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Agro-climatic Factors of Pilsen Region

Master thesis

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Abstract

This thesis aims to create large-scale calculations of agro-climatic factors from global climatic data with high granularity. I use freely available climatic data ERA5-Land from the Copernicus Climate Change Service as input climatic data. I describe related calculations and visualizations of agro-climatic factors. I delineate the created procedures, algorithms, and visualizations for the Pilsen region. Created agro-climatic factors are frost dates, frost-free periods, growing degree units, heat stress units, number of growing days, number of optimal growing days, dates of fall nitrogen application, precipitation, evapotranspiration, and runoff sums, water balance - changes in storage or differences between precipitation and evapotranspiration. Procedures are useable anywhere else in the world, especially in temperate and subtropical zones.

Key words

Agro-climatic factors, ERA5-Land, frost dates, frost-free period, precipitation, evapotranspiration, water balance, runoff, growing degree units, heat stress units, solar radiation, Pilsen region, nitrogen application, soil temperature, temperature, growing period, crop planning, agriculture

Declaration

I declare that this thesis is my original work of authorship that I have created myself. All resources, sources, and literature, which I used in my thesis, is cited indicating the full link to the appropriate source.

In Pilsen ....

....
Jiří Valeš

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Contents

Introduction

Nowadays very detailed global meteorological models are being developed to capture a lot of climate information over the last few decades. Availability of climatic data to users increases. Users are no longer dependent on previous realizations created in their area or on the availability of data from meteorological stations but can also have free immediate access to detailed climate data in their territory.

Climate data are widely used in agriculture and gardening. Based on the knowledge of agro-climatic factors and their influence on specific crops (or groups of crops), we can optimize the cultivation of crops and works/workload related to them.

In this thesis, I create large-scale calculations of agro-climatic factors from global data with high granularity. I use freely available climatic data ERA5-Land from the Copernicus Climate Change Service as input climatic data. I refer to related calculations and visualizations of agro-climatic factors. I explain selected agro-climatic factors, their calculation, use for cultivation of crops, visualization, and I also provide an algorithm for their calculation. I demonstrate calculations of agro-climatic factors in the Pilsen region. Created procedures, algorithms are in the same way usable anywhere else in the world, especially in temperate and subtropical zones.

1 Related works dealing with calculations and visualizations of agro-climatic factors

The term agro-climatic factor is usually understood for climatic factors affecting agriculture, especially crop growth. Temperature, solar radiation, precipitation, evapotranspiration, and soil moisture are agro-climatic factors often mentioned in the literature, however, the term of agro-climatic factor is used without deeper definition, see e.g.: The Effect of agro-climatic factors on Cash Crops Production in Nigeria [8], Agro-climatic factors and characteristics of the composition of virgin olive-oils [26] or Agroclimate Factors of Oil Palm in Nigeria. [13]

I describe fundamental agro-climatic factors bellow. I briefly present selected related works with basic characteristics such as data source, area, parameters, type of visualization. Selected agro-climatic maps, calculations are related to the bellow created agro-climatic factors, are significant/interesting/noticeable on a global scale, or are calculated for the area to which the thesis applies - Pilsen region, or rather the whole Czech Republic.

1.1 Temperature

Talking about temperature as an agro-climatic factor, we focus on temperature effect to crop growth - a possibility, quality, speed. Low or high temperatures can have a devastating effect on crops. It is useful to know when frost occurs in a given locality. Specifically, the dates of the last frost in the spring, the dates of the first frost in the fall, the times between these dates - frost-free periods.[10] It is also helpful to appreciate the time suitable for (optimal) crop growth, calculation of growing degree units, length of the growing period, number of days with optimal temperature for the crop. Beneficial information about high temperatures can be obtained from the calculated heat stress units. The soil temperature is interesting due to the optimal application of nitrogen fertilizers.[20]

1.1.1 Frost dates

NOAA: Day of The Last Spring Freeze

The National Centers for Environmental Information created a map of the last spring frost from American climate standards from 1981-2010. The map is for the mainland US (excluding Alaska) for temperatures of 16 °F, 20 °F, 24 °F, 28 °F, 32 °F and 36 °F and probabilities of 10%, 20%, 30%, 40%, 60%, 70%, 80% and 90%. The phenomenon is cartographically captured from interpolated data using isopleths.[25] Many US servers use data of freeze from NOAA for calculation of specific place after entering a ZIP code, allowing gardeners and farmers to view the last spring and first fall freeze date for their location from that data. For example, Almanac.com sites, which allow users to find frost data with a 30% probability. [11]

Agroclimatic Atlas Of Canada

Agroclimatic Atlas Of Canada contains maps Spring Freeze Dates (for 0 and -2 ° C, 10% and 50% probability), Fall Freeze Dates (for 0 and -2 ° C, 10% and 50% probability), Freeze-Free Dates (of 0° C and -2° C). Maps are calculated for the area of Canada from monthly temperature data (1931-1961) from meteorological station records and are visualized using isopleths.[10]

Average Date of Last Spring Freeze in Poland

Efforts to calculate the dates of last/first frosts are also in other countries in the world. For example, as part of the work Late Spring Freezes in Poland in Relation to Atmospheric Circulation, a map of Average Date of Last Spring Freeze was created from data from Polish weather stations. The average dates are cartographically captured from interpolated data using isopleths.[33]

Risk assessments (Cold events) worldwide from Meteoblue

Meteoblue provides probabilities of a lower temperature than the temperature specified by the user. The probability is displayed throughout the year in graphs for locations around the world. It is possible to enter how many hours a day the daily temperature is below the selected temperature. Data are calculated from 30 years, since 1985 and can be downloaded as CSV files. The service is paid.[22]

Frost days, ice days, frost risks in the Czech Republic

In the Czech Republic, the Global Change Research Institute has developed the following maps. The average number of frost days from years 1981-2010 (number of days with the minimum daily temperature below 0 °C), Average number of ice days (number of days with the maximum daily temperature below 0 °C). These maps are created from Czech weather stations and subsequently interpolated to a spatial resolution of 500 x 500 m. Furthermore, the Global Change Research Institute has created maps Late Frost Risk (the map shows the occurrence of a minimum daily temperature below 0 °C for five consecutive days with an average daily temperature above 10 °C in a row) and the Late Significant Frost Risk (daily temperatures below 0 °C for five consecutive days with an average daily temperature above 15 ° C in a row - expressed as a percentage of years in the reference period when this condition occurred for 1 or more days). Frost risk maps are obtained from data from 5 global circulation models. Phenomenons are visualized by coloring the pixels with gradation created by interpolation.[11]

1.1.2 Soil temperature dates

The average fall last date with soil temperatures above 15.6 °C and 10 °C

Illinois Agronomy Handbook contains map: The average last dates in autumn when Illinois 4-inch soil temperatures were above 60 °F (15.6 °C) and 50 °F (10 °C), 1971 to 2000. The map is created for the Illinois area and visualized using isolines.[20]

Soil Temperature Date Maps

Publication of Soil Temperature: A Guide for Planting Agronomic and Horticulture Crops in Nebraska has many soil temperature date maps. The maps capture data when the five-day running average soil temperature reached selected temperatures between 40 °F and 70 °F (5 °F intervals, 2000-2009). Soil temperature data were obtained from the High Plains Regional Climate Center's Automated Weather Data Network (AWDN) stations, interpolated using IDW and visualized by isopleths.[27]

1.1.3 Heat stress

Risk assessments (Warm events) worldwide from Meteoblue

Meteoblue provides probabilities of a higher temperature than the temperature specified by the user. The probability is displayed throughout the year in graphs for locations around the world. It is possible to enter how many hours a day the daily temperature is above the selected temperature. Data are calculated from 30 years, since 1985 and can be downloaded as CSV files. The service is paid.[22]

Risk of temperature stress, risk of hot or dry periods, extremes in the Czech Republic

In the Czech Republic, the Global Change Research Institute created many maps focused on high temperatures: Extremes - temperature above 35 °C in July, Tropical days (average annual number of days with maximum daily air temperature above 30 °C), Risk of temperature stress - degree of alertness (the map shows the average number of days with temperature index >= 27 ° C), Risk of hot or/and dry periods. Data are between 1981-2010 from 5 global circulation models and meteorological stations in the Czech republic. Phenomenons are visualized by coloring the pixels (500 x 500 m) with gradation created by interpolation.[11]

1.1.4 Growing degree units/days

Degree-Day Data and Maps of USA

Growing degree units calculated using 3 thresholds: 32 °F, 41 °F, and 50 °F. Historical maps for regions of USA from 30-year (1971-2000) historical average from the National Climate Date Center. Maps are visualized by coloring the pixels with gradation created by inverse-distance squared interpolation.[1]

Isle Of Grain Weather - Growing degree days

Sites Isle Of Grain Weather provides calculation of growing degree days (GDD) for the United Kingdom and regions of UK as annual averages of GDD - 1981-2010, 1961-1990, 1971-2000. GDDs are visualized by coloring the pixels with gradation.[23]

New Zealand's Environmental Reporting Series - Growing degree days

Interactive map showing weather stations and their GDD graphs. Graphs include annual values of GDD (10 °C threshold) and trends. Data are from 1971 to 2015, year starts 1 July. The map displays where the trend of GDD is increasing and where it is decreasing.[2]

Selected agroclimatic characteristics of the Czech Republic - temperature sums above 5 °C, 10 °C and 15 °C

The Czech Hydrometeorological Institute calculated and visualized average temperature sums above 5 °C, 10 °C and 15 °C from years 1961-2000 from meteorological stations. The input temperature data were interpolated using IDW to the resulting 10 km grid. The maps show the distribution of the resulting sums in the Czech Republic, one map also shows the duration of the period with the average daily air temperature above 5 °C.[36]

1.1.5 Number of growing days, length of the growing period

The length of the growing season, the length of growing summer season in the Czech Republic

In Czechia, the Global Change Research Institute has developed the following maps. The map of the length of the growing summer season demonstrates the average length of the growing summer (continuous period with an average daily temperature above 15 °C). The map of the length of the growing season shows the length of the growing season (continuous period with an average daily temperature above 5 °C). Maps are obtained from data from 5 global circulation models. Numbers of days are visualized by coloring the pixels with gradation created by interpolation.[11]

Length of Growing Period (LGP), in Days worldwide

Map of Length of Growing Period (LGP), in Days displays the number of days of the growing period in the world scale. Calculation combines temperature and moisture considerations. It is the number of days under rainfed conditions with temperatures above 5 °C (minimum temperature for wheat to grow). Numbers of days are presented by coloring the pixels with gradation.[3]

1.2 Solar radiation

Another essential input for plant growth is solar radiation. The amount of solar energy affects the production of the plant. Therefore, it is advisable to have an overview of the amount of incident solar radiation during the year. Moreover using solar energy available for a crop, we can estimate the efficiency of solar radiation use by crop.[20]

Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries

The agro atlas contains maps of averaged mean annual total solar radiation (yearly maps, maps for each month). Pixel has 10 x 10 km, solar radiation is in Kcal/(sq cm * year). The average is from the period from 1984 to 1991. Data are from the Surface Solar Irradiance database, NASA GISS, USA (1997). Visualization is by the color gradient.[12]

Daily solar energy throughout the year for four regions in Illinois

Illinois Agronomy Handbook contains calculated daily solar energy received on clear days throughout the year for four regions in Illinois. Solar energy is displayed using a graph with displayed values for each day in units $MJ/m^2/day$.[20]

Global Solar Atlas

A global interactive map contains information about the different types of sunlight falling on the surface for a year or a day in kWh/m^2. The data source is ERA5. The website also contains information about accuracy based on validation from meteorological station data.[32] Although the portal focuses mainly on data for solar power plants, the data can also be used for agricultural purposes.

1.3 Precipitation and evapotranspiration

The intensity, timing, and amount of precipitation received during the year play critical roles in crop productivity. Therefore we are interested in monthly/weekly precipitation totals or intensity of the rains (rainfalls greater than 12.7 cm/hr are less efficient than lighter showers).[20]

Evapotranspiration has impact on the amount of water in the landscape.[20] It consists of evaporation (which means the movement of water to the air from sources such as the soil and waterbodies) and transpiration (movement of water within a plant and the subsequent loss of water as vapor through its leaves). If we want to calculate water balance, water deficits, we need precipitation, evapotranspiration, and runoff.[21] [16]

1.3.1 Precipitation

Australia Yearly Rainfall Averages

Sites El Dorado Weather provides many maps about rainfall averages, one of them is Australia Yearly Rainfall Averages. Annual precipitation totals from the years 1961-1990 are captured in this map and visualized by isopleths. Units are millimeters.[4]

Average precipitation totals in the Czech Republic

The Global Change Research Institute created maps: Average annual precipitation, Daily total precipitation over 5 mm, Daily total precipitation over 10 mm, Average total precipitation in summer. Averages are in days or millimeters from the years 1981-2010 from 5 global models. Values are visualized by coloring the pixels (500 x 500 m) with gradation created by interpolation.[11]

1.3.2 Evapotranspiration

Agroclimatic Atlas Of Canada: annual and seasonal evapotranspiration

Agroclimatic Atlas of Canada contains maps Annual Potential EvapoTranspiration and Seasonal EvapoTranspiration. Maps are calculated for the area of Canada with 50% probability from monthly evapotranspiration data (1931-1961) from meteorological station records and are visualized using isopleths. Units are millimeters or inches, the season is from May to September.[10]

1.3.3 Water balance / water deficits

Agroclimatic Atlas Of Canada: Seasonal Water Deficits

Seasonal water deficits are calculated and visualized in Agroclimatic Atlas of Canada. Water deficits are for 100 or 25 mm storage with 50% or 10% probability.

The season is from May to September. Maps are calculated for the area of Canada from monthly potential evapotranspiration and precipitation data (1931-1961) from meteorological station records and are visualized using isopleths.[10]

Water balance in the landscape in Czech Republic

Global Change Research Institute has developed many maps focused on deficits and changes in storage, for example Changes in a landscape water regime, Changes in a landscape water regime during the growing period (April - September). These changes were calculated as the difference between precipitation and reference evapotranspiration during the whole year or season. Maps are obtained from data from 5 global circulation models. Numbers of days are visualized by coloring the pixels with gradation created by interpolation. Units are millimeters.[11]

1.4 Soil moisture

Wet soils during the spring period play an important role in determining how many days are suitable for fieldwork. Excessive soil moisture during late spring / early summer can cause loss of nitrogen through denitrification and leaching and may lead to the development of seed, root, and crown diseases. Dry soil during planting may result in poor stand establishment and also may cause plant stress during dryness occurs in the periods of flowering and spreading seeds.[20]

The used hourly climate data Era5-Land does not contain information about soil moisture, this factor is not calculated in the thesis.

1.5 Summary of related works

Most previous works calculate agro-climatic factors from data of local weather stations. The input climate data are usually not global and are less detailed than the data used in this thesis. The creators use interpolation methods, often mention the IDW method. This method is also used in this thesis. The creators do not often describe the calculations in detail, calculations are only briefly indicated. They commonly use isopleths to visualize factors. Isopleths are also used in this thesis to depict agro-climatic factors.

2 Climatic data

Emphasis was placed on the use of freely available data with worldwide coverage and as much granularity as possible. So that the created algorithms can be easily applied anywhere in the world and this master thesis is an example of the use of this data. Therefore dataset ERA5-Land hourly data from 1981 to present from the European Centre for Medium-Range Weather Forecasts (ECMWF) downloaded by Copernicus Climate Data Store was used.

The ERA5-Land dataset is a more detailed successor to the ERA5 dataset. ERA5 is linked to a less detailed EDA (Ensemble of Data Assimilations) model, which contains climate data uncertainties (more in chapter 2.5).

2.1 Description of ERA5-Land hourly data

ERA5-Land is a reanalysis dataset providing a consistent view of the evolution of land climatic variables over several decades. Horizontal coverage is global with resolution 0.1° x 0.1°. Vertical coverage is from 2 m above the surface level to a soil depth of 289 cm. Temporal coverage is now from January 1981 to present with hourly resolution. The data format is GRIB or NetCDF (this thesis work with NetCDF format).[35]

Era5-land is still under development and should be completed during 2020 and incorporates data from 1950 to 2-3 months before the present.[6] During the creation of the thesis, data were available first for the period 1990-2019, later for 1981-2019 (the year 1981 was incomplete). Therefore, the calculations of individual agro-climatic factors are based on these periods. Occasionally, incorrect units appeared for some variables (for example runoff was supposed to be in meters but was in units of m * 0.0001, these errors were corrected by the appropriate constants in the algorithm.

The climatic model used in the production of ERA5-Land is the tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). More information about the used climatic model CY45R1 can be found in its documentation (how individual variables are calculated, spatial interpolations, etc.).[5]

2.2 Selected weather variables of the dataset

In this subchapter, I describe the used climatic variables of the ERA5-Land dataset for calculations in chapter 3.

2.2.1 2 metre temperature

The variable 2 meter temperature was used to calculate agro-climatic factors related to temperature - Frost dates, Frost-free period, GDU, HSU or LGP. This variable provides data on the surface temperature. The units are kelvins, which were subsequently converted to degrees Celsius.

2.2.2 Soil temperature level 2

The soil temperature variable provides information on the soil temperature at a depth of 7-28 cm. It was used to search for autumn days suitable for the application of nitrogen fertilizers. The units are kelvins, which were subsequently converted to degrees Celsius.

2.2.3 Evaporation

Accumulated amount of water evaporated from the Earth's surface and transpired from vegetation. This variable is used in the calculation of weekly, monthly evaporation and water balance. Units are meters of water equivalent.

2.2.4 Runoff

Outgoing water, either over the surface (surface runoff), or under the ground (subsurface runoff). Runoff is used for calculation water balance. The units are meters.

2.2.5 Total precipitation

Accumulated liquid, rain or snow, used for weekly, monthly precipitation totals, water balance calculations.The units are meters.

2.2.6 Surface net solar radiation

Amount of solar radiation reaching the surface of the Earth (direct + diffuse) minus the amount reflected by the Earth's surface used for calculations of received solar radiation. The units are meters $J{\cdot}m^{-2}$.

2.3 Area of interest

To calculate the agro-climatic factors in the Pilsen region, a set of points (= data with climatic variables) was used, in the range of a rectangle covering the entire Pilsen region. So that only interpolation is used for visualization of agro-climatic factors, not extrapolation. Area of Pilsen region and the selection set of points can be seen in the following figure.

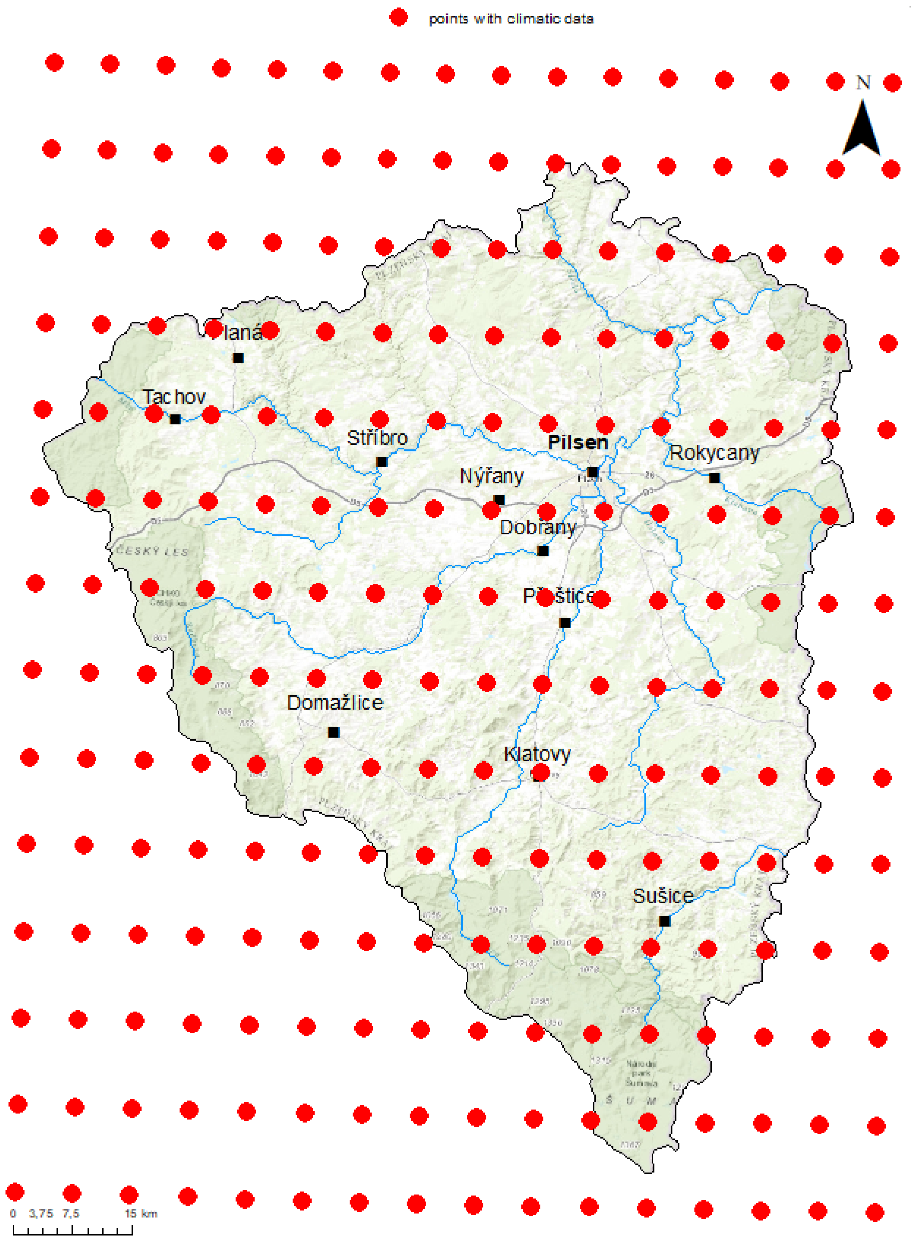

Fig. 1: Pilsen area and points with climatic data attributes used for agro-climatic factor calculation and following visualization (WGS 1984, UTM 33N)

2.4 Used time coverage

Hourly data from 1982 to 2019 or from 1990 to 2019 were used for the calculation of agro-climatic factors in the Pilsen region. The years 1979-1981 showed incomplete data during the calculation and were thus excluded from the calculations.

2.5 Uncertainty

For the time being, ERA5-Land in Copernicus Climate Change Service does not allow the download of information about uncertainties of an associated EDA model for specific ERA5-Land places. In case of an attempt to download the associated uncertainties based on the EDA, it is necessary to go through the download of EDA information connected with the ERA5 dataset.

ERA5 climate data contains some uncertainty provided by the EDA (Ensemble of Data Assimilations) system. Uncertainty estimation help understand the relative accuracy of the ERA5 (or ERA5-Land) system, to identify areas/periods where the products are thought to be less or more reliable, although the uncertainty values provided by the EDA system should not be taken at face value. The EDA system addresses uncertainties related to the observing system, sea surface temperature and the model (through its physical parametrizations).[19]

The uncertainty as defined for ERA5 by the EDA system is not a classical measure of error concerning the ERA5 product. The EDA takes into account mostly random uncertainties in the observations (sea surface temperature and the physical parametrizations of the model). In principle, if these uncertainties are properly described and also there are no additional sources of uncertainty, then the EDA system will properly describe the reanalysis uncertainties. Nonetheless, systematic model errors are not taken into account by the EDA and the uncertainties as defined by the EDA are uncorrelated. Moreover, the EDA has a lower resolution than ERA5 itself (and much lower than ERA5-Land), so the EDA system is unable to directly describe all the uncertainties of ERA. Consequently, there are limitations on the use of the EDA system for uncertainty estimation in ERA5 and ERA5-Land because not all the uncertainties are accounted for and also because the EDA system was not designed for uncertainty estimation. Nevertheless, comparison of uncertainties provides information on where and when the reanalysis products are more or less accurate, and where for a given day or season there are larger uncertainties.[19]

Estimates of uncertainties are provided in a horizontal resolution of about 60 km and temporal resolution of 3 hours.[19]

3 Calculated agro-climatic factors

This chapter includes a description, calculation, and results of selected fundamental agro-climatic factors.

