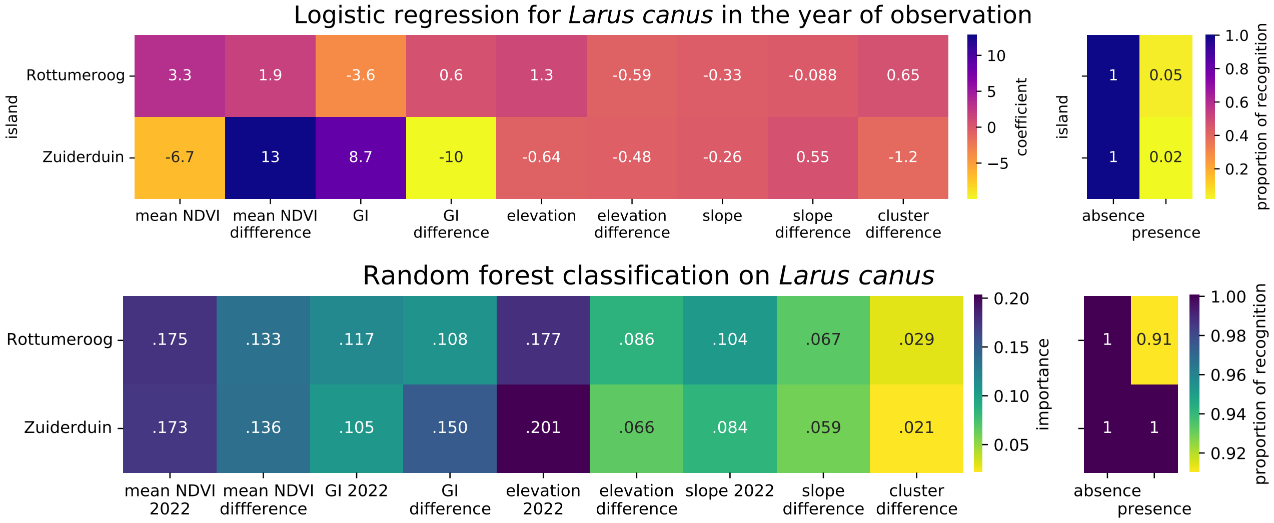


Figure J.4: Logistic regression and Random Forest classification to predict the absence or presence of *Larus canus* in the year of observation per island

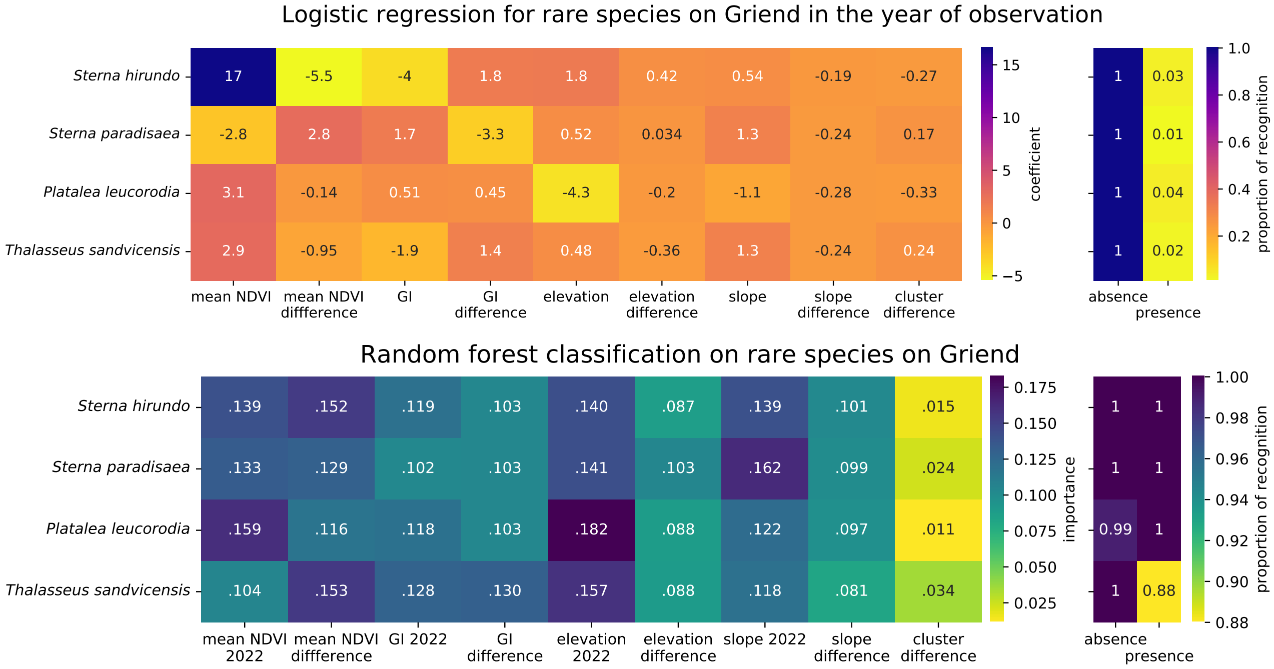


Figure J.5: Logistic regression and Random Forest classification to predict the absence or presence of rare species on Griend in the year of observation