Agro-climatic factors were selected based on related previous works, climatic data. Subsequently, their calculation was searched, proposed, and consulted with Meteoblue.

3.1 Frost-free period, frost dates

3.1.1 Description of the use of frost data in agriculture

The agricultural season is primarily determined by the period of suitable temperatures for growing crops. Temperatures above zero are a necessary condition for crop growth. Frost has a devastating effect on crops. In light frost (between 0°C and -1/-2 °C) the tender plants are killed. Moderate freeze (between -2 °C and -4 °C) is widely destructive to most vegetation and lower frost is already causing severe damage to most plants.[34][15] This is a general simplification, the effects also vary for different growth stages (see following picture) and different crops. Therefore, it is important for farmers to know the frost-free period in their agricultural areas. Especially the last spring frost date for starting agricultural work and first fall frost date for the cessation of agricultural activities. The likelihood of frost and frost trends over the years will help effective planning.

Growth Stage	Danger Temperature	Symptoms of Damage	Effect on Yield
Tillering	-11 C	Loss of leaf colour, burnt leaf tips, blue cast to crop	Slight to Moderate
Jointing	-4 C	Death of growing points, leaf yellowing, burnt leaves, splitting and bending of lower stems	Moderate to Severe
Boot	-2 C	Leaf discolouration, floret sterility, spike trapped in boot, damage to lower stem	Moderate to Severe
Heading	-1 C	Leaf discolouration, floret sterility, damage to lower stem, white awns or spikes	Severe
Flowering	-1 C	Leaf discolouration, floret sterility, damage to lower stem, white awns or spikes	Severe
Milk	-2 C	Leaf discolouration, damage to lower stem, white awns or spikes, shrunken, rough or discoloured kernels	Moderate to Severe
Dough	-2 C	Shrivelled, discoloured kernels, poor germination	Slight to Moderate

Fig. 2: How Frost Damage Affects Crops [7]

The last spring frost date, the first fall frost date

The last spring date is usually called the last day during spring (more correctly from winter to summer) when the minimum daytime temperature is less than 0 °C. The first fall date as the first day in the second half of the year (during autumn), when the minimum temperature is below zero. Usually, this date is given with a 50% or 10% probability (statistically from several years) that it will freeze later (spring date) or sooner (fall date). For farmers, knowledge of days with a low probability of frost is necessary for farming planning and decision-making to avoid destructive effects, hence dates with a last/first frost with a low probability (eg 10%) are desirable. Sometimes frost dates are also given for other freezing temperatures e.g. for moderate freeze - 2 °C as you can see for example in the Agroclimatic Atlas of Canada.[10]

Frost-free period

The frost-free period is a period from the last spring frost to the first fall frost. It includes a period suitable for growing crops.

3.1.2 Algorithm of calculating the frost-free period and the frost dates

Description of the algorithm

The minimum daily temperatures are a necessary variable for determining frost dates. The daily minimum is determined to be the lowest value of the hourly temperatures each day. It is also possible to reduce the searching for the minimum temperature of the day calculation to the time around sunrise, as usually the lowest daytime temperatures are just after sunrise.[7] The algorithm also allows us to request more hours of frost per day to mark a day as the day of frost if we are only interested in more hours of frost daily (one hour of frost is negligible for us). We search for the days where the minimum is below 0°C. Subsequently the algorithm calculates the last freezing day of each year for the spring period and the first freezing day for the autumn period. The spring period is set as a six-month period from the coldest month, the autumn period as 6 months before the coldest month. For the sake of simplicity, the coldest month is designated as January for the northern hemisphere and July for the southern hemisphere, which is the central month of the meteorologist winter season.[18][24]

The hemisphere is determined from latitude. The resulting last spring frost date and first autumn frost date are calculated from the annual frost dates with a corresponding probability. The frost-free period is calculated as the period between the last and the first frost date. Similarly, it is possible to calculate the dates for another temperature threshold (for example for moderate freeze -2°C).

There are also occasional frosts in summer in some areas, therefore, by altering the input parameters, it is possible to calculate more first/last days of frost in a row as the last/first frost date. The last/first frost date with defined probability is calculated from all selected years using the normal distribution. Standard deviation and mean for the normal distribution is calculated from the frost dates of each year. Frost-free period with defined probability is calculated as the difference between these last/first frost dates. The scheme of the algorithm is in following figure.

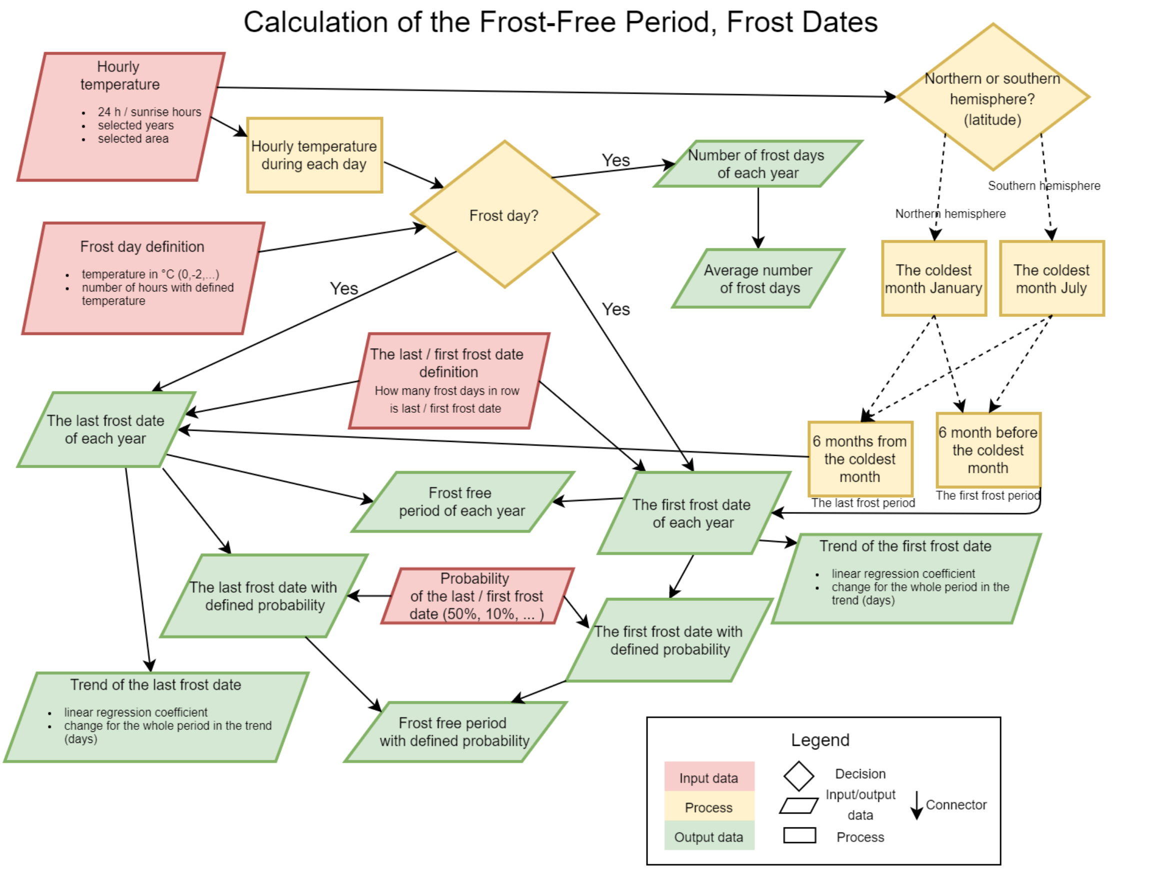

Fig. 3: Scheme of the algorithm for calculation frost dates and frost-free period

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variable 2m temperature (NECDF files by years, selected area)[35]
- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates frost-free periods and frost dates of each year between these years and the probability of frost-free period and frost date from all these years.
- Parameters of daily hours of minimum temperatures: start hour (integer, values between 0 and 23), end hour (integer, values between 0 and 23). It can be set to 0, 23 or changed to sunrise hours
- Parameters of frost day definition: a defined temperature in °C (integer), for example, the already mentioned 0 or -2 °C number of hours with defined temperature (integer, values between 1 and 24)
- Parameters of the last/first frost date definition number of frost days in a row considered as the last/first frost date (integer, values equal to one or greater)
- Parameter of a probability: a defined probability of the frost-free period and frost dates from selected years to get results with corresponding probability (integer, percent, values between 10 and 90). This probability can be obtained in the case of 2 or more calculated years.

Output

Geojson and Shapefile - points with attributes:

- The first frost date of each year (date)
- The last frost date of each year (date)
- The frost-free period of each year (integer, days)
- The first frost date with a defined probability (date)
- The last frost date with a defined probability (date)
- The frost-free season with a defined probability (integer, days)
- Number of frost days of each year (integer, days)
- The average number of frost days (integer, days)
- The trend of the first/last frost dates

- Linear regression coefficient (decimal number)
- Change for the whole period in the trend (integer, days)

3.1.3 Calculation

Frost dates and Frost-free period was calculated for Pilsen region and years 2010-2019 (0/-2 °C, 50/10% probability), 2000-2009 (0 °C, 50% probability), 1990-1999 (0 °C, 50% probability) and 1982-2019 (0/-2°C, 50% probability). Temperature and percentage thresholds were set following the Agroclimatic Atlas of Canada, temperatures for light or moderate freeze, average (50% probability), or low probability (10%).[10] The minimum daily temperature was calculated from 24 hours and only 1 frost hour a day was enough to mark the day as a frost day. All possible years were counted (1982-2019, complete climate data are since 1982), and also the ten-year periods were chosen for comparison. The scheme of calculation with the described parameters can be seen in following figure. The spring period in this area is during the first half of the year.

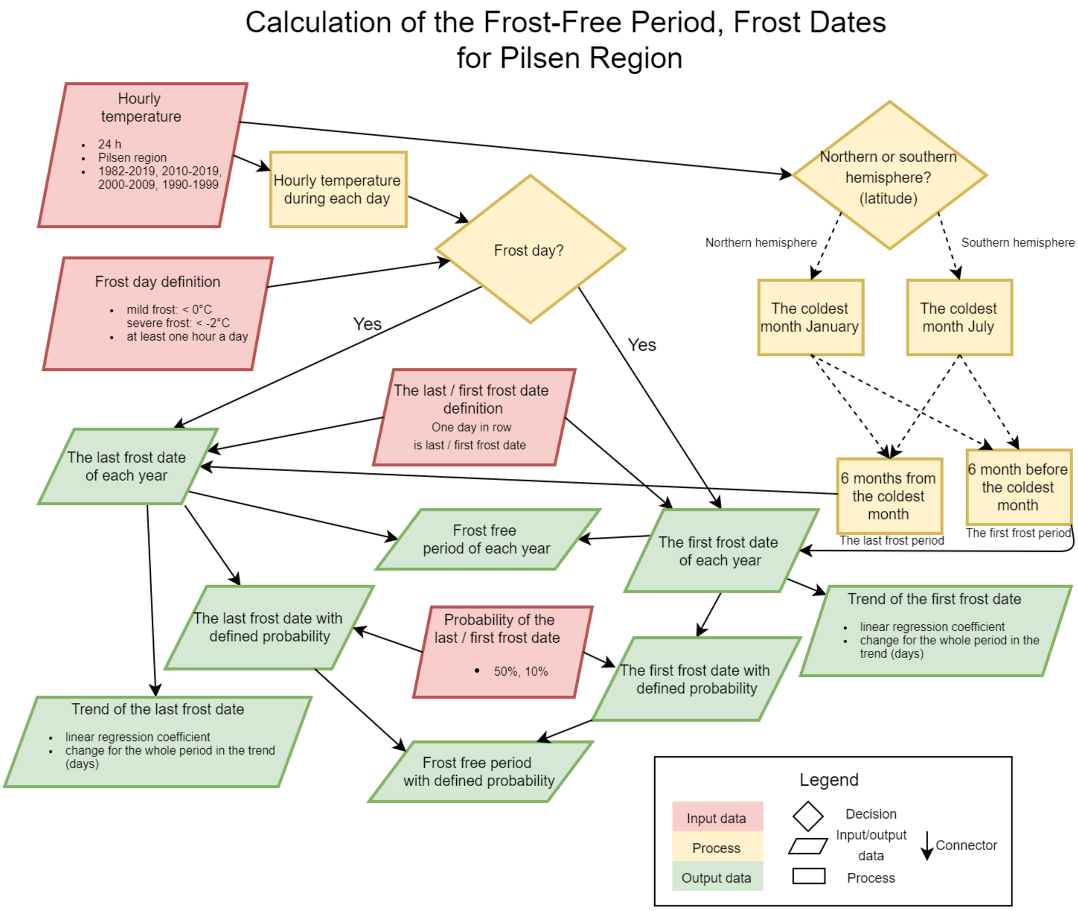

Fig. 4: Diagram of frost dates and frost-free period calculation for Pilsen Region

3.1.4 Results

The results were saved to Geojson and Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by following 15 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31]

Created maps (in annexe):

- 1 - Dates of Last Spring Freeze of 0 °C, 2010-2019, 50% Probability, Pilsen Region
- 2 - Dates of Last Spring Freeze of 0 °C, 2010-2019, 10% Probability, Pilsen Region
- 3 - Dates of Last Spring Freeze of -2 °C, 2010-2019, 50% Probability, Pilsen Region
- 4 - Dates of Last Spring Freeze of -2 °C, 2010-2019, 10% Probability, Pilsen Region

- 5 - Dates of Last Spring Freeze of 0 °C, 1982-2019, 50% Probability, Pilsen Region
- 6 - Dates of Last Spring Freeze in Last Three Decades 1990-1999, 2000-2009, 2010-2019 (0 °C, 50% Probability, Pilsen Region)
- 7 - Dates of First Fall Freeze of 0 °C, 2010-2019, 50% Probability, Pilsen Region
- 8 - Dates of First Fall Freeze of 0 °C, 2010-2019, 10% Probability, Pilsen Region
- 9 - Dates of First Fall Freeze of -2 °C, 2010-2019, 50% Probability, Pilsen Region
- 10 - Dates of First Fall Freeze of -2 °C, 2010-2019, 10% Probability, Pilsen Region
- 11 - Dates of First Fall Freeze of 0 °C, 1982-2019, 50% Probability, Pilsen Region
- 12 - Dates of First Fall Freeze in Last Three Decades 1990-1999, 2000-2009, 2010-2019 (0 °C, 50% Probability, Pilsen Region)
- 13 - Frost-Free Period of 0 °C, 2010-2019, 50% Probability, Pilsen Region
- 14 - Frost-Free Period of 0 °C, 2010-2019, 10% Probability, Pilsen Region
- 15 - Frost-Free Period of 0 °C, 1982-2019, 50% Probability, Pilsen Region

Graphs of results for one specific location in the following figures, including a simple trend view.

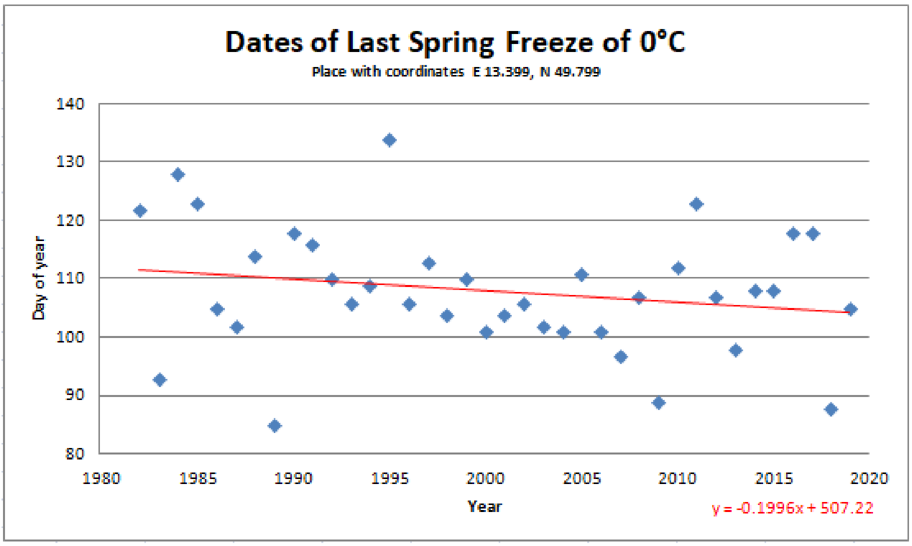

Fig. 5: Graph of Dates of Last Spring Freeze of 0 °C between years 1982-2019 with linear regression function (trend)

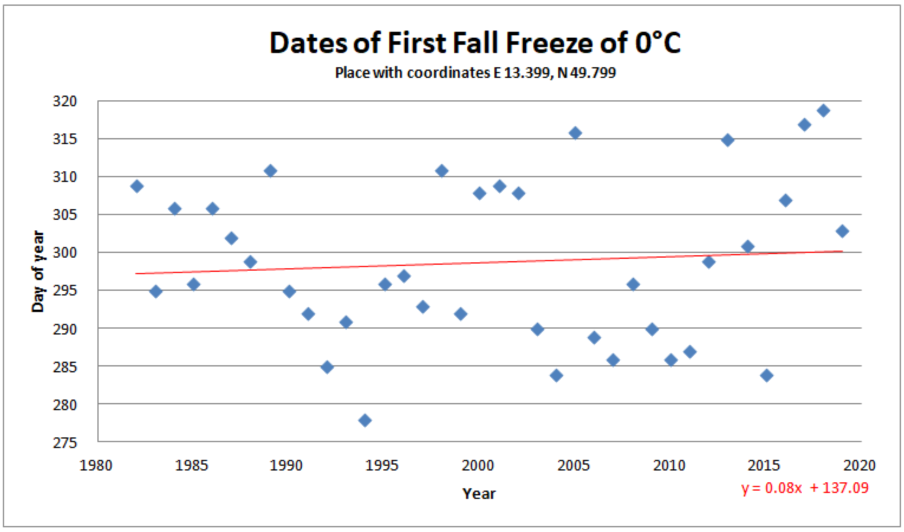

Fig. 6: Graph of Dates of First Fall Freeze of 0 °C between years 1982-2019 with linear regression function (trend)

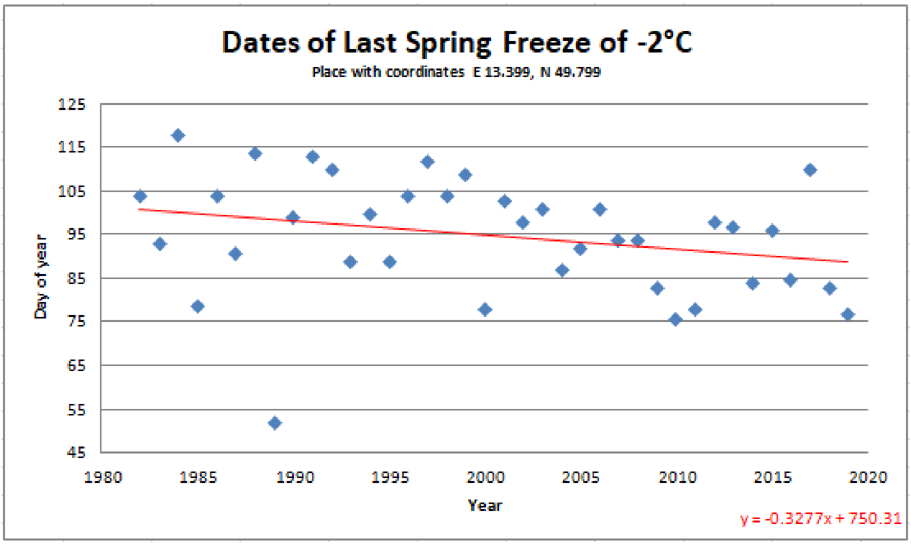

Fig. 7: Graph of Dates of Last Spring Freeze of -2 °C between years 1982-2019 with linear regression function (trend)

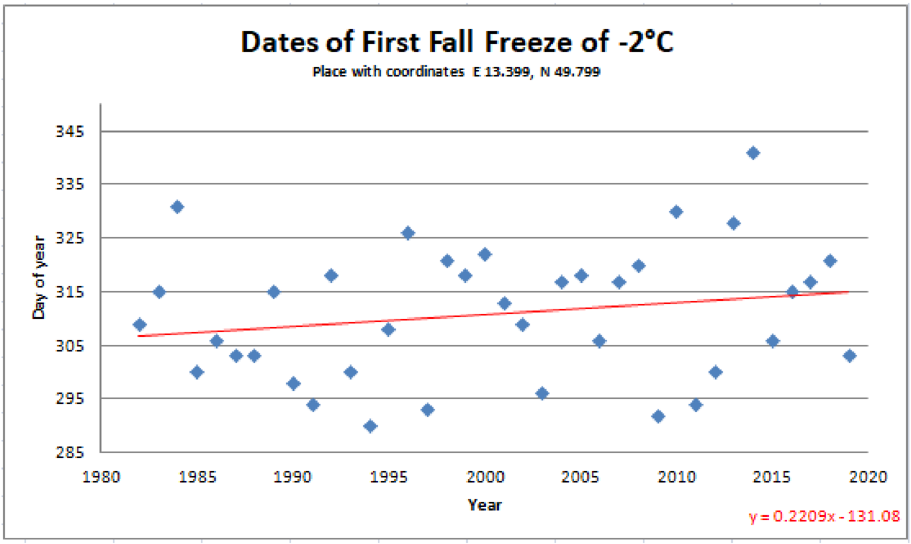

Fig. 8: Graph of Dates of First Fall Freeze of -2 °C between years 1982-2019 with linear regression function (trend)

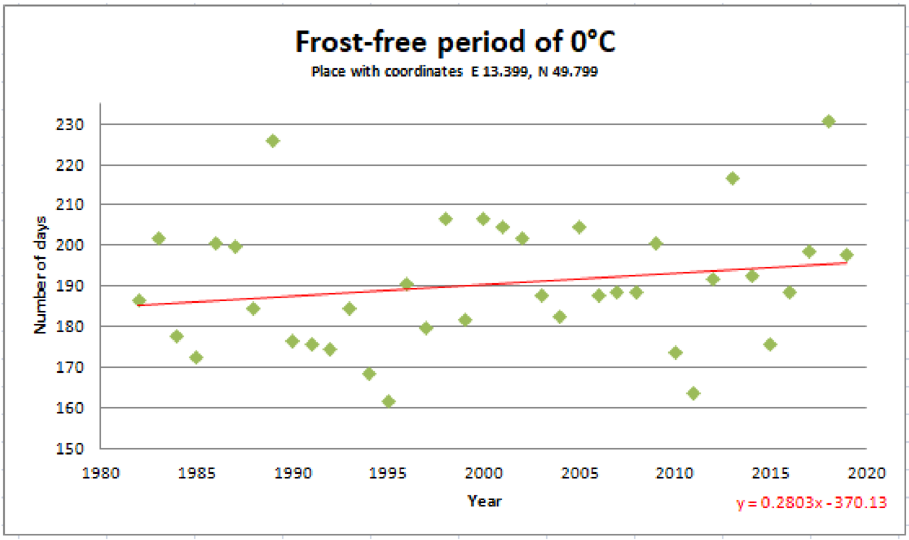

Fig. 9: Graph of Frost-free period of 0 °C between years 1982-2019 with linear regression function (trend)

3.2 Dates of Fall Nitrogen Application

3.2.1 Description of the use of soil temperatures for fall nitrogen application

Fall soil temperatures (10 cm depth) determine when ammonium nitrogen fertilization can be applied without excessive nitrification during the autumn and winter.

It is recommended to wait until the soil temperatures remain below 10 °C. Otherwise the forms of nitrogen can potentially be lost from soils. Denitrification below 10 °C is limited. A way to slow conversion of ammonium to nitrate is to have cold soil temperatures (simplified soil nitrogen cycle in Figure 1). Therefore we search for last fall dates with soil temperature above 10°C.[30]

The last date when the temperature is above 16°C is sometimes used as a guide for estimating when anhydrous ammonia application with a nitrification inhibitor may begin. Usually these dates are given with a 50% probability (statistically from several years).[20]

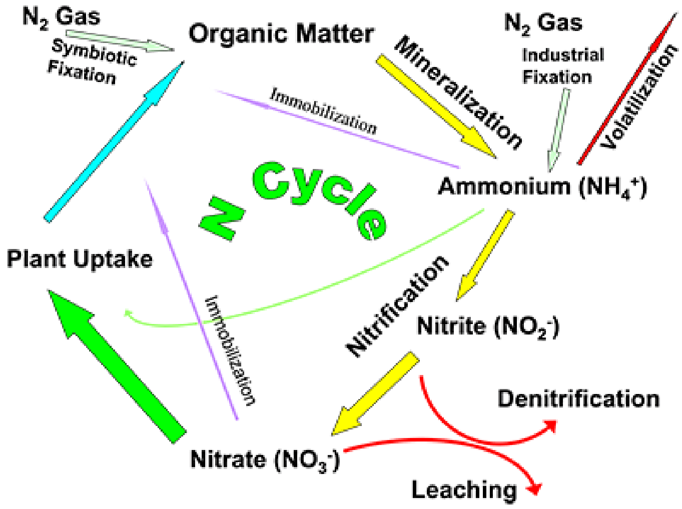

Fig. 10: Simplified soil nitrogen cycle [30]

3.2.2 Algorithm of calculating the last fall dates with required soil temperature

Description of algorithm

The last fall date with required soil temperature is calculated from daily average temperatures. Either the average can be calculated from all hours of the day or the calculation can be simplified to a lower number of hours (soil temperatures do not have significant daily variability). We find days that are during the fall period and where the daily average is above a soil temperature threshold. Subsequently, the searched date of each year is the last day of these days. The fall period is set as 6 months before the coldest month. For the sake of simplicity, the coldest month is designated as January for the northern hemisphere and July for the southern hemisphere, which is the central month of the meteorologist winter season.[18][24]

The last fall date with defined probability is calculated from all selected years using the normal distribution. Standard deviation and mean for the normal distribution is calculated from the last dates of each year. The scheme of the algorithm is in following figure.

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variable Soil temperature level 2 (NECDF files by years, selected area)[35]
- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates the last fall date of each year between these years and the probability of the fall date from all these years.
- Parameters of daily hours with soil temperatures: start hour (integer, values between 0 and 23), end hour (integer, values between 0 and 23). It can be set to 0, 23, or limited to fewer hours if necessary.
- Parameter of temperature threshold for fall nitrogen application (integer, degrees Celsius, recommended values: 10 or 16)
- Parameter of a probability: a defined probability of the last fall date from selected years to get results with corresponding probability (integer, percent, values between 10 and 90). This probability can be obtained in the case of 2 or more calculated years.

Output

Geojson and Shapefile - points with attributes:

- The last fall date of each year (date)
- The last fall date with a defined probability (date)
- The trend of the last fall dates
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (integer, days)

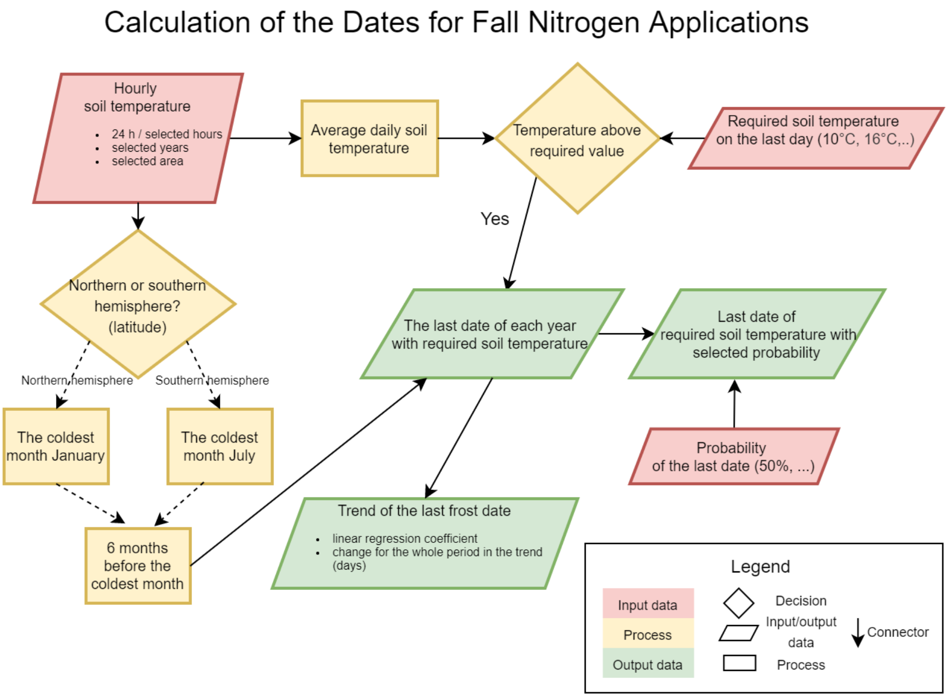

Fig. 11: Scheme of the algorithm for calculation dates for fall nitrogen applications

3.2.3 Calculation

Dates for fall nitrogen application was calculated for Pilsen region and years 2010-2019 (10/16°C, 50% probability), 2000-2009 (10°C, 50% probability), 1990-1999 (10°C, 50% probability) and 1982-2019 (10/16°C, 50% probability). Temperature thresholds were set following the Illinois Agronomy Handbook to 10 or 16 degrees.[20] The average daily temperature was calculated from 24 hours. All possible years were counted (1982-2019, complete climate data are since 1982), and also the ten-year periods were chosen for comparison. The scheme of calculation with the described parameters can be seen in following figure. The fall period in this area is during the second half of the year.

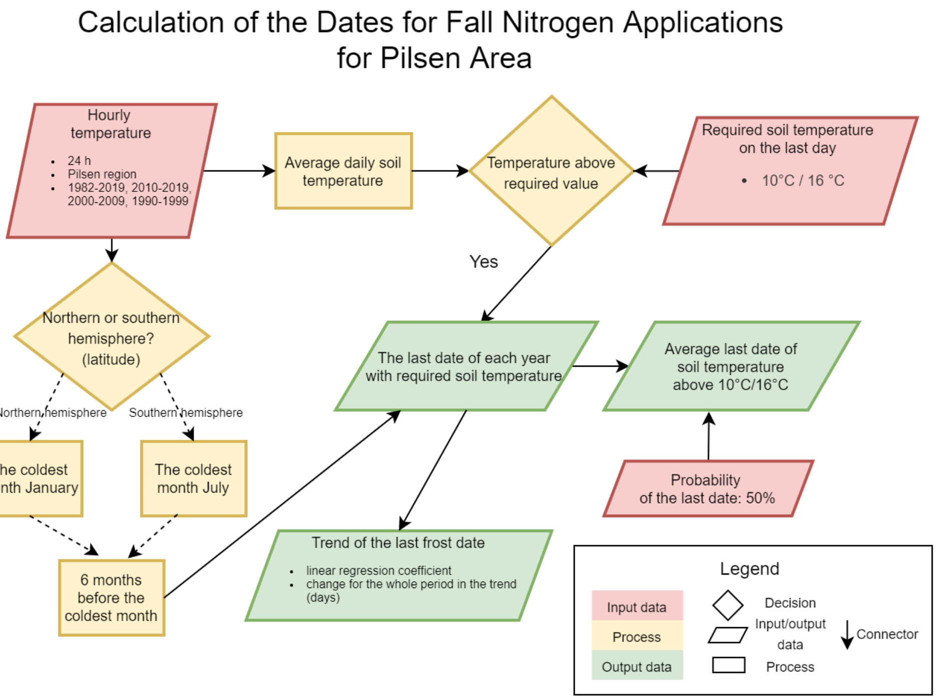

Fig. 12: Diagram of dates for fall nitrogen applications in Pilsen region

3.2.4 Results

The results were saved to Geojson, Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by the following 5 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31]

Created maps (in annexe):

- 16 - Dates of Last Fall Soil Temperature above 10°C, 2010-2019, 7-28 cm, 50% Probability, Pilsen Region
- 17 - Dates of Last Fall Soil Temperature above 16°C, 2010-2019, 7-28 cm, 50% Probability, Pilsen Region
- 18 - Dates of Last Fall Soil Temperature above 10°C, 1982-2019, 7-28 cm, 50% Probability, Pilsen Region
- 19 - Dates of Last Fall Soil Temperature above 16°C, 1982-2019, 7-28 cm, 50% Probability, Pilsen Region
- 20 - Dates of Last Fall Soil Temperature above 10°C in Last Three Decades 1990-1999, 2000-2009, 2010-2019 (7-28 cm, 50% Probability, Pilsen Region)

Graphs of results for one specific location in the following figures, including a simple trend view.

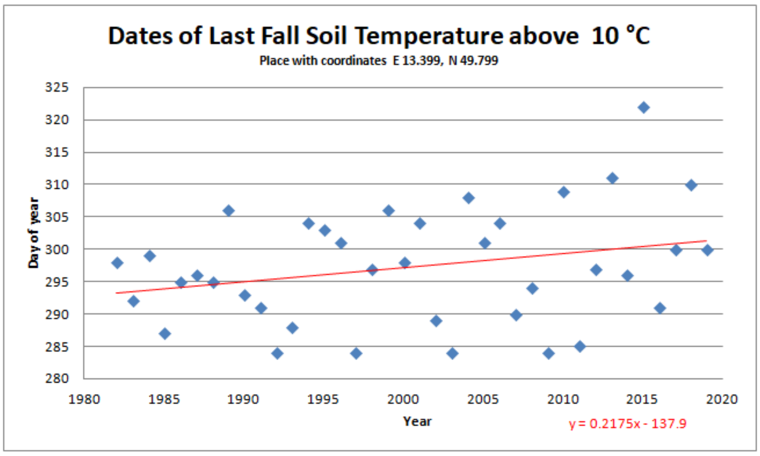

Fig. 13: Graph of Dates of Last Fall Soil Temperature above 10°C between years 1982-2019 with linear regression function (trend)

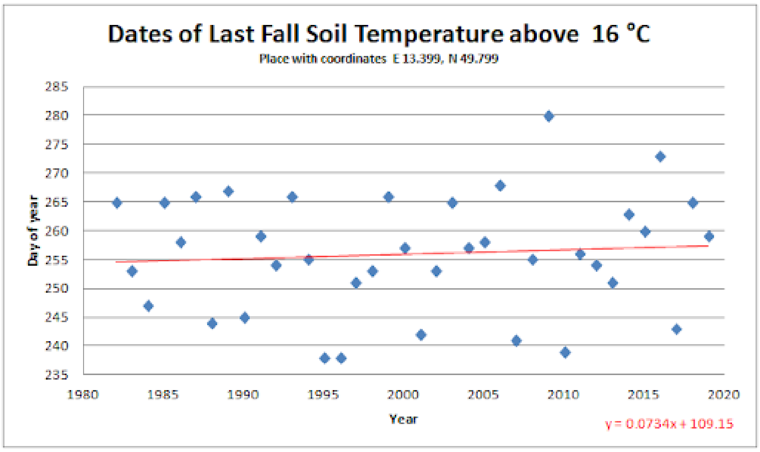

Fig. 14: Graph of Dates of Last Fall Soil Temperature above 16°C between years 1982-2019 with linear regression function (trend)

3.3 Solar radiation

3.3.1 Description of the use of solar radiation in agriculture

Solar radiation is essential for crop growth. Plants absorb sunlight and use it to fix carbon dioxide from the atmosphere into carbohydrates that cause plants to grow and reproduce.[20] The above-ground biomass of the crop grows with the amount of captured solar radiation, the relationship for crops C4 and C3 can be seen in following figure.[9]

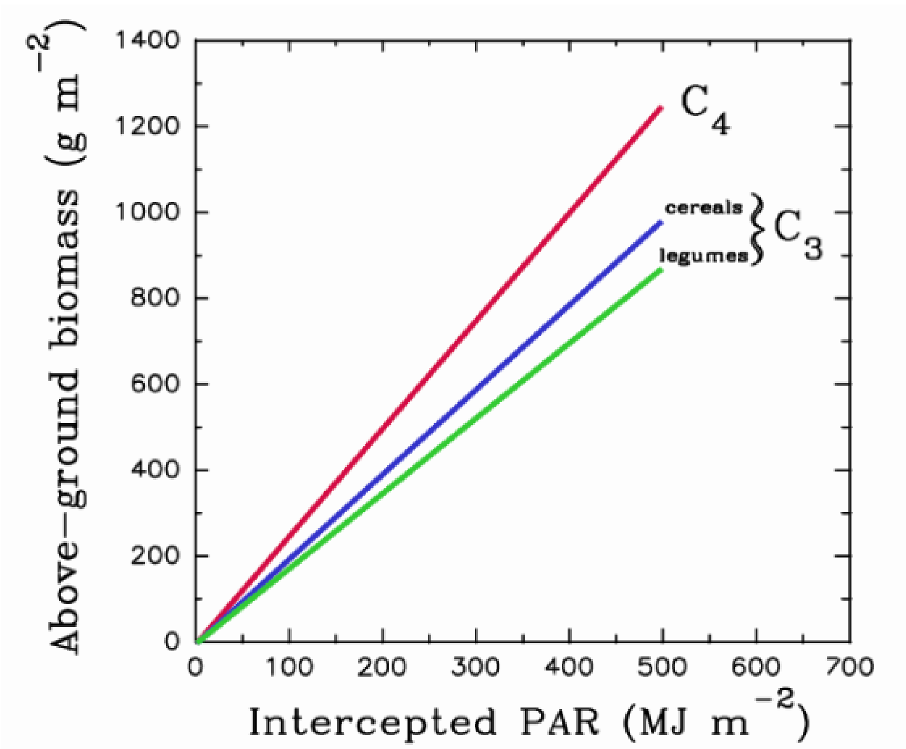

Fig. 15: Relationships between accumulated aboveground biomass and accumulated intercepted solar radiation for C4 and C3 crops [17]

Farmers can increase the crop potential to capture sunlight based on information about the amount of sunlight falling in a given period. The amount of solar radiation is usually given in megajoules per square meter. The information is often presented using accumulated solar radiation during the year and averages from the last few years.[20]

3.3.2 Algorithm of calculating information about solar radiation during the year

Description of the algorithm

Daily solar radiation is obtained from the sum of hourly solar radiation. Subsequently, weekly solar radiation is calculated from daily values. The weeks do not correspond to the weeks in the calendar, but they are seven-day cycles from the beginning of the year (or selected another start of the year, eg the start of the growing season). Solar radiation accumulated weekly is then calculated for each year a then there is also calculated average value of year accumulation. The accumulated values give information on the annual availability of solar radiation for crops. Average weekly radiation is calculated from weekly values and is used to provide information on the likely amount of radiation available during each week and the trend over the years. The algorithm also calculates the annual radiation, the average of the selected years, and the coefficient of the linear trend of these values. The scheme of the algorithm is in following figure.

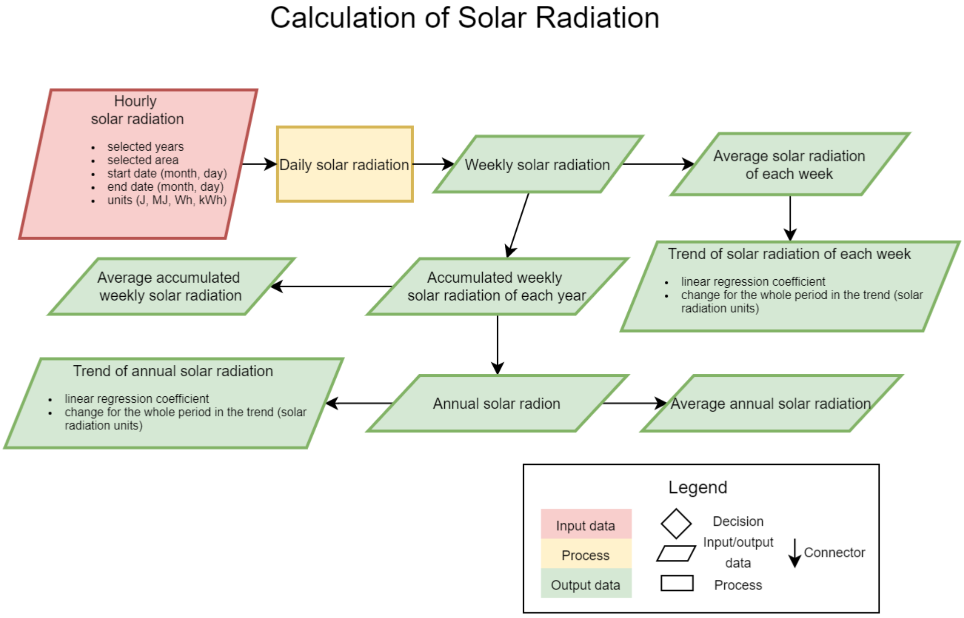

Fig. 16: Scheme of the algorithm for calculation information about solar radiation during the year

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variable
- Surface net solar radiation (NECDF files by years, selected area) [35]

- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates solar of each year between these years and the average of solar radiation from all these years. Average can be obtained in the case of 2 or more calculated years.
- Parameters of a selected period of the year, start date: start month (integer), start day (integer), end date: end month (integer), end day (integer). Solar radiation can be calculated for the whole year, growing season, or other selected period.
- Parameter of units, offered units: J*m^{-2}, MJ*m^{-2}, Wh, kWh

Output

Geojson and Shapefile (more files) - points with attributes:

- The annual sum of solar radiation of each year (decimal number)
- The average annual sum of solar radiation (decimal number)
- The trend of the annual solar radiation
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)
- The accumulated solar radiation weekly of each year (decimal number)
- The average accumulated solar radiation weekly (decimal number)
- The weekly solar radiation of each year (decimal number)
- The average weekly solar radiation (decimal number)
- The trend of the solar radiation of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)

3.3.3 Calculation

Solar radiation was calculated for Pilsen region and years 2010-2019, 2000-2009, 1990-1999, and 1982-2019. The solar radiation was calculated for whole years. All possible years were counted (1982-2019, complete climate data are since 1982), and also the ten-year periods were chosen for comparison. The scheme of calculation with the described parameters can be seen in following figure.

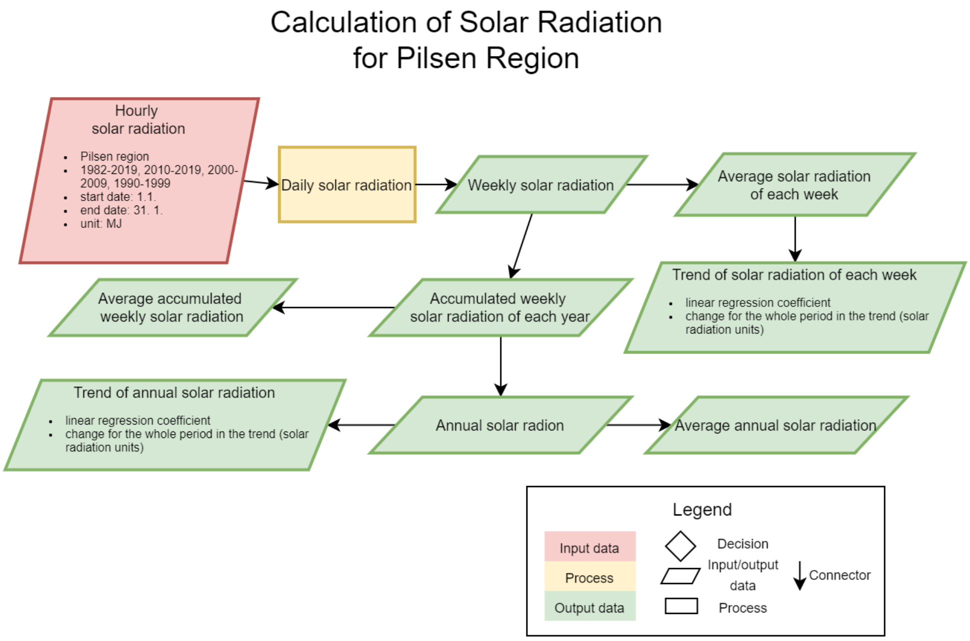

Fig. 17: Diagram of solar radiation calculation for Pilsen Region

3.3.4 Results

The results were saved to Geojson and Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by the following 2 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31]

Created maps (in annexe):

- 21 - Average Annual Solar Radiation 2010-2019 in Pilsen Region
- 22 - Average Annual Solar Radiation in Last Three Decades 1990-1999, 2000-2009, 2010-2019, Pilsen Region

Graphs of results for one specific location in the following figures.

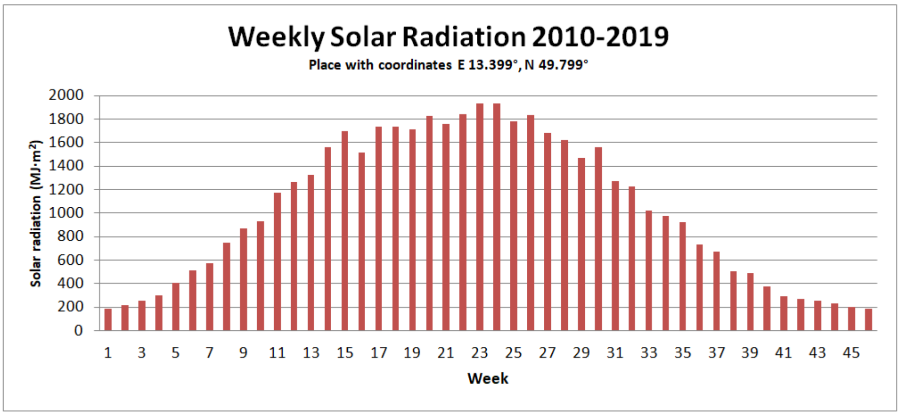

Fig. 18: Graph of average solar radiation of each week between the years 2010 and 2019

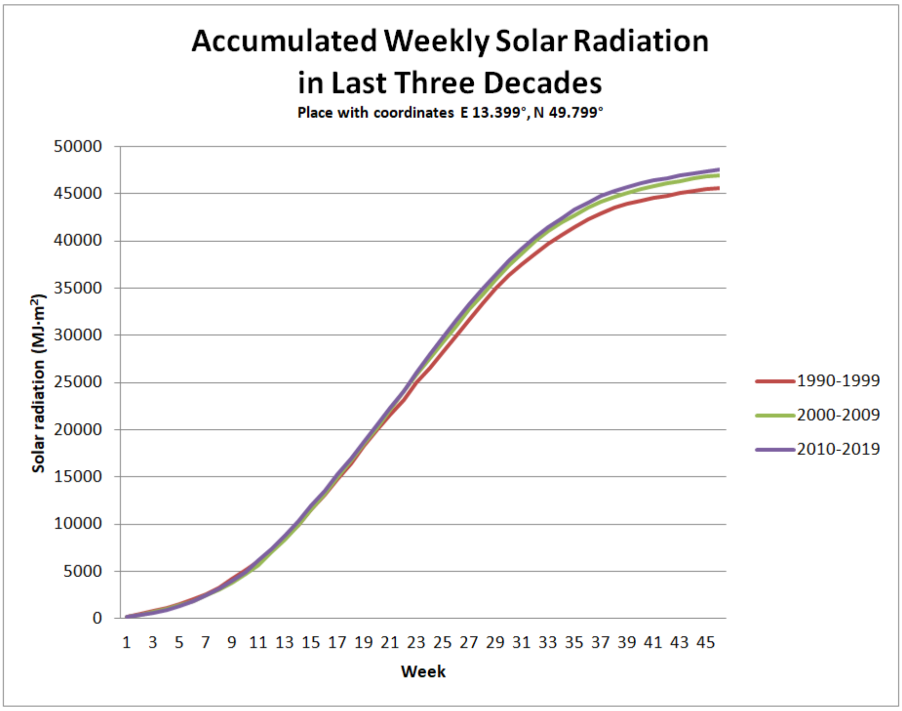

Fig. 19: Graph of accumulated weekly solar radiation in the last three decades

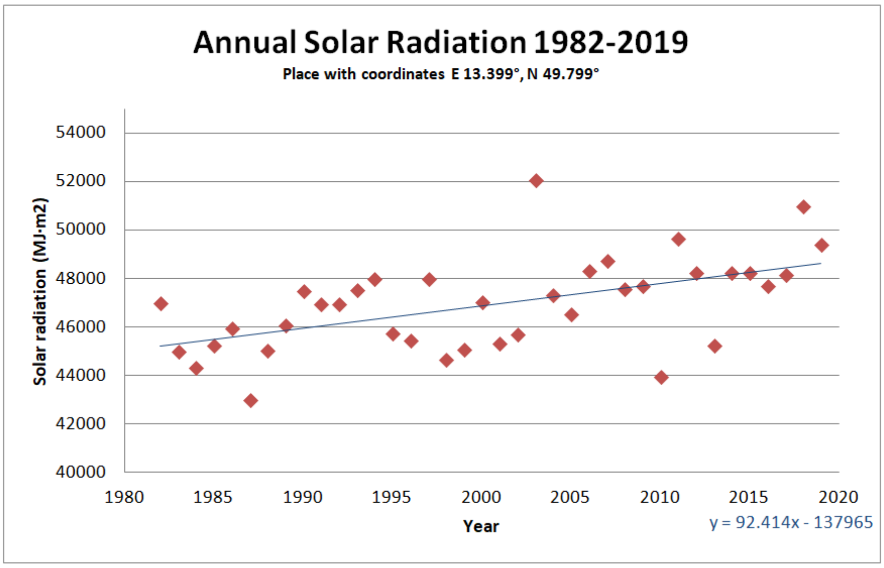

Fig. 20: Graph of the annual sum of solar radiation between years 1982-2019 with linear regression function (trend)

3.4 Growing degree units, heat stress units, number of growing days, number of days with optimal temperatures for growing

There are four temperature thresholds, the cardinal temperatures, that define relationship between temperature and crop growth. These thresholds are the absolute minimum, the optimum minimum, the optimum maximum and the absolute maximum. [20] Thresholds for C3, C4 crops can be seen in following figure.

3.4.1 Description of growing degree units

Growing degree units (GDU) are used to relate temperature to crop development. GDU are accumulated when the average daily temperature exceeds the absolute minimum temperature threshold for the growth of a given crop. The difference between the daily temperature average and the temperature threshold of the plant is the accumulated GDU value for a given day.[20] For example, when the temperature is two degrees higher than the minimum for plant growth, 2 growing degree units are added.

3.4.2 Description of heat stress units

Heat stress units (HSU) are used to detect high temperatures unsuitable for crop growth. When the maximum daily temperature is higher than the absolute maximum temperature for crop growth, HSU are accumulated.[20] For example, if the threshold is exceeded by three degrees, three units are added.

3.4.3 Description of number of growing days

The number of growing days includes all growth days, days when the average temperature is in the interval from the absolute minimum to the absolute maximum of selected crop.

3.4.4 Description of number of days with optimal temperatures for growing

Number of days with optimal temperatures for growing is sum of days when the average daily temperature is at the best temperatures for crop growth, between the optimal minimum and optimal maximum of selected crop.

C4 crops

the absolute minimum: 7 - 10 °C
the optimum minimum: 15 - 27 °C
the optimum maximum: 33 - 40 °C
the absolute maximum: 40 - 47 °C

C3 crops

the absolute minimum: 2 - 5 °C
the optimum minimum: 15 - 20 °C
the optimum maximum: 23 - 33 °C
the absolute maximum: 27 - 38 °C

(Source: Weather and Crops)

Fig. 21: Temperature thresholds for C3, C4 crops [20]

3.4.5 Algorithm of calculating GDU, HSU, number of growing days, number of days with optimal temperatures for growing

Description of the algorithm

First, the daily temperature average and the daily temperature maximum are calculated from the hourly temperatures. To calculate the HSU, the calculated daily maximum temperature is taken and compared with the entered maximum absolute temperature threshold of the crop. When a maximum daily temperature is greater than a threshold, the difference is allocated for that day as an HSU value. Similarly, the daily GDU value is calculated, based on a comparison of the average daily temperature and the entered minimum absolute temperature for crop growth. The daily average is also used to calculate whether each day is suitable for crop growth and optimal crop growth. When the daily average temperature is between the absolute maximum and the absolute minimum of the plant, the day is assigned to calculate the number of growing days. Analogously, it is determined whether the daily average is in the specified optimal thresholds for the plant.

All these factors calculated for each day (HSU, GDU, growing day, optimal growing day) are then added up weekly. Weeks do not correspond to the calendar, but are calculated as seven day cycles from the first day (the first day of the year or another specified day - the beginning of the growing season). Weekly averages from all years, weekly accumulation of factors for each year, average accumulation are calculated. The annual sum and average of annual sum from the selected years are also calculated. Annual trends (linear regression) are also calculated for annual sums and week sums, and the change of these values for selected period is detected from trend. The calculation scheme can be seen in following figure.

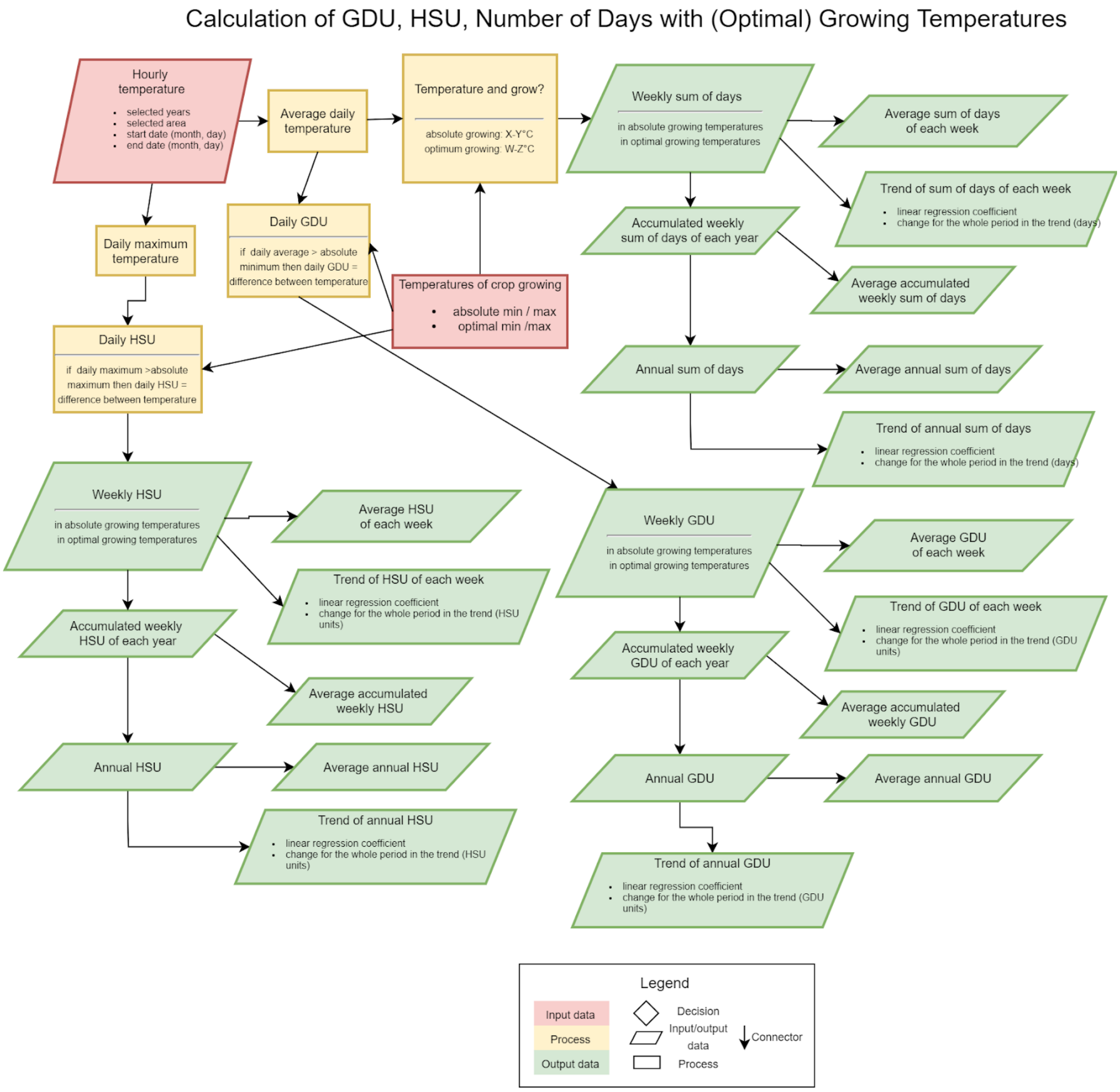

Fig. 22: Scheme of the algorithm for calculation GDU, HSU, number of day with (optimal) growing temperatures

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variable 2m temperature (NECDF files by years, selected area) [35]
- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates GDU, HSU, number of days with growing temperatures, number of days with optimal growing temperatures of each year between these years and average of these factors from all these years.
- Parameters of a selected period of the year, start date: start month (integer),

start day (integer), end date: end month (integer), end day (integer). These factors can be calculated for the whole year, growing season, or other selected period.

- Parameters of temperature thresholds for crop. The absolute minimum (decimal number, degrees of Celsius), the optimum minimum (decimal number, degrees of Celsius), the optimum maximum (decimal number, degrees of Celsius), the absolute maximum (decimal number, degrees of Celsius)

Output

Geojson and Shapefile (more files) - points with attributes:

- The annual sum of GDU of each year (decimal number)
- The annual sum of HSU of each year (decimal number)
- The annual sum of days with growing temperatures of each year (decimal number)
- The annual sum of days with optimal growing temperatures of each year (decimal number)
- The average annual sum of GDU (decimal number)
- The average annual sum of HSU (decimal number)
- The average annual sum of days with growing temperatures (decimal number)
- The average annual sum of days with optimal growing temperatures (decimal number)
- The trend of the annual GDU
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, GDU units)
- The trend of the annual HSU
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, HSU units)
- The trend of the annual sum of days with growing temperatures
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, days)

- The trend of the annual sum of days with optimal growing temperatures
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, days)
- The accumulated GDU weekly of each year (decimal number)
- The accumulated HSU weekly of each year (decimal number)
- The accumulated sum of days with growing temperatures weekly of each year (decimal number)
- The accumulated sum of days with optimal growing temperatures weekly of each year (decimal number)
- The average accumulated GDU weekly (decimal number)
- The average accumulated HSU weekly (decimal number)
- The average accumulated sum of days with growing temperatures weekly (decimal number)
- The average accumulated sum of days with optimal growing temperatures weekly (decimal number)
- The weekly GDU of each year (decimal number)
- The weekly HSU of each year (decimal number)
- The weekly sum of days with growing temperatures of each year (decimal number)
- The weekly sum of days with optimal growing temperatures of each year (decimal number)
- The average weekly GDU (decimal number)
- The average weekly HSU (decimal number)
- The average weekly sum of days with growing temperatures (decimal number)
- The average weekly sum of days with optimal growing temperatures (decimal number)
- The trend of the GDU of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, GDU units)

- The trend of the HSU of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, HSU units)
- The trend of the sum of days with growing temperatures of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, days)
- The trend of the sum of days with optimal growing temperatures of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, days)

3.4.6 Calculation

GDU, HSU, number of days with growing temperatures, number of days with optimal growing temperatures were calculated for Pilsen region and years 2010-2019 and 1982-2019. It was calculated for whole years. All possible years were counted (1982-2019, complete climate data are since 1982), and also the ten-year periods were chosen for comparison. The scheme of calculation with the described parameters can be seen in following figure. This was generally calculated for average C3, C4 plants. Crop temperature thresholds were set as the average of a given group threshold range. For C3 crops the absolute minimum was set to 3.5 °C, the optimum minimum as 17.5 °C, the optimum maximum as 28 °C and the absolute maximum to 32.5 °C. For C4 crops the absolute minimum was set to 8.5 °C, the optimum minimum as 21 °C, the optimum maximum as 36.5 °C and the absolute maximum to 43.5 °C.

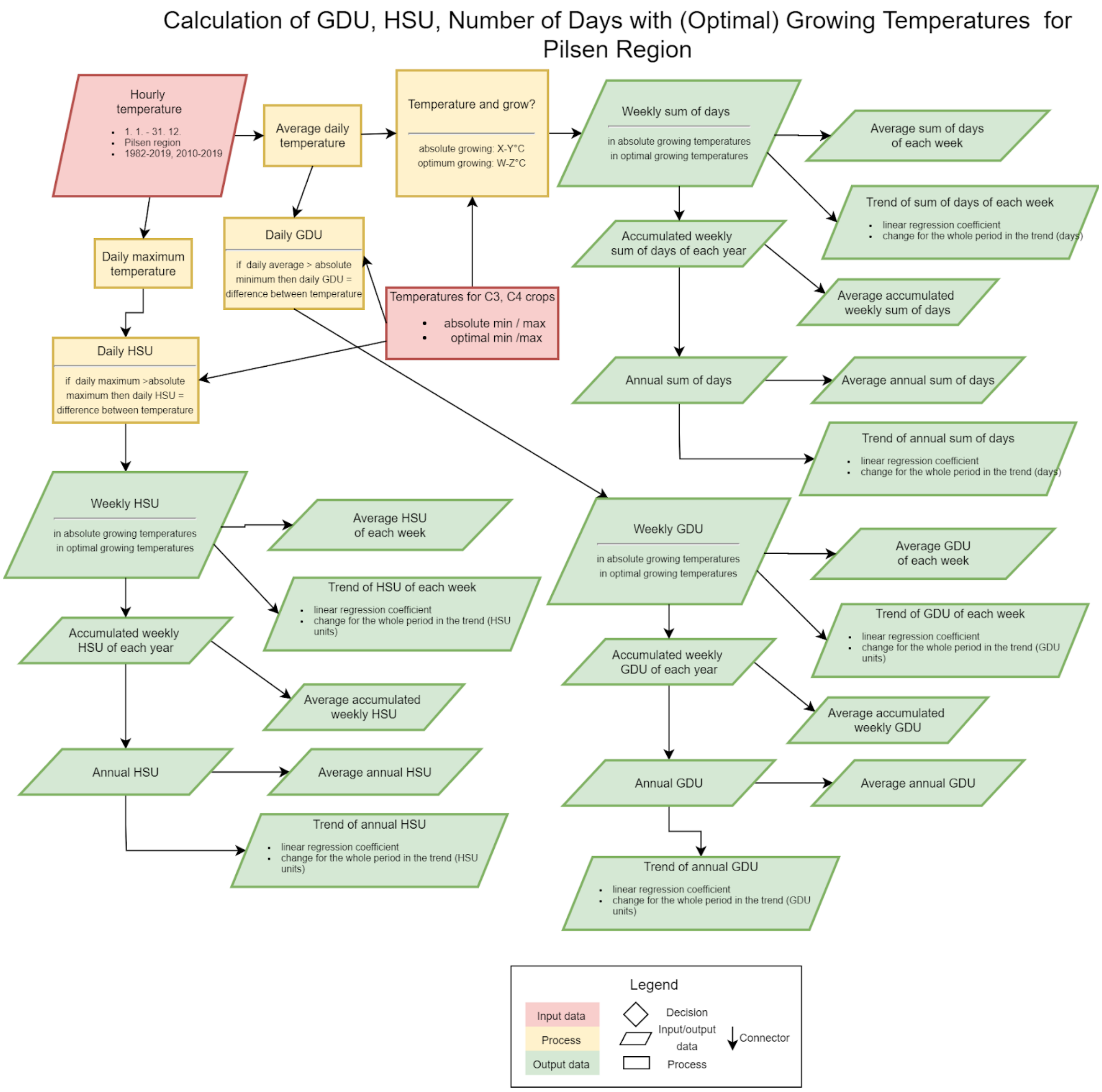

Fig. 23: Diagram of GDU, HSU, number of growing days calculation for Pilsen Region

3.4.7 Results

The results were saved to Geojson and Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by following 7 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31] Heat stress units for C4 crops between years 1982-2019 were not detected.

Created maps (in annexe):

- 23 - Average GDU for C3 Crops 2010-2019 in Pilsen Region
- 24 - Average GDU for C4 Crops 2010-2019 in Pilsen Region
- 25 - Average HSU for C3 Crops 2010-2019 in Pilsen Region
- 26 - Average Number of Growing Days for C3 Crops 2010-2019 in Pilsen Region
- 27 - Average Number of Growing Days for C4 Crops 2010-2019 in Pilsen Region
- 28 - Average Number of Optimal Growing Days for C3 Crops 2010-2019 in Pilsen Region
- 29 - Average Number of Optimal Growing Days for C4 Crops 2010-2019 in Pilsen Region

Graphs of results for one specific location in the following figures, including a simple trend view.

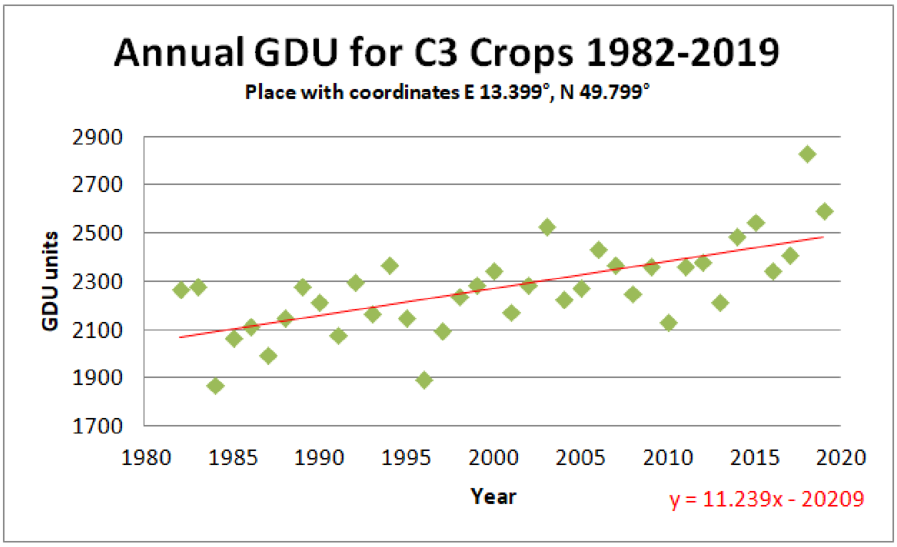

Fig. 24: Graph of annual GDU for C3 crops between years 1982-2019 with linear regression function (trend)

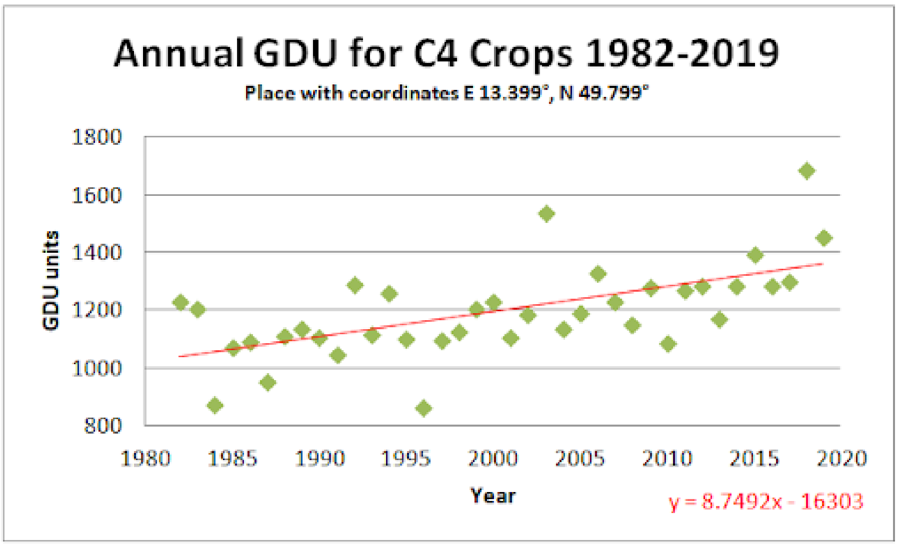

Fig. 25: Graph of annual GDU for C4 crops between years 1982-2019 with linear regression function (trend)

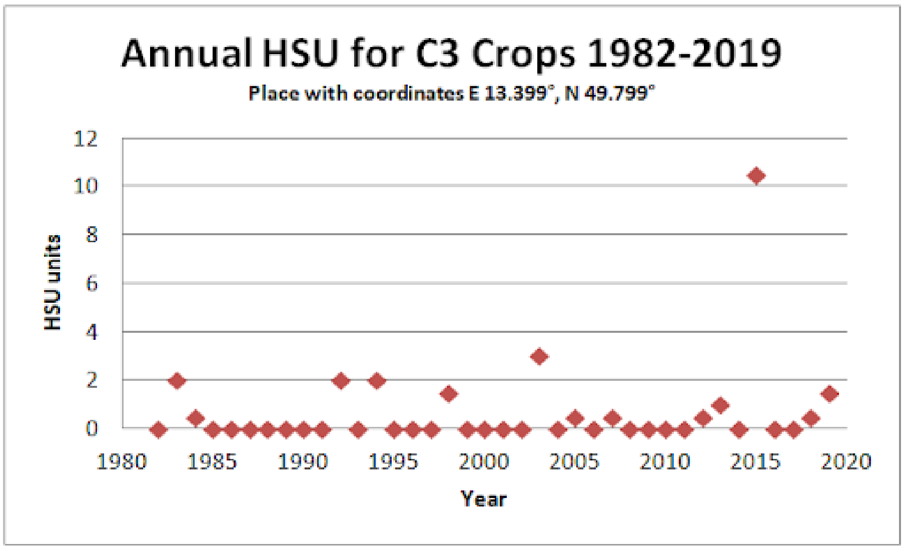

Fig. 26: Graph of annual HSU for C3 crops between years 1982-2019

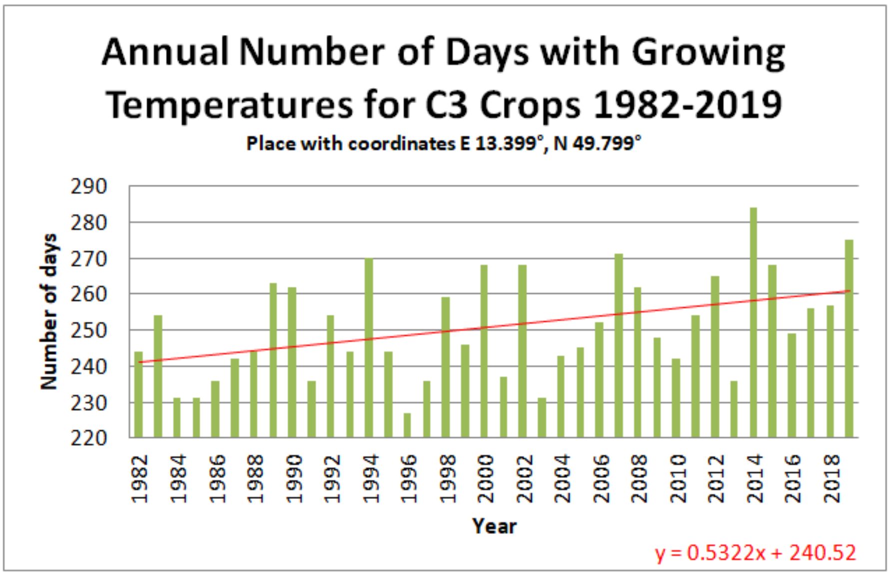

Fig. 27: Graph of annual number of days with growing temperatures for C3 crops between years 1982-2019 with linear regression function (trend)

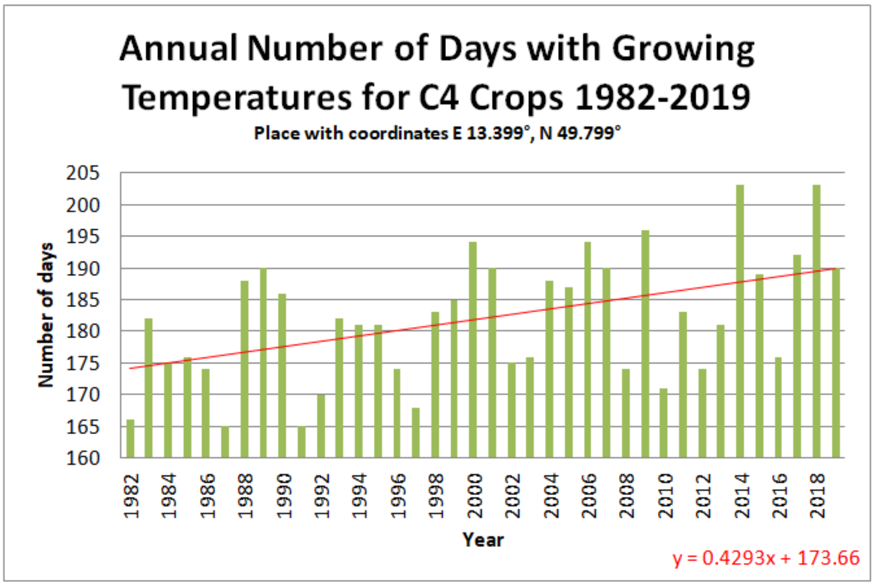

Fig. 28: Graph of annual number of days with growing temperatures for C4 crops between years 1982-2019 with linear regression function (trend)

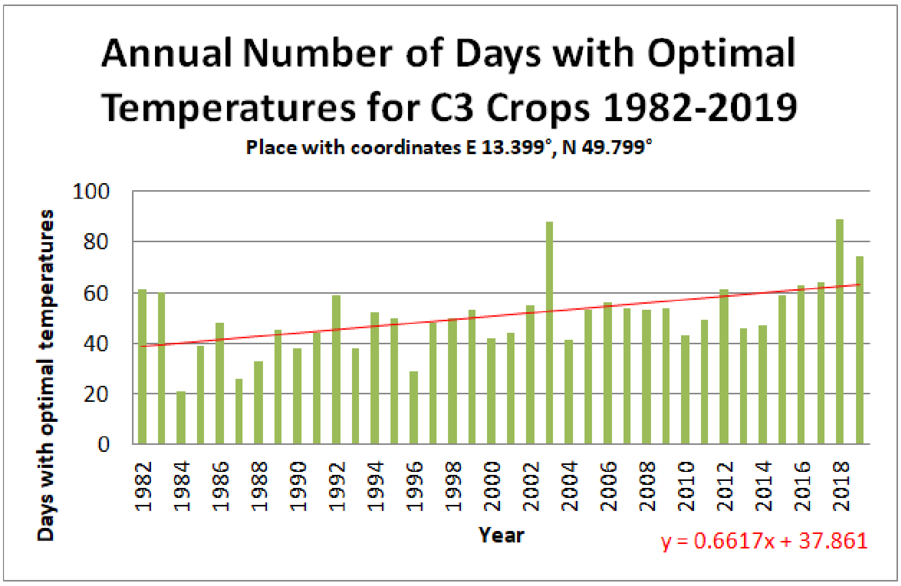

Fig. 29: Graph of annual number of days with optimal growing temperatures for C3 crops between years 1982-2019 with linear regression function (trend)

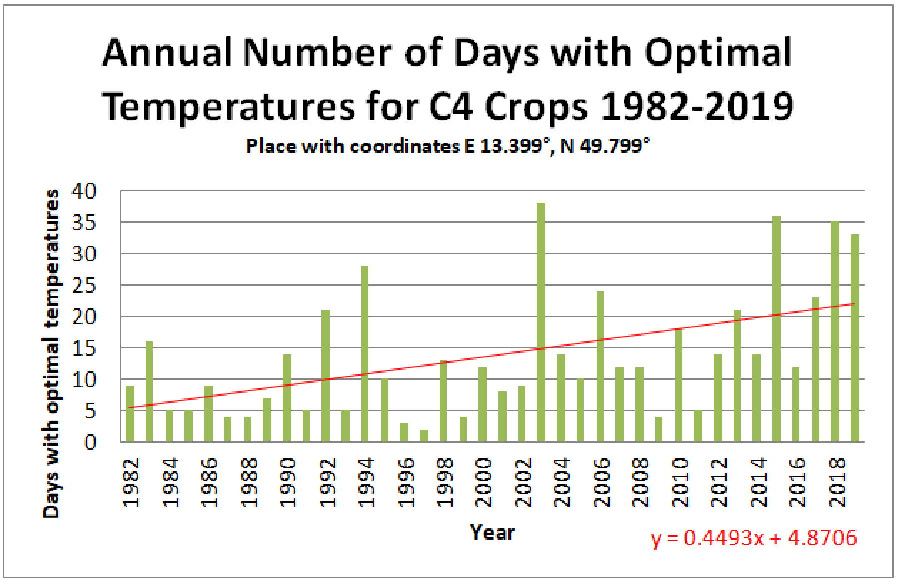

Fig. 30: Graph of annual number of days with optimal growing temperatures for C4 crops between years 1982-2019 with linear regression function (trend)

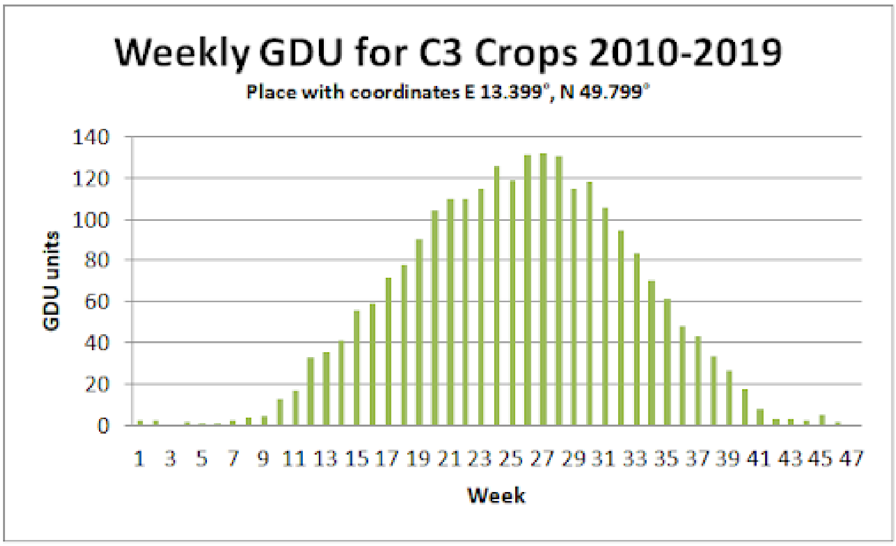

Fig. 31: Graph of weekly GDU for C3 crops, average of 2010-2019

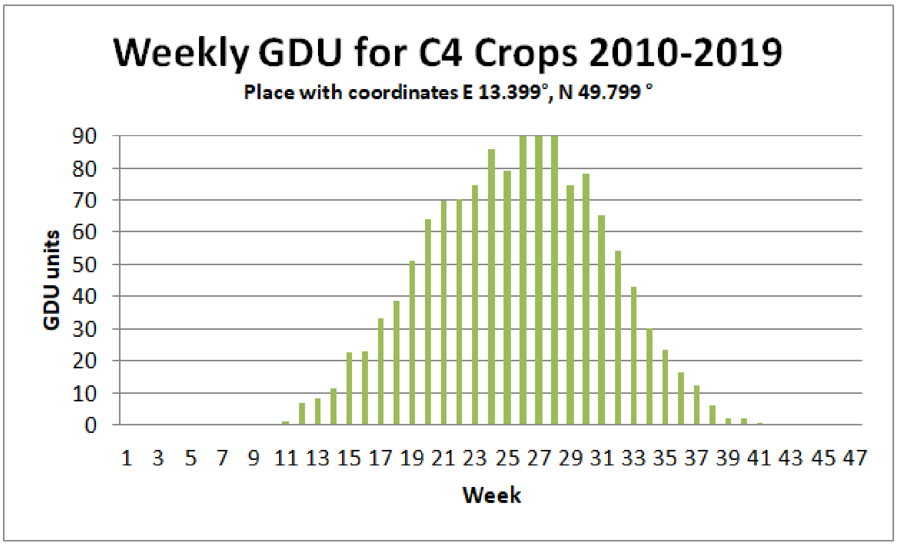

Fig. 32: Graph of weekly GDU for C4 crops, average of 2010-2019

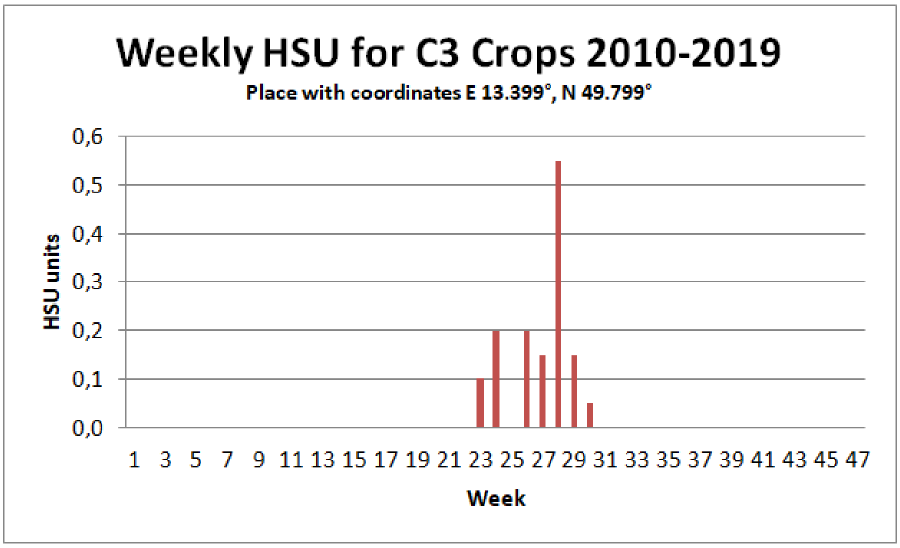

Fig. 33: Graph of weekly HSU for C3 crops, average of 2010-2019

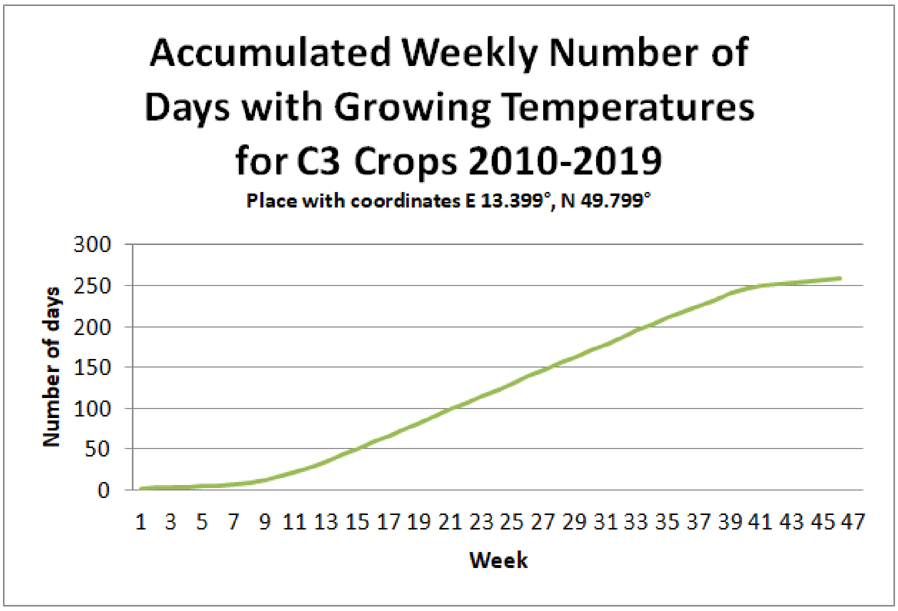

Fig. 34: Graph of accumulated weekly number of days with growing temperatures for C3 crops, average of 2010-2019

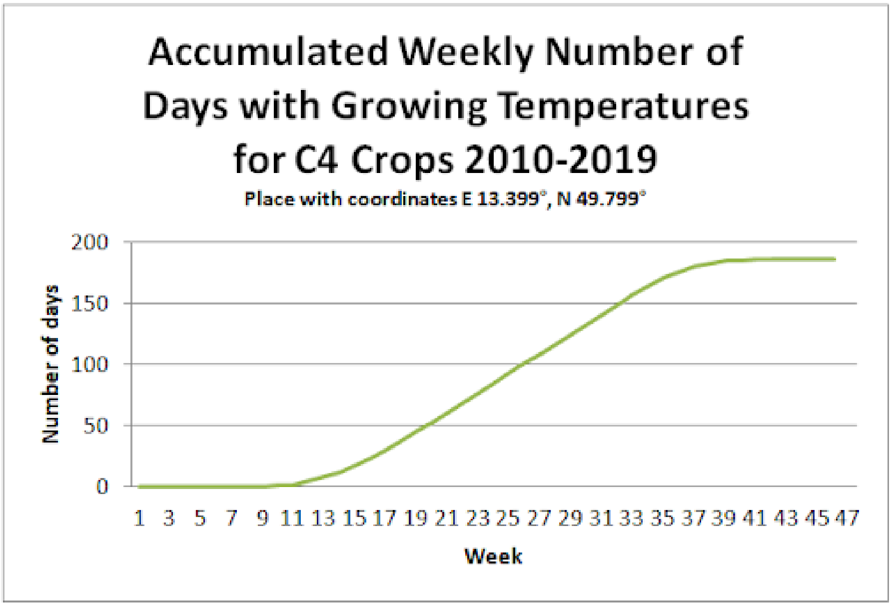

Fig. 35: Graph of accumulated weekly number of days with growing temperatures for C4 crops, average of 2010-2019

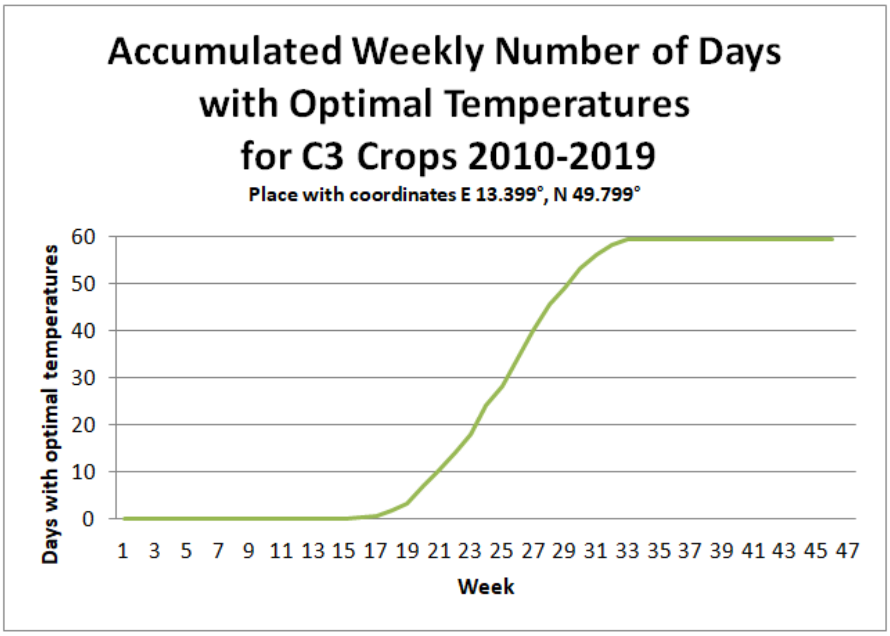

Fig. 36: Graph of accumulated weekly number of days with optimal growing temperatures for C3 crops, average of 2010-2019

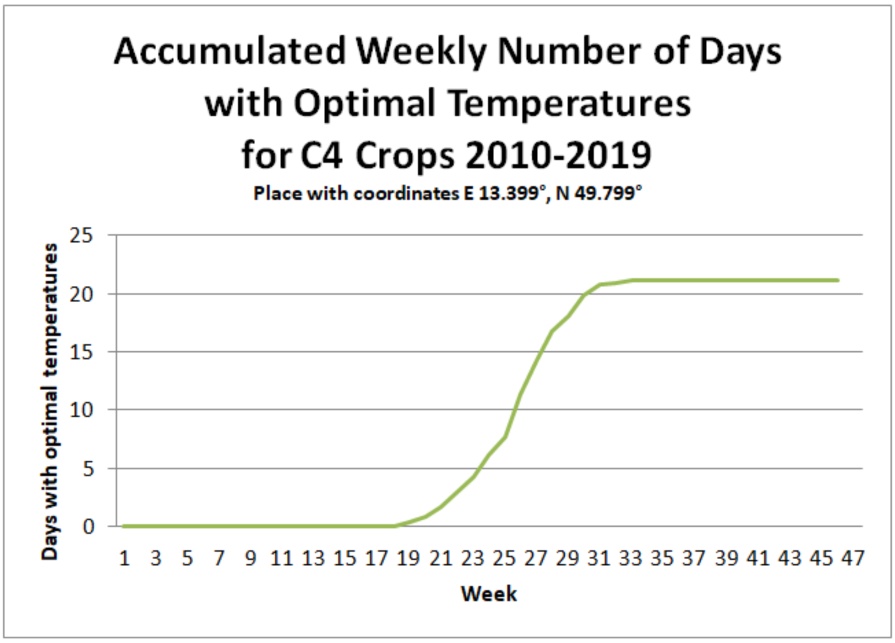

Fig. 37: Graph of accumulated weekly number of days with optimal growing temperatures for C4 crops, average of 2010-2019

3.5 Precipitation

3.5.1 Description of the use of precipitation information in agriculture

Precipitation is one of the basic agroclimatic factors. Crop quantity and timing are important for crop growth. The type of precipitation, intensity, or form (rain, snow) also plays an important role. Too much rain during seeding can result in seed diseases or can saturate the soil, causing poor soil aeration. Drought during germination and stand establishment can result in poor seed germination or weak and small plants. Too much rain during the crop growth phase can result in a smaller root span, the formation of shallow roots, and then less resistance to subsequent dry periods.[20]

The amount of fallen rainfall and its timing is therefore an essential factor for crop growth. Information about the usual amount of precipitation of each period, the trend of this amount can help farmers respond to unfavorable trends or optimize time work in the fields or types of used crops. The plant water cycle can be seen in following figure.

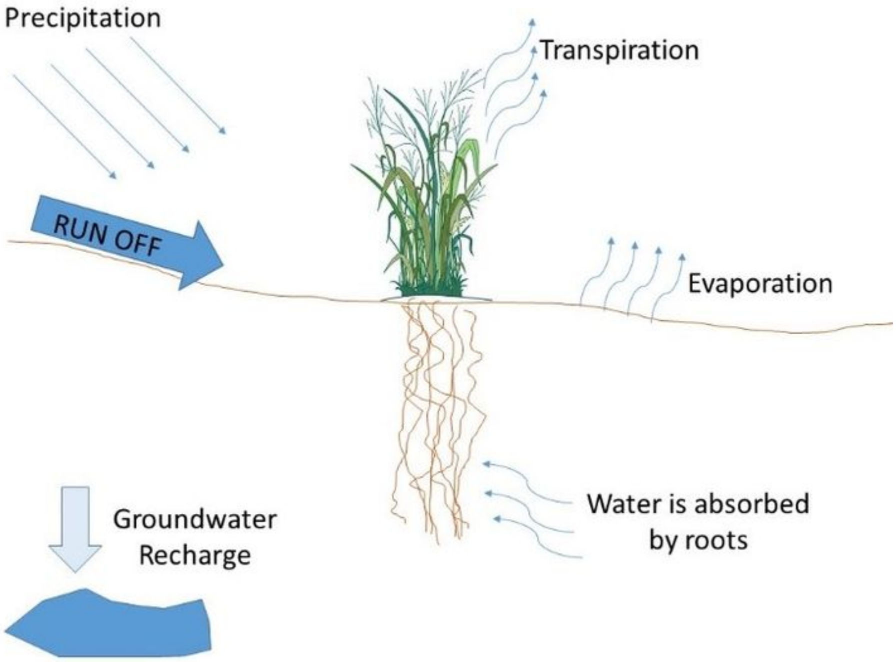

Fig. 38: Plant water cycle [28]

3.5.2 Algorithm of calculating amounts of precipitation during the year

Description of the algorithm

Daily rainfall is obtained from hourly precipitation totals. Then weekly and monthly totals are calculated. While the monthly totals correspond to the months in the calendar, the weekly totals do not correspond to the calendar weeks, but they are seven-day cycles from the first calculated day of the year. The start and end of the calculation can be the first and last day of the year or other entered dates, such as seasonal dates.

Rainfall accumulated weekly is then calculated for each year a then there is also calculated average values of year accumulation. The accumulated values give information on the annual availability of water for crops. Average weekly rainfall is calculated from weekly values and is used to provide information on the likely amount of precipitation available during each week and the trend over the years. The algorithm also calculates the annual sums of precipitation, the average sum of the selected years, and the coefficient of the linear trend of these values. The scheme of calculation is in following figure.

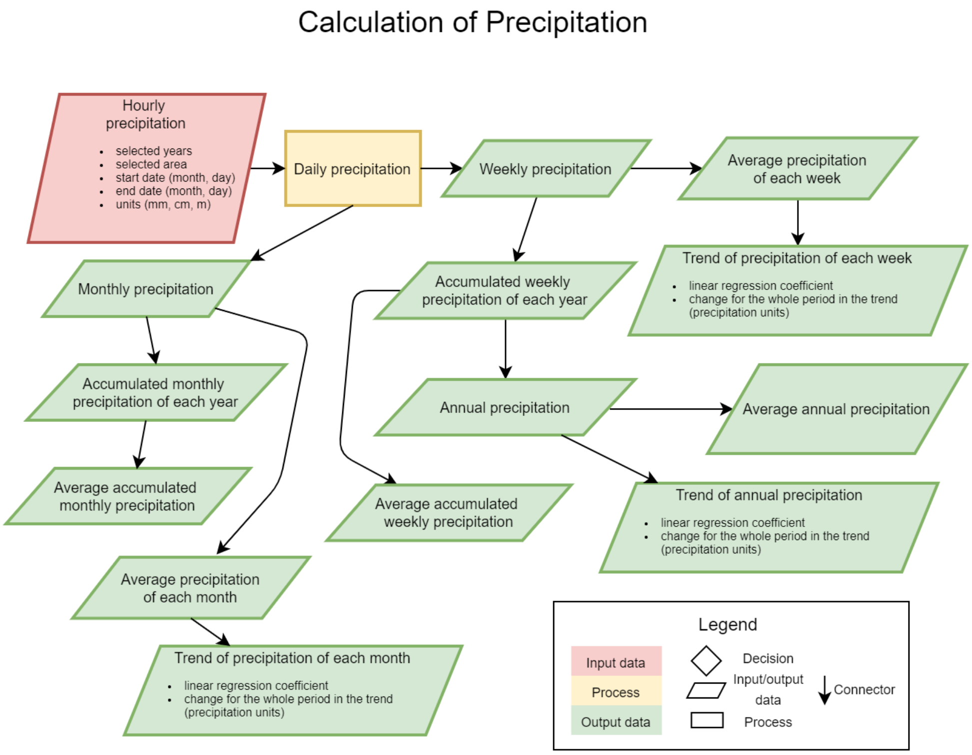

Fig. 39: Scheme of the algorithm for calculation information about precipitation during the year

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variable Total precipitation (NECDF files by years, selected area)[35]
- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates precipitation of each year between these years and the average of rainfall from all these years. Average can be obtained in the case of 2 or more calculated years.
- Parameters of a selected period of the year, start date: start month (integer), start day (integer), end date: end month (integer), end day (integer). Rainfall can be calculated for the whole year, growing season, or other selected period.
- Parameter of units, offered units: m, cm, mm

Output

Geojson and Shapefile (more files) - points with attributes:

- The annual sum of precipitation of each year (decimal number)

- The average annual sum of precipitation (decimal number)
- The trend of the annual rainfall
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)
- The accumulated rainfall weekly of each year (decimal number)
- The average accumulated rainfall weekly (decimal number)
- The weekly rainfall of each year (decimal number)
- The average weekly rainfall (decimal number)
- The trend of the rainfall of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)
- The accumulated rainfall monthly of each year (decimal number)
- The average accumulated rainfall monthly (decimal number)
- The monthly rainfall of each year (decimal number)
- The average monthly rainfall (decimal number)
- The trend of the rainfall of each month
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)

3.5.3 Calculation

Total precipitation was calculated for the Pilsen region and years 2010-2019, 2000-2009, 1990-1999. The rainfall was always calculated for the whole year. The ten-year periods were chosen for comparison. Precipitation units are millimeters. The scheme of calculation with the described parameters can be seen in following figure.

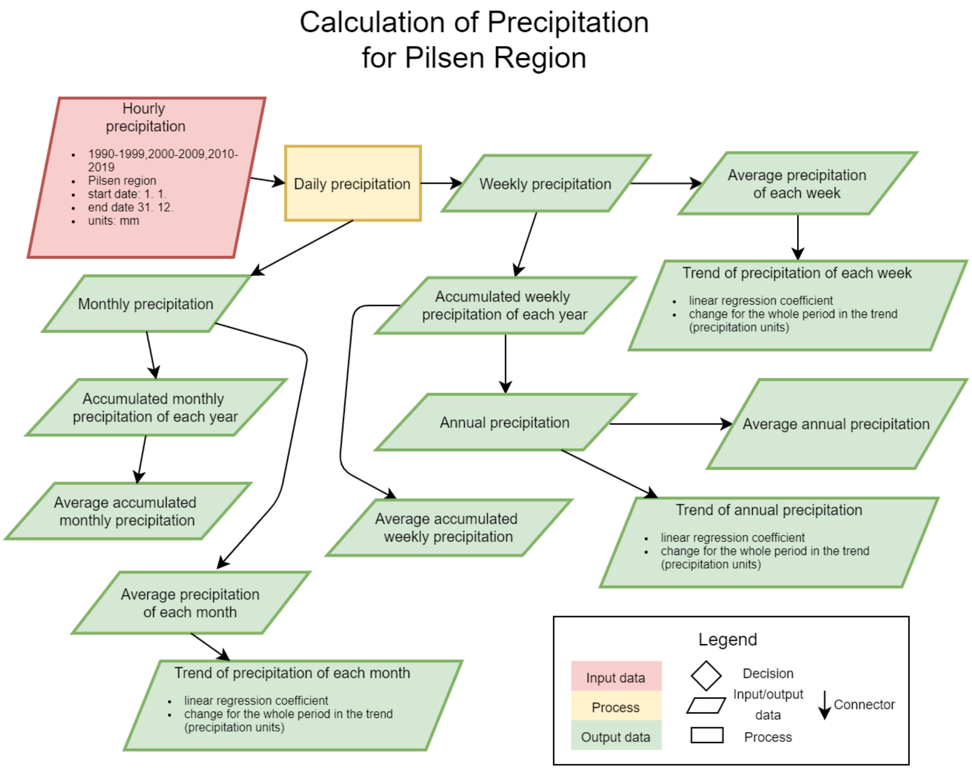

Fig. 40: Diagram of calculation precipitation for Pilsen Region

3.5.4 Results

The results were saved to Geojson and Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by the following 2 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31]

Created maps (in annexe):

- 30 - Average Annual Precipitation 2010-2019 in Pilsen Region
- 31 - Average Annual Precipitation in Last Three Decades 1990-1999, 2000-2009, 2010-2019, Pilsen Region

Graphs of results for one specific location in the following figures.

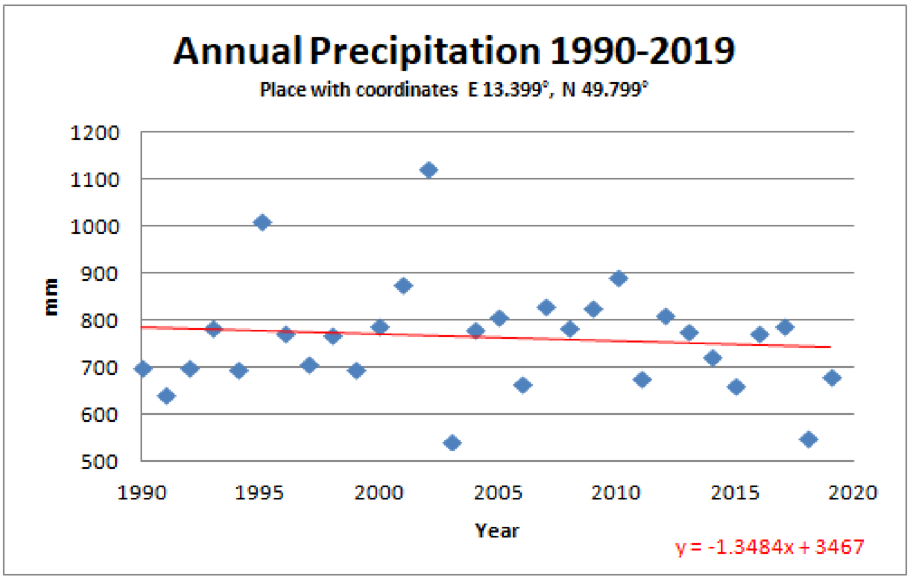

Fig. 41: Graph of annual precipitation between years 1990-2019 with linear regression function (trend)

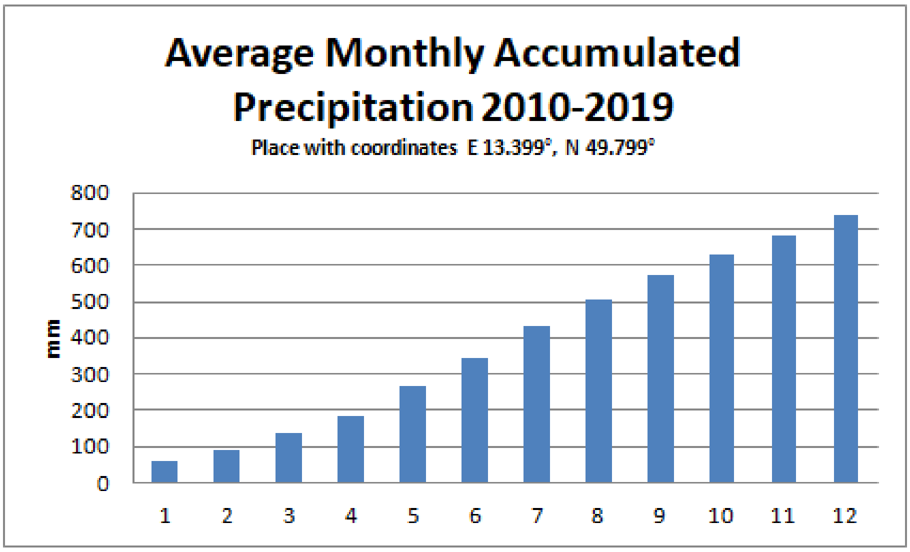

Fig. 42: Graph of average monthly accumulated precipitation in 2010-2019 in one selected place.

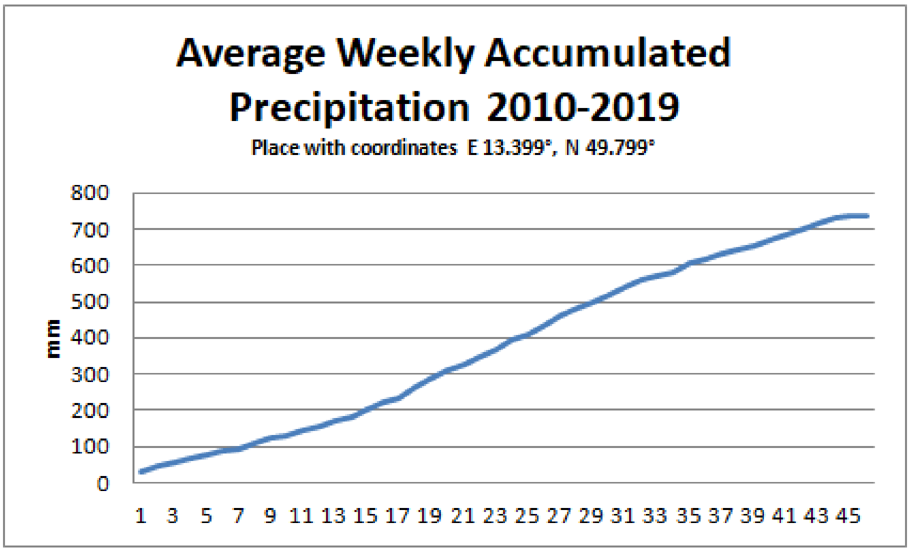

Fig. 43: Graph of average weekly accumulated precipitation in 2010-2019

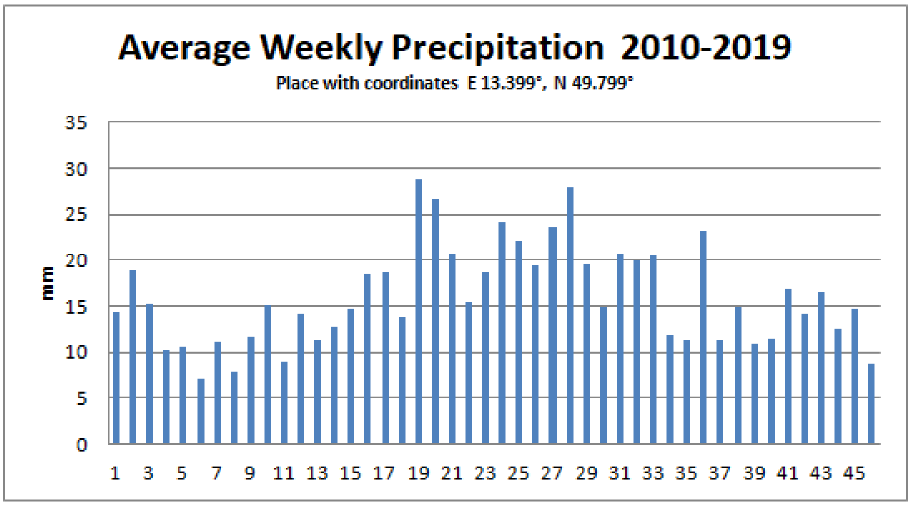

Fig. 44: Graph of average weekly precipitation in 2010-2019

3.6 Evapotranspiration

3.6.1 Description of the use of information about evapotranspiration in agriculture

Evapotranspiration consists of evaporation and transpiration. It gives us information about the amount of water which is transferred from the land to the atmosphere. Evapotranspiration dries the surface and, depending on the timing and amount of precipitation and evapotranspiration, the surface/soil has sufficient or insufficient moisture for optimal crop growth.

Information about the usual amount of evapotranspiration of each period, the trend of this amount can help together with other factors farmers respond to unfavorable trends or optimize time work in the fields or types of used crops.[20]

3.6.2 Algorithm of calculating amounts of evapotranspiration during the year

Description of the algorithm

The calculation is almost the same as the calculation of precipitation. Daily evapotranspiration is calculated from hourly evapotranspiration. Then weekly and monthly sums are calculated. Months correspond to months in the calendar, the weeks do not correspond to the calendar weeks, but they are seven-day cycles from the first calculated day of the year. The start and end of the calculation can be the first and last day of the year or other entered dates, eg seasonal dates.

Evapotranspiration accumulated weekly is then calculated for each year a then there is also calculated average value of year accumulation. The accumulated values give information about the annual timing of the amount of transpired water. Average weekly evapotranspiration is calculated from weekly values and is used to provide information on the likely amount of evapotranspiration available during each week and the trend over the years. The algorithm also calculates the annual sum of evapotranspiration, the average of the selected years, and the coefficient of the linear trend of these values. The scheme of calculation is in following figure.

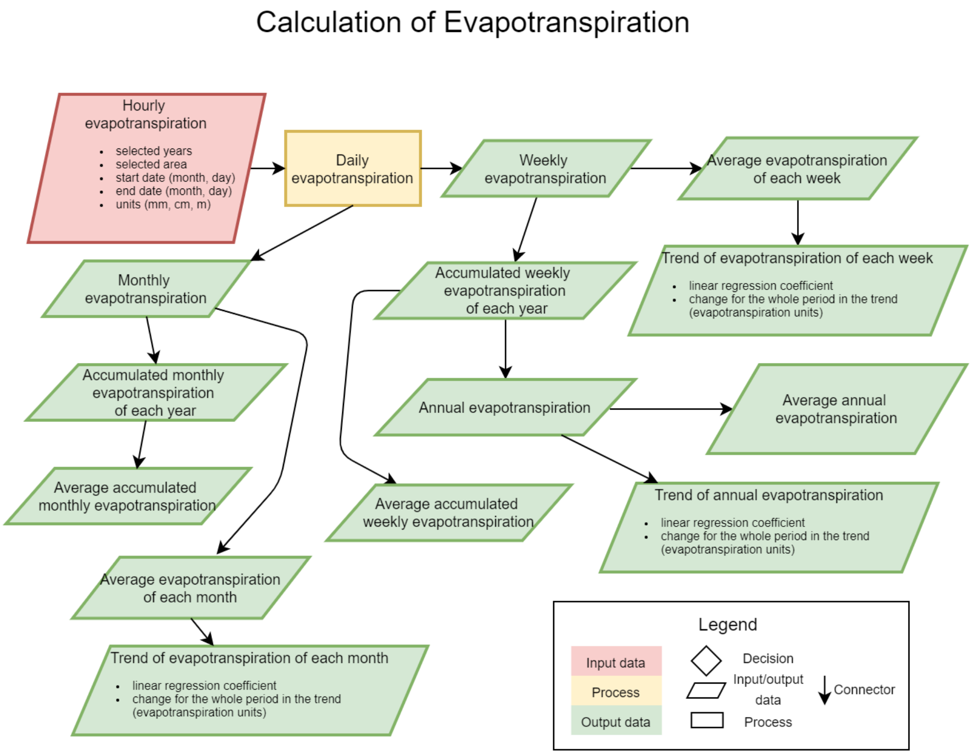

Fig. 45: Scheme of the algorithm for calculation information about evapotranspiration during the year

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variable Evaporation (NECDF files by years, selected area)[35]
- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates the evapotranspiration of each year between these years and the average of evapotranspiration from all these years. Average can be obtained in the case of 2 or more calculated years.
- Parameters of a selected period of the year, start date: start month (integer), start day (integer), end date: end month (integer), end day (integer). Evapotranspiration can be calculated for the whole year, growing season, or other selected period.
- Parameter of units, offered units: m, cm, mm

Output

Geojson and Shapefile (more files) - points with attributes:

- The annual sum of evapotranspiration of each year (decimal number)
- The average annual sum of evapotranspiration (decimal number)
- The trend of the annual evapotranspiration
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)
- The accumulated evapotranspiration weekly of each year (decimal number)
- The average accumulated evapotranspiration weekly (decimal number)
- The weekly evapotranspiration of each year (decimal number)
- The average weekly evapotranspiration (decimal number)
- The trend of the evapotranspiration of each week
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)
- The accumulated evapotranspiration monthly of each year (decimal number)
- The average accumulated evapotranspiration monthly (decimal number)
- The monthly evapotranspiration of each year (decimal number)
- The average monthly evapotranspiration (decimal number)
- The trend of the evapotranspiration of each month
  - Linear regression coefficient (decimal number)
  - Change for the whole period in the trend (decimal number, selected units)

3.6.3 Calculation

Sums of evapotranspiration were calculated for the Pilsen region and years 2010-2019, 2000-2009, 1990-1999. Evapotranspiration was calculated for whole years. The ten-year periods were chosen for comparison. The scheme of calculation with the described parameters can be seen in following figure. Units are millimeters.

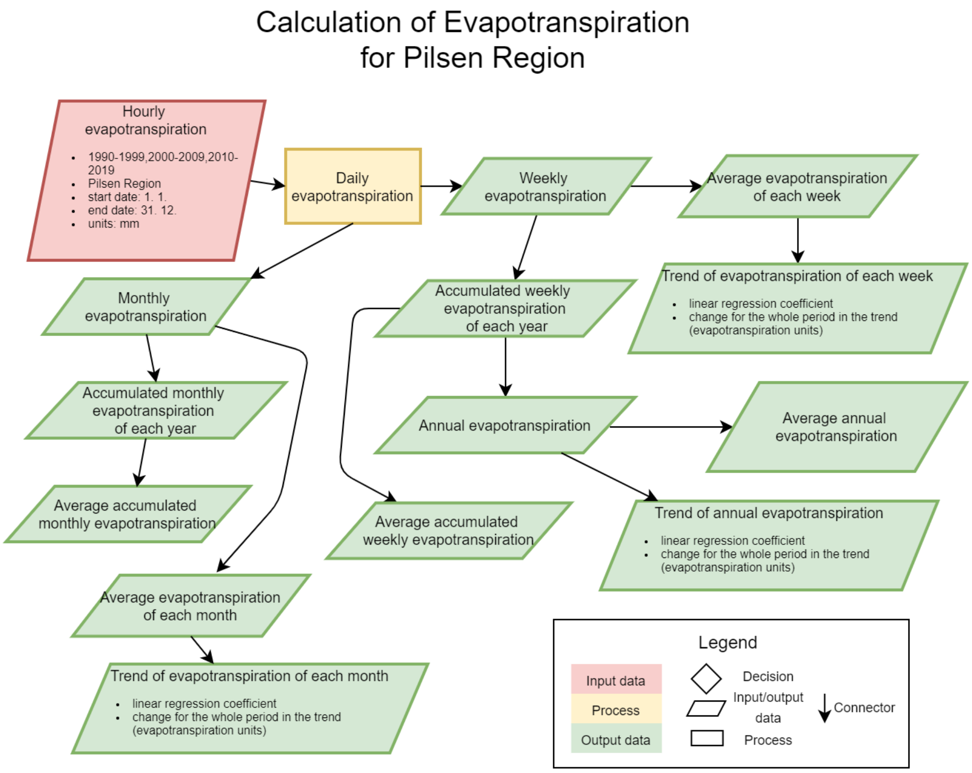

Fig. 46: Diagram of calculation evapotranspiration for Pilsen Region

3.6.4 Results

The results were saved to Geojson and Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by the following 2 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31]

Created maps (in annexe):

- 32 - Average Annual Evapotranspiration 2010-2019 in Pilsen Region
- 33 - Average Annual Evapotranspiration in Last Three Decades 1990-1999, 2000-2009, 2010-2019, Pilsen Region

Graphs of results for one specific location in the following figures.

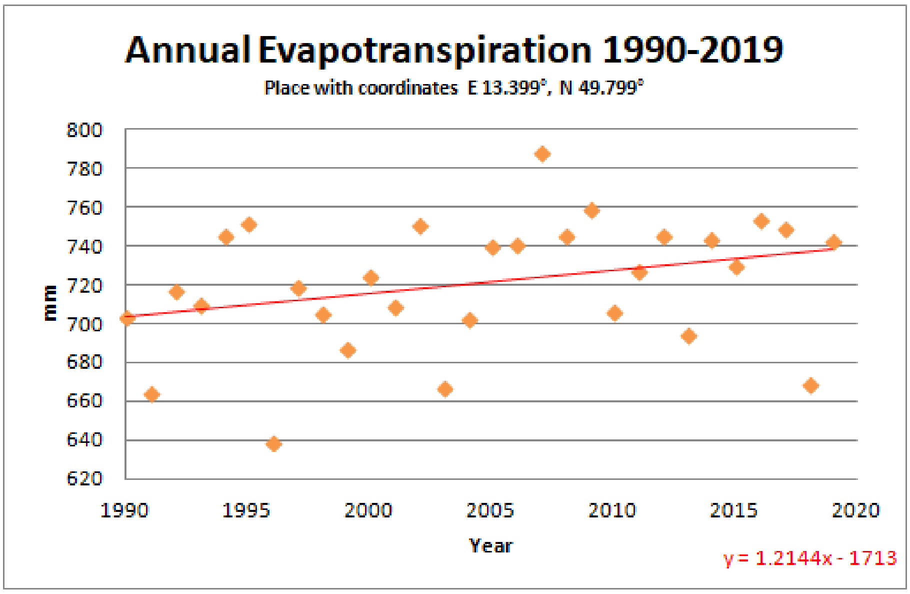

Fig. 47: Graph of annual evapotranspiration between years 1990-2019 with linear regression function (trend)

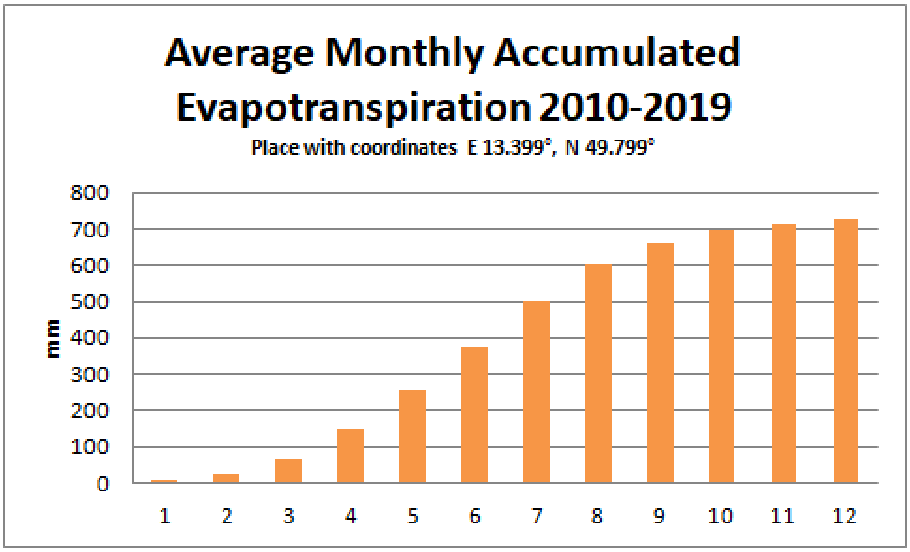

Fig. 48: Graph of average monthly accumulated evapotranspiration in the years 2010-2019

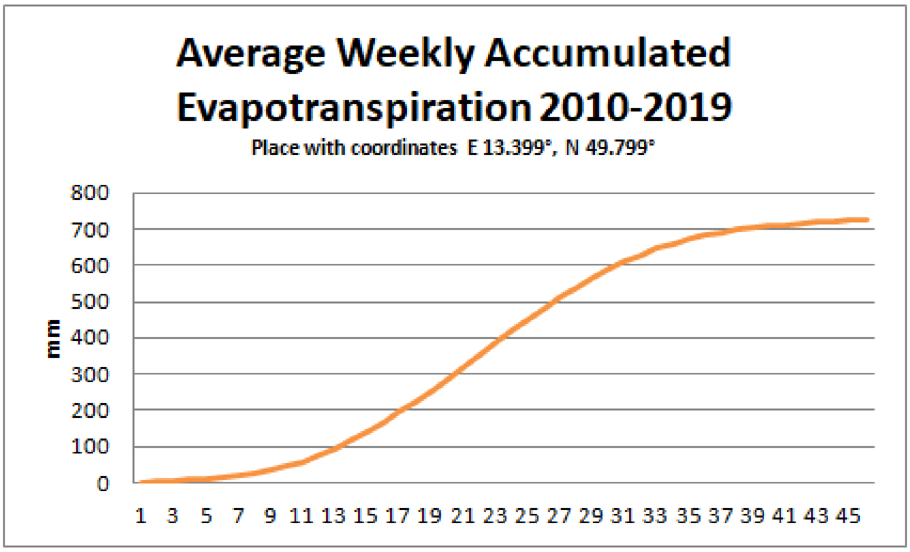

Fig. 49: Graph of average weekly accumulated evapotranspiration between the years 2010-2019

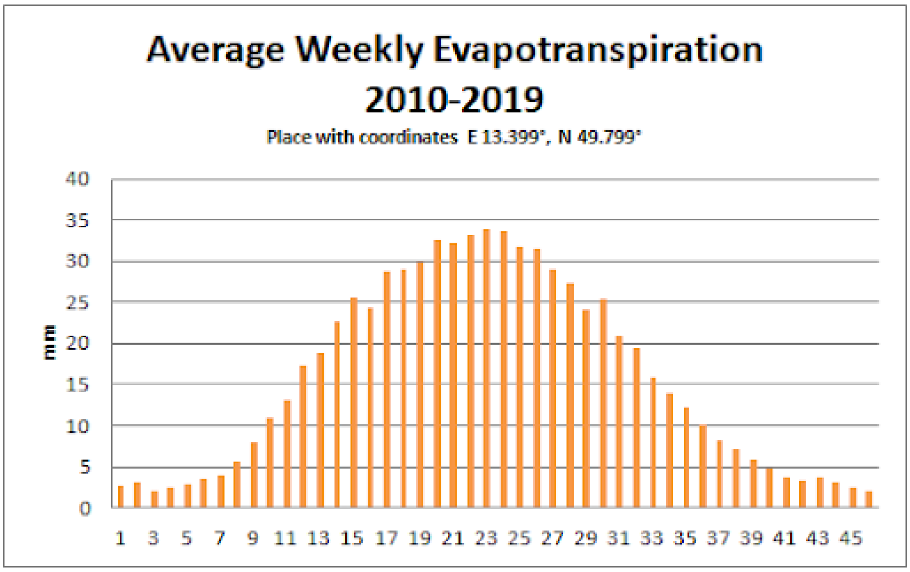

Fig. 50: Graph of average weekly evapotranspiration between the years 2010-2019

3.7 Water balance

3.7.1 Description of the use of information about water balance in agriculture

The balance between water inputs and outputs is known as the water balance. Water balance formula is precipitation = evapotranspiration + runoff +- changes in storage.[16] Sometimes water balance is simplified to average precipitation = average evapotranspiration +- surplus or deficit of water.[29]

Water is essential for crop growth, and its excess or deficit during the growing period can reduce crop yields or have devastating effects. Therefore, it is important to know the water balance, whether there are water deficits or, for example, floods in some periods of the growing season. Differences between precipitation, evapotranspiration, and runoff from previous formulas can help us with information about changes in groundwater amount.

3.7.2 Algorithm of calculating changes in water storage during the year

Description of the algorithm

Hourly change in water storage is calculated from the formula: hourly precipitation + hourly evapotranspiration (values of evapotranspiration are with the minus sign) - hourly runoff. The sum of all hours of the day is a daily change in storage. Then weekly and monthly sums are calculated. Months correspond to months in the calendar, the weeks do not correspond to the calendar weeks, but they are seven-day cycles from the first calculated day of the year. The start and end of the calculation can be the first and last day of the year or other entered dates, eg seasonal dates.

Change in storage accumulated weekly is then calculated for each year a then there is also calculated average value of year accumulation. The accumulated values give information about changes in storage during the year. Average weekly changes in storage are calculated from weekly values and are used to provide information on the likely amount of changes in storage during each week and the trend over the years. The algorithm calculates the annual sum of changes in storage, the average of the selected years, and the coefficient of the linear trend of these values. The scheme of calculation is in following figure.

The algorithm also calculates precipitation, evapotranspiration, and runoff information. The outputs are the same as the descriptive outputs of changes in storage (more information about precipitation and evapotranspiration in previous chapters).

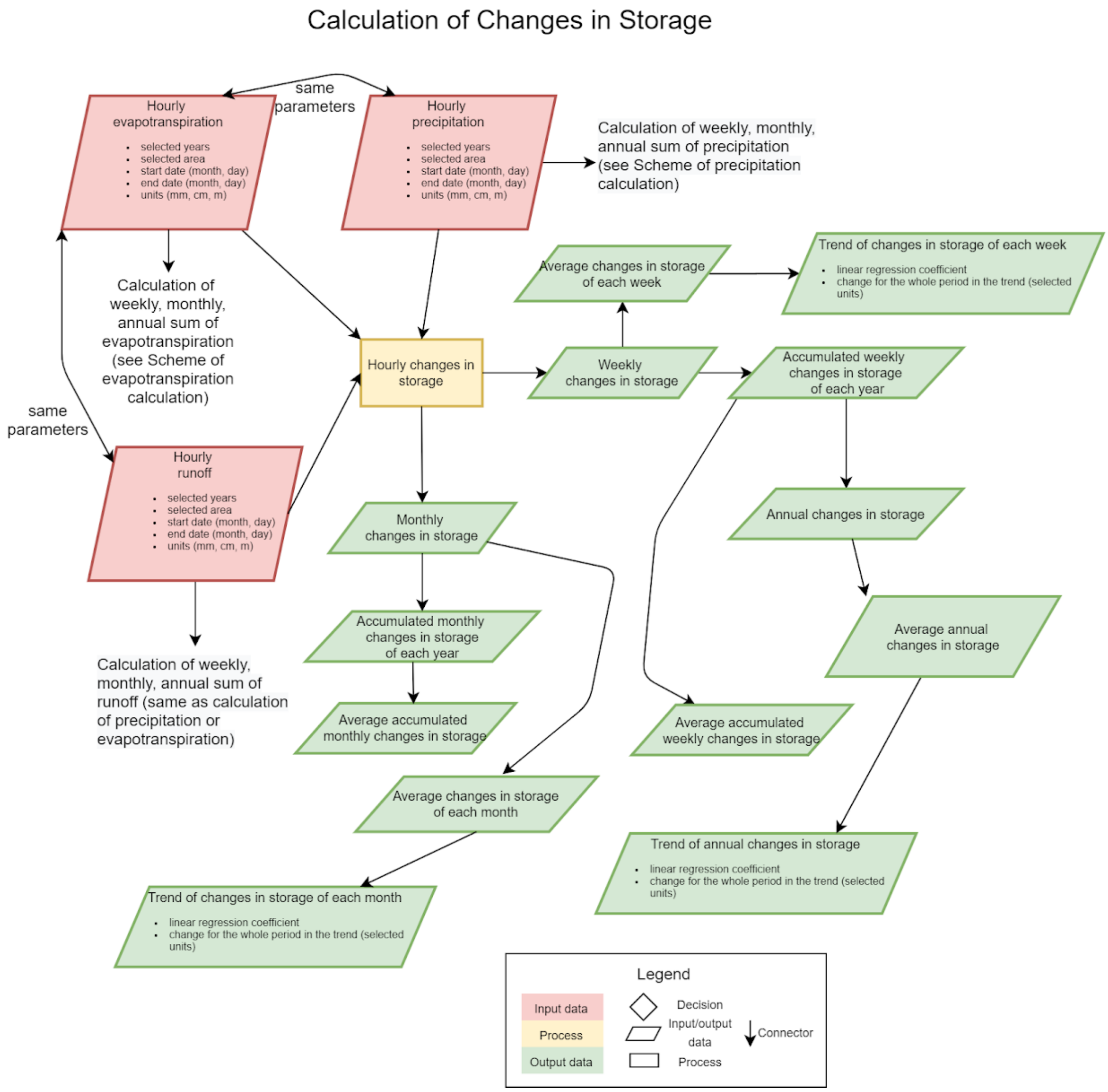

Fig. 51: Scheme of the algorithm for calculation information about changes in storage during the year.

Input

- Copernicus ERA5-Land hourly data from 1979 to present, variables:
- Evaporation, Total precipitation, Runoff (NECDF files by years, selected area)[35]
- Parameters of selected years: start year (integer), end year (integer). The algorithm calculates the changes in storage of each year between these years and the average of the change in storage from all these years. Average can be obtained in the case of 2 or more calculated years.
- Parameters of a selected period of the year, start date: start month (integer), start day (integer), end date: end month (integer), end day (integer). Change can be calculated for the whole year, growing season, or other selected period.
- Parameter of units, offered units: m, cm, mm

Output

Geojson and Shapefile (more files) - points with attributes:

- The annual sums of changes in storage, precipitation, evapotranspiration, runoff of each year (decimal numbers)
- The average annual sums of changes in storage, precipitation, evapotranspiration, runoff (decimal numbers)
- The trend of the annual changes in storage, precipitation, evapotranspiration, runoff
  - Linear regression coefficient (decimal numbers)
  - Change for the whole period in the trend (decimal numbers, selected units)
- The accumulated changes in storage, precipitation, evapotranspiration, runoff of each year (decimal numbers)
- The average accumulated changes in storage, precipitation, evapotranspiration, runoff weekly (decimal numbers)
- The weekly changes in storage, precipitation, evapotranspiration, runoff of each year (decimal numbers)
- The average weekly changes in storage, precipitation, evapotranspiration, runoff (decimal numbers)

- The trend of the changes in storage, precipitation, evapotranspiration, runoff of each week
  - Linear regression coefficient (decimal numbers)
  - Change for the whole period in the trend (decimal numbers, selected units)
- The accumulated changes in storage, precipitation, evapotranspiration, runoff monthly of each year (decimal numbers)
- The average accumulated changes in storage, precipitation, evapotranspiration, runoff monthly (decimal numbers)
- The monthly changes in storage, precipitation, evapotranspiration, runoff of each year (decimal numbers)
- The average monthly changes in storage, precipitation, evapotranspiration, runoff (decimal numbers)
- The trend of the changes in storage, precipitation, evapotranspiration, runoff of each month
  - Linear regression coefficient (decimal numbers)
  - Change for the whole period in the trend (decimal numbers, selected units)

3.7.3 Algorithm of calculating differences between precipitation and evapotranspiration during the year

The algorithm, input, and output is the same as the algorithm for changes in storage only runoff missing, so instead of the hourly change in storage we have the hourly difference between precipitation and evapotranspiration calculated as precipitation plus evapotranspiration (values of evapotranspiration are with minus sign).

3.7.4 Calculation

Sums of changes in storage (or differences between precipitation and evapotranspiration), precipitation, evapotranspiration, runoff were calculated for the Pilsen region and years 2010-2019, 2000-2009, 1990-1999. It was calculated for whole years. The ten-year periods were chosen for comparison. The scheme of calculation changes in storage with the described parameters can be seen in following figure. Units are millimeters.

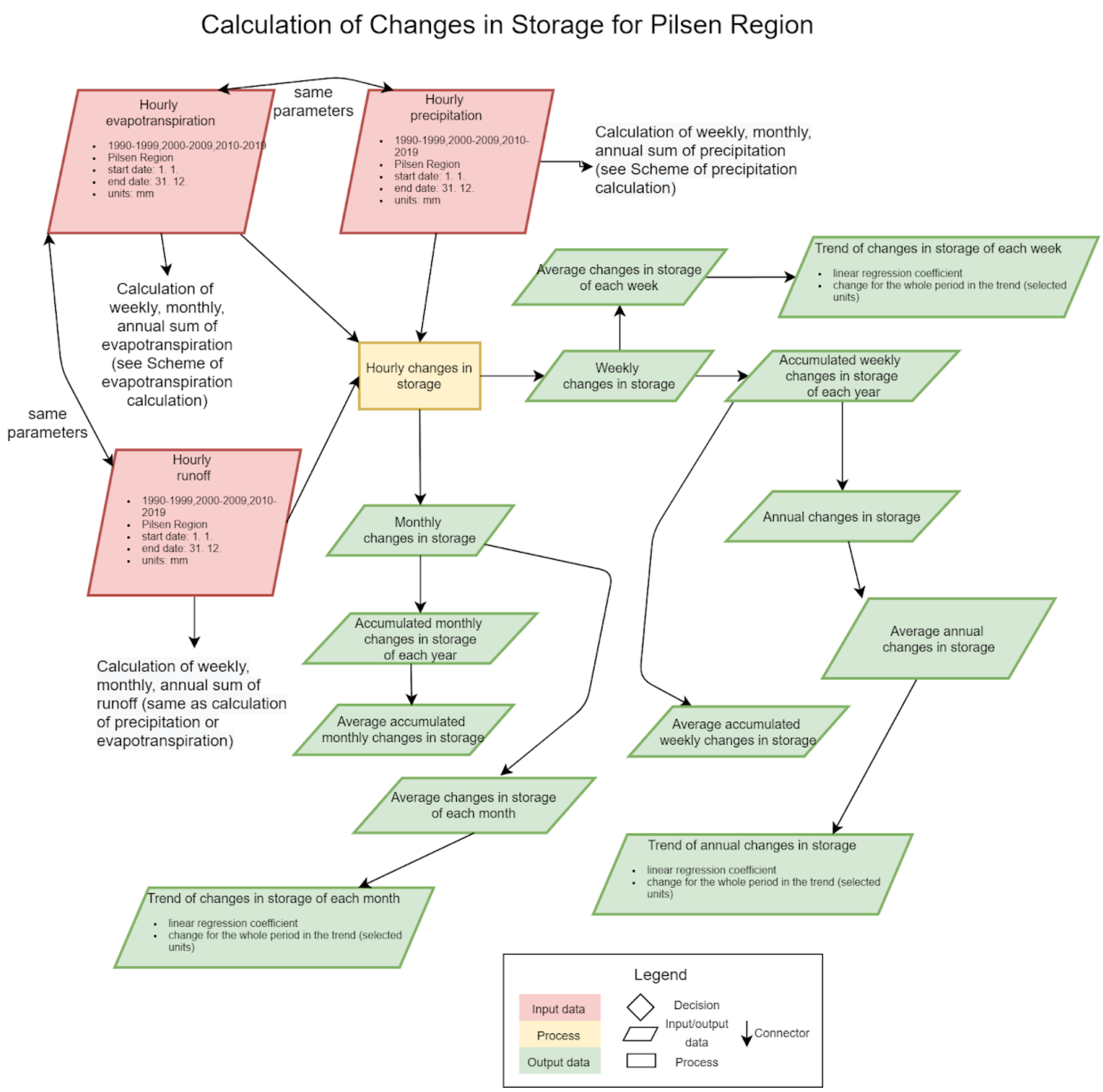

Fig. 52: Diagram of calculation changes in storage for Pilsen Region

3.7.5 Results

The results were saved to Geojson and Shapefile, interpolated using Inverse Distance Weighting (always used 4 nearest calculated points), and then visualized by the following 4 maps. The IDW method was chosen because it is one of the most used and promising techniques for interpolating meteorological data.[31]

Created maps (in annexe):

- 34 - Water Balance - Average Annual Changes in Storage 2010-2019 in Pilsen Region
- 35 - Water Balance - Average Annual Changes in Storage in Last Three Decades 1990-1999, 2000-2009, 2010-2019, Pilsen Region
- 36 - Average Annual Difference between Precipitation and Evapotranspiration 2010-2019 in Pilsen Region
- 37 - Average Annual Difference between Precipitation and Evapotranspiration in Last Three Decades 1990-1999, 2000-2009, 2010-2019, Pilsen Region

Graphs of results for one specific location in the following figures.

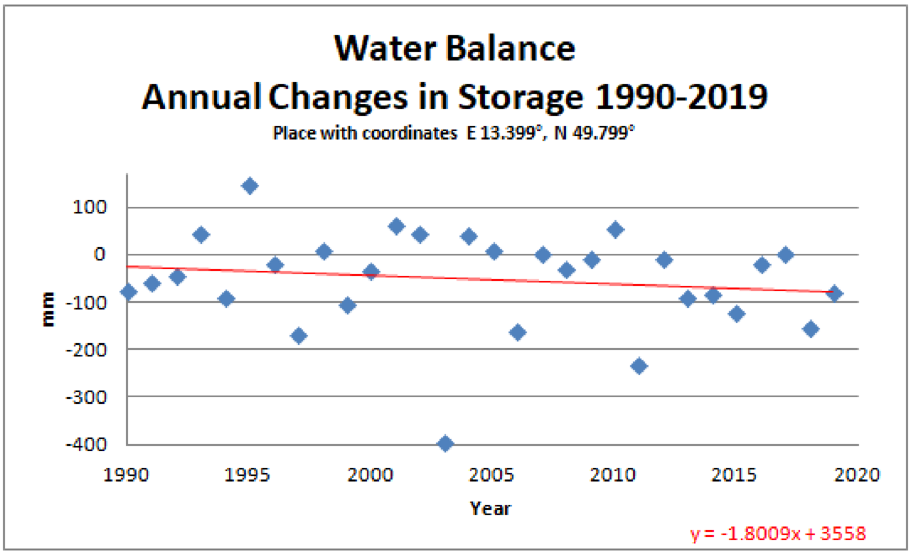

Fig. 53: Graph of annual changes in storage between years 1990-2019 with linear regression function (trend)

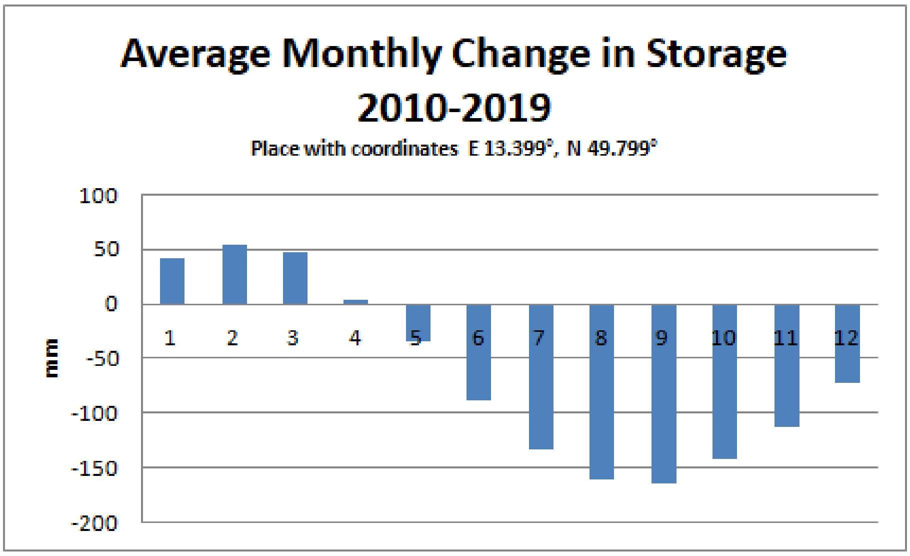

Fig. 54: Graph of the average monthly change in storage in years 2010-2019 in one selected place.

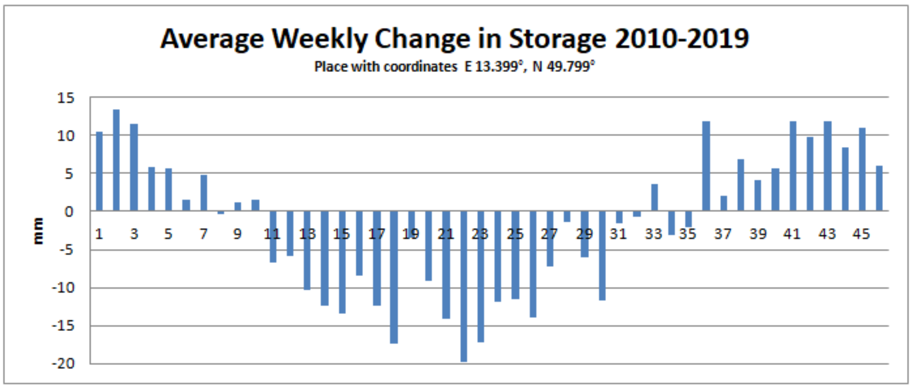

Fig. 55: Graph of the average weekly change in storage in years 2010-2019 in one selected place.

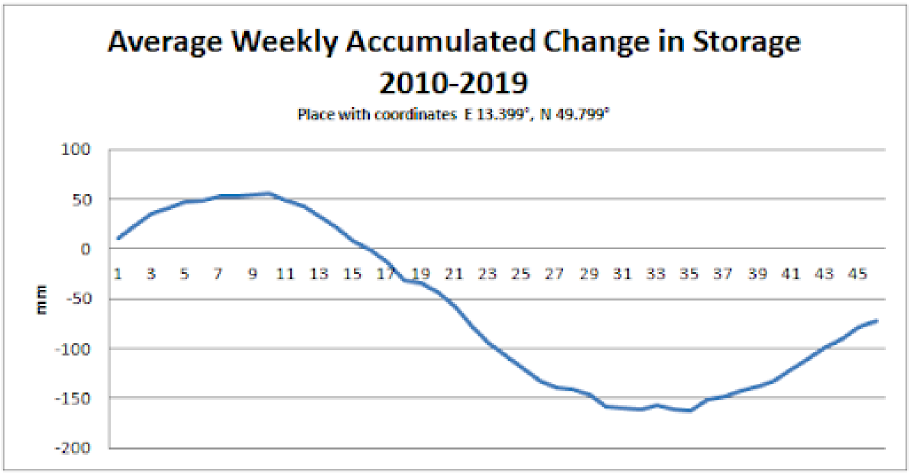

Fig. 56: Graph of the average weekly accumulated change in storage in years 2010-2019 in one selected place.

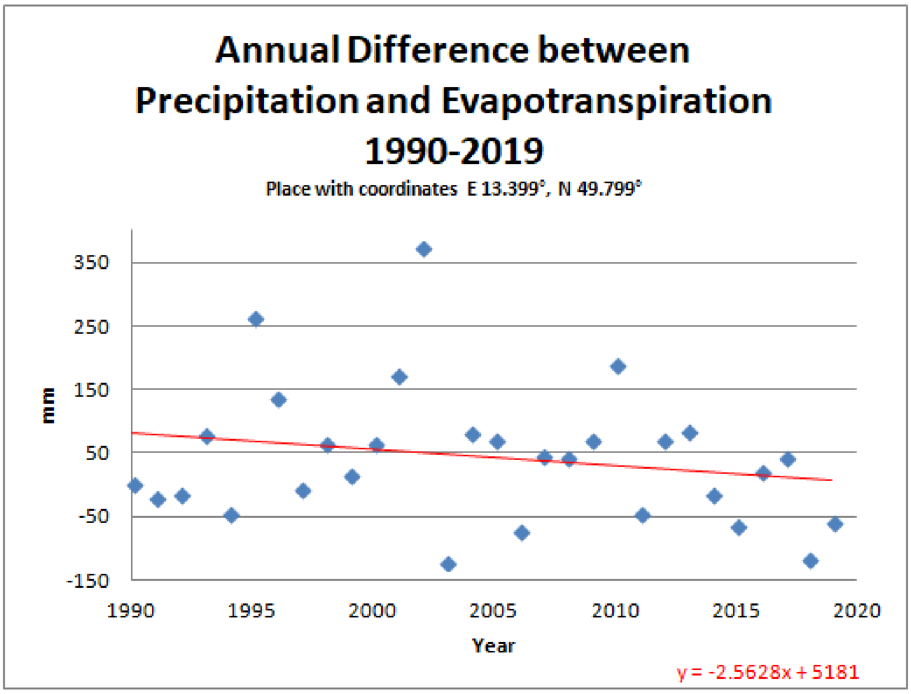

Fig. 57: Graph of annual difference between precipitation and evapotranspiration between years 1990-2019 with linear regression function (trend)

4 Publishing of scripts

The algorithms created and described in chapter 3 have been published on the GitHub web service. They are available on the website:
https://github.com/JiriVales/agroclimatic-factors. After the publication of this thesis, there will be links to this thesis there.

5 Discussion

Global climate models from satellite and meteorological station data provide detailed information on agro-climatic factors and will be even more detailed in the future. Global data can serve as an alternative or complement to direct measurements of meteorological variables for agricultural purposes or to imagine what values agro-climatic factors reach in a particular area and how they evolve over time (useful for climatologists and others). It is necessary to take into account that global models will eliminate extremes/fluctuations in individual localities due to averaging, interpolation. Meteorological stations capture variables in their location accurately, including fluctuations.

This thesis strives to deepen knowledge about the possibility of using global climatic data for agro-climatic purposes, to describe how individual agro-climatic factors can be obtained without limitation to already calculated localities, calculated factors, meteorological offices, and other providers. Neither the described calculations (algorithms, flowcharts) nor the use of detailed and freely available hourly ERA5-Land data was found in the previously available literature.

Nowadays, the absolute accuracy of climatic data and calculated agro-climatic factors is unknown, as well as the relative accuracy of newly created detailed models. Their uncertainty over time is also different, so it is necessary to take the calculated data and calculated linear trends with caution if there is the absence of uncertainties estimation. To get an idea of the accuracy of the data, it is necessary to compare the data with sensor measurements directly in the given localities or, if necessary, wait for more detailed information about the uncertainties.

The calculated agroclimatic factors can also be used for advanced work with specific crop, modeling of crop growth, or creating agro-ecological / agro-climatic zones. An Agro-ecological Zone is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use. [14] These zones were not calculated in the thesis (the territory of the Pilsen Region is not large enough for having a specific range of potentials and constraints for land use). The thesis captures areas with the same value for individual agro-climatic factors by isopleths, so a user can know areas with the same conditions of each agro-climatic factor.

The thesis did not solve the use of individual factors for specific crops but remained in the general description of the use of individual agro-climatic factors for agricultural purposes because the issue of using agro-climatic factors for individual crops is so extensive that it would take a separate thesis. For example, GDU, HSU, number of (optimal) growing days were calculated only as an example for the average crop of a group of crops.

Some algorithms from this thesis were used in the EUXDAT project (European e-Infrastructure for Extreme Data Analytics in Sustainable Development).These algorithms use high-performance computing and have got user interface. Specifically, a web interface was created for Frost Dates, where the user selects the location for which the given agro-climatic factor is to be calculated and enters the required parameters. Then user receives the output data of the algorithm (demonstration of user interface in annexe).

6 Conclusion

The thesis starts with description of fundamental agro-climatic factors and provides information on previous calculations and visualizations through a selection related realizations. Next, the used climatic data, the ERA5-Land dataset is described including the used variables. The main part of the thesis describes the calculated agro-climatic factors, their use in agriculture, and the algorithm of their creation. The author calculated agro-climatic factors for the Pilsen region and visualized the results using graphs and maps.

Created algorithms and descriptions of agro-climatic factors are related to air temperature (frost dates, frost-free period, growing degree units, heat stress units, number of growing days, number of optimal growing days), soil temperature (dates of fall nitrogen application), precipitation, evapotranspiration, and runoff (precipitation sums, evapotranspiration sums, water balance - changes in water storage or differences between precipitation and evapotranspiration).

The main contribution of the thesis is the design, development, and thorough description of algorithms for agro-climatic factors calculation. The algorithms are connected to freely available global climatic data - ERA5-Land. The thesis serves as demonstration of the use of a very detailed ERA5-Land dataset for agricultural purposes. The thesis provides and visualizes agro-climatic factors in the Pilsen Region which can be suitable for climatologists, farmers, gardeners.

7 Bibliography

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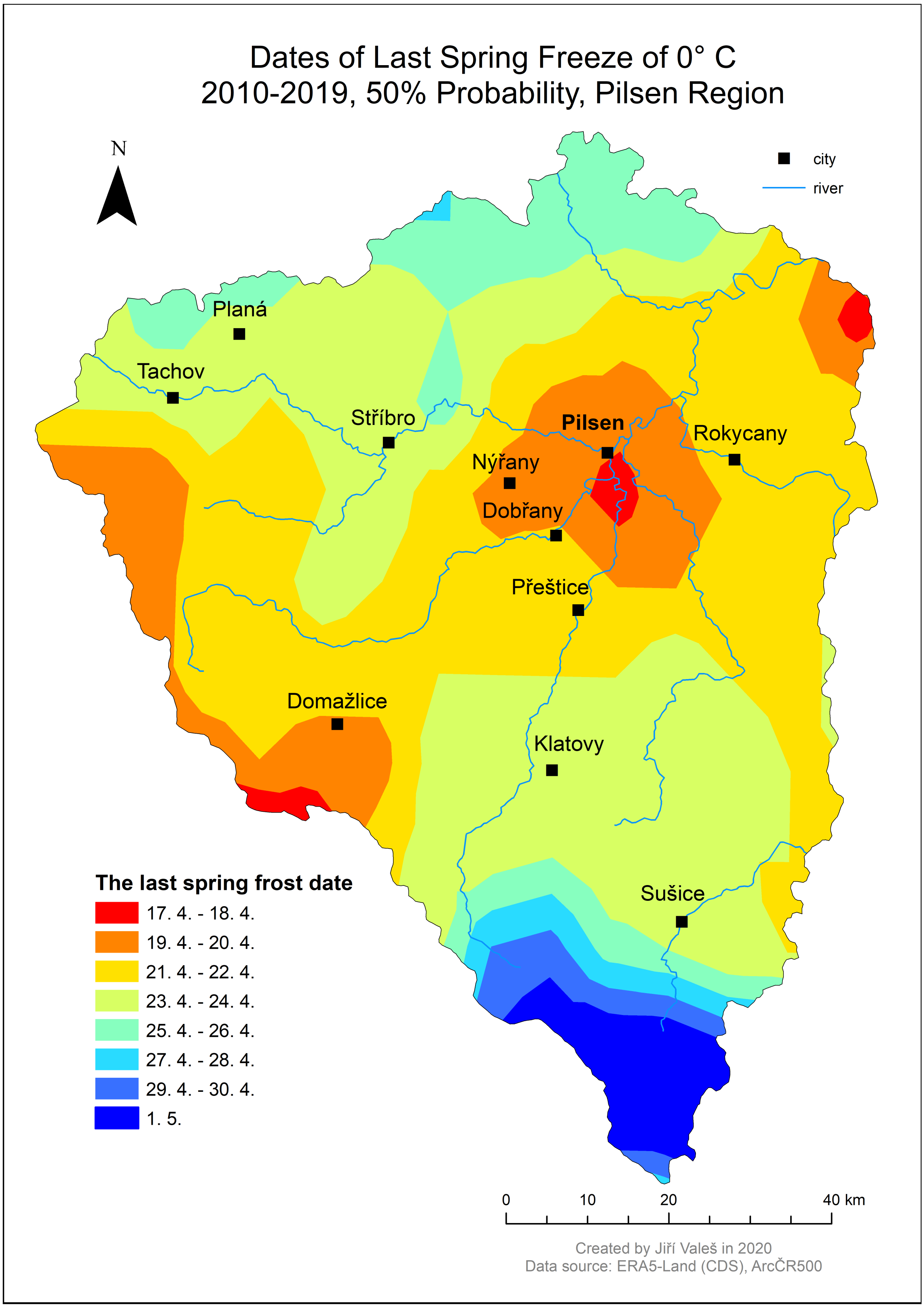
8 Annexe

The enclosed CD contains the text of the thesis, with all annexes, algorithms, and output data that have been visualized (files in geojson, shapefile).

Created maps

This part of annexe contains created maps of agro-climatic factors. They are sorted by the order in chapter 3. Isopleths and bar charts were used in the visualization. The coordinate system is WGS 1984, UTM Zone 33N.



Dates of Last Spring Freeze of 0° C
2010-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last spring frost date
17. 4. - 18. 4.
19. 4. - 20. 4.
21. 4. - 22. 4.
23. 4. - 24. 4.
25. 4. - 26. 4.
27. 4. - 28. 4.
29. 4. - 30. 4.
1. 5.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 58: Map 1

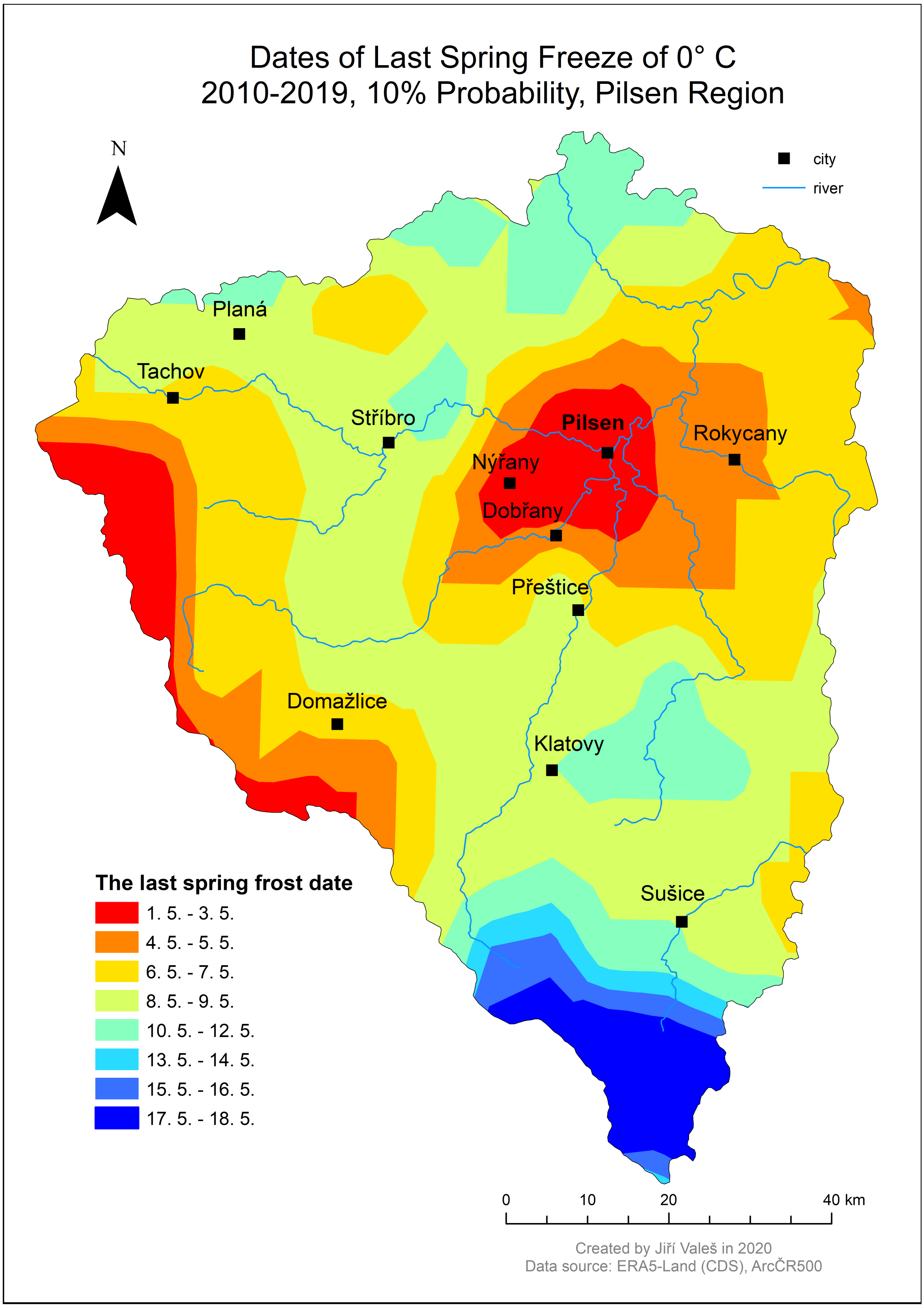
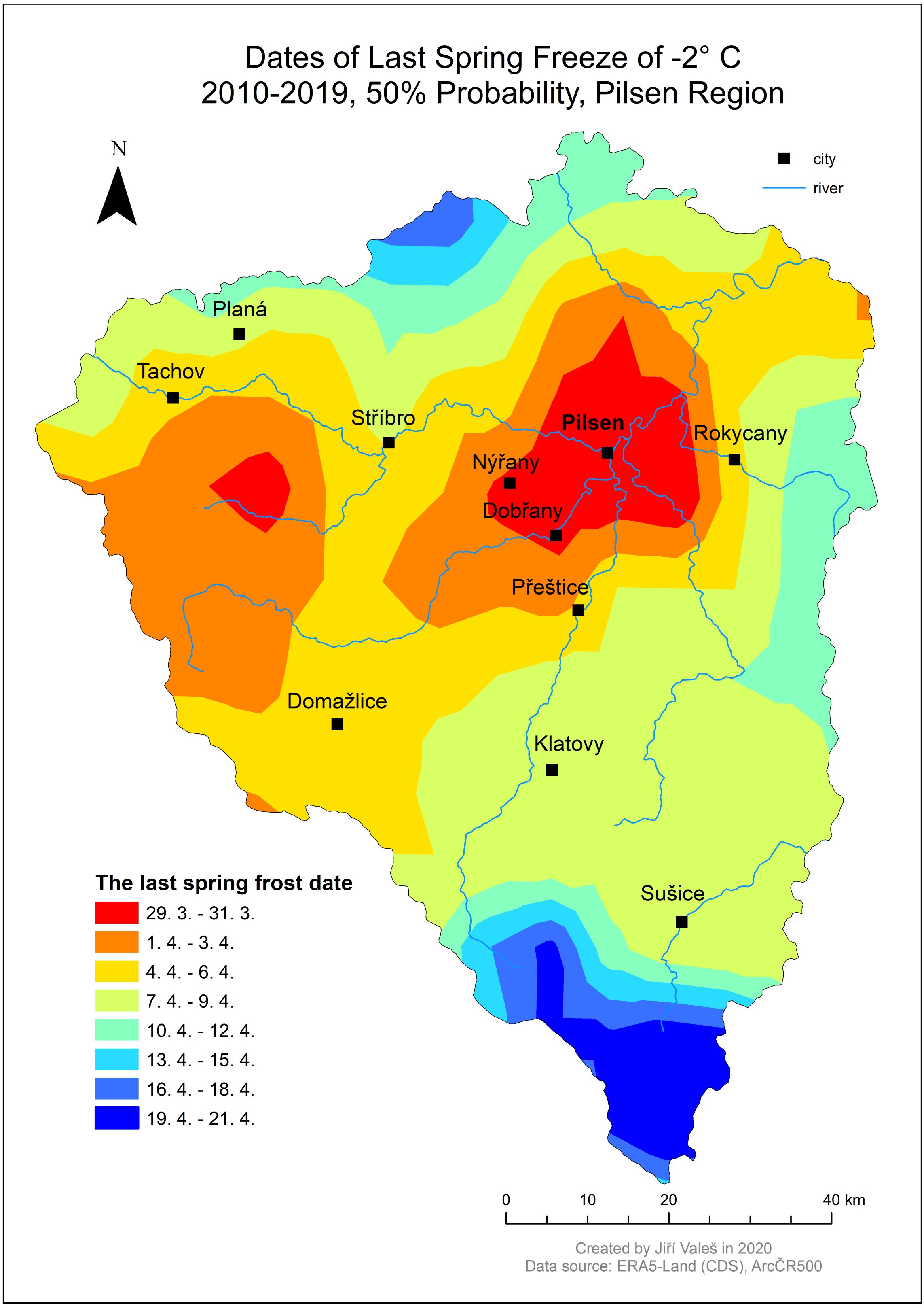

Dates of Last Spring Freeze of 0° C
2010-2019, 10% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last spring frost date
1. 5. - 3. 5.
4. 5. - 5. 5.
6. 5. - 7. 5.
8. 5. - 9. 5.
10. 5. - 12. 5.
13. 5. - 14. 5.
15. 5. - 16. 5.
17. 5. - 18. 5.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 59: Map 2



Dates of Last Spring Freeze of -2° C
2010-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last spring frost date
29. 3. - 31. 3.
1. 4. - 3. 4.
4. 4. - 6. 4.
7. 4. - 9. 4.
10. 4. - 12. 4.
13. 4. - 15. 4.
16. 4. - 18. 4.
19. 4. - 21. 4.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 60: Map 3

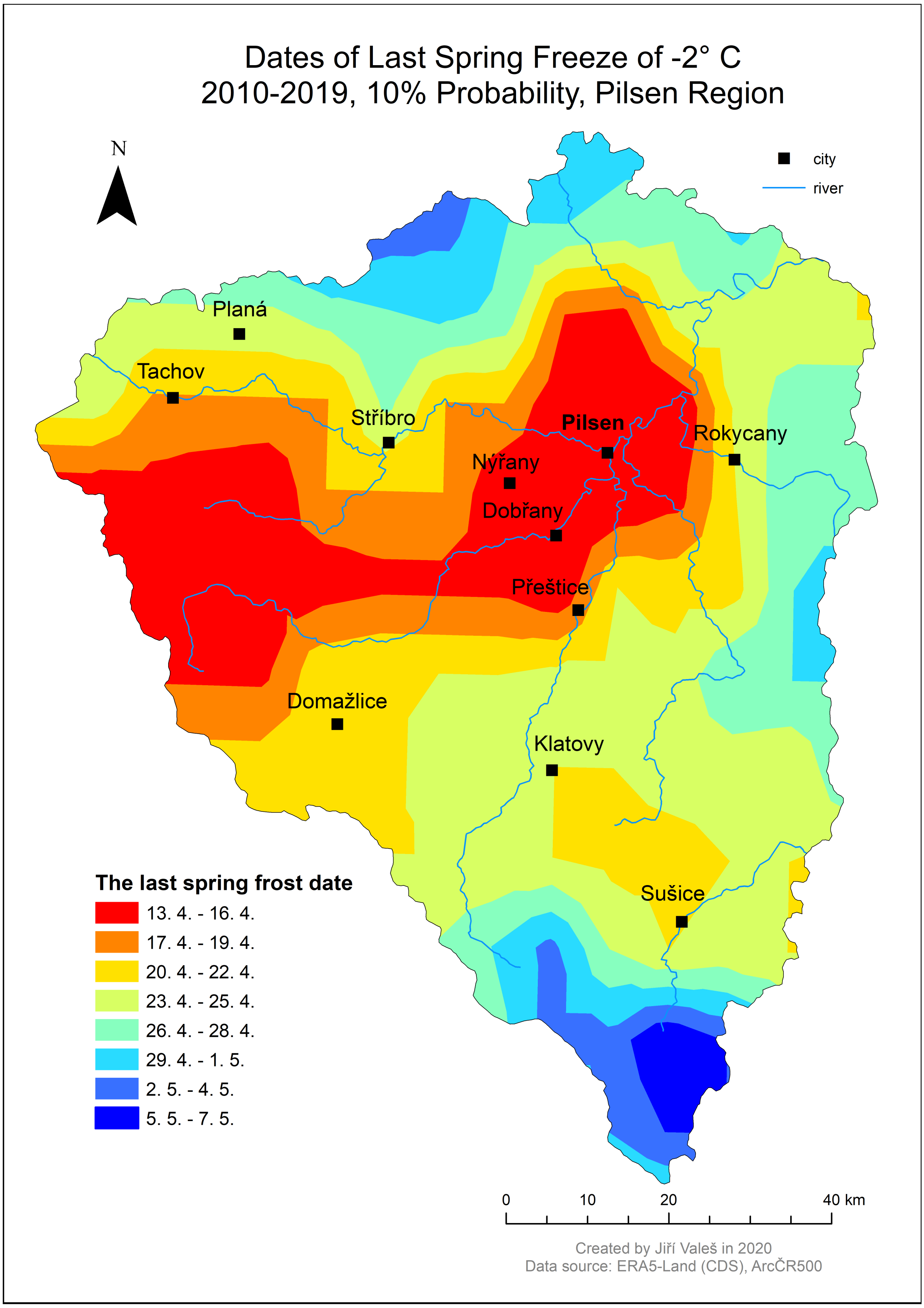

Dates of Last Spring Freeze of -2° C
2010-2019, 10% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last spring frost date
13. 4. - 16. 4.
17. 4. - 19. 4.
20. 4. - 22. 4.
23. 4. - 25. 4.
26. 4. - 28. 4.
29. 4. - 1. 5.
2. 5. - 4. 5.
5. 5. - 7. 5.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 61: Map 4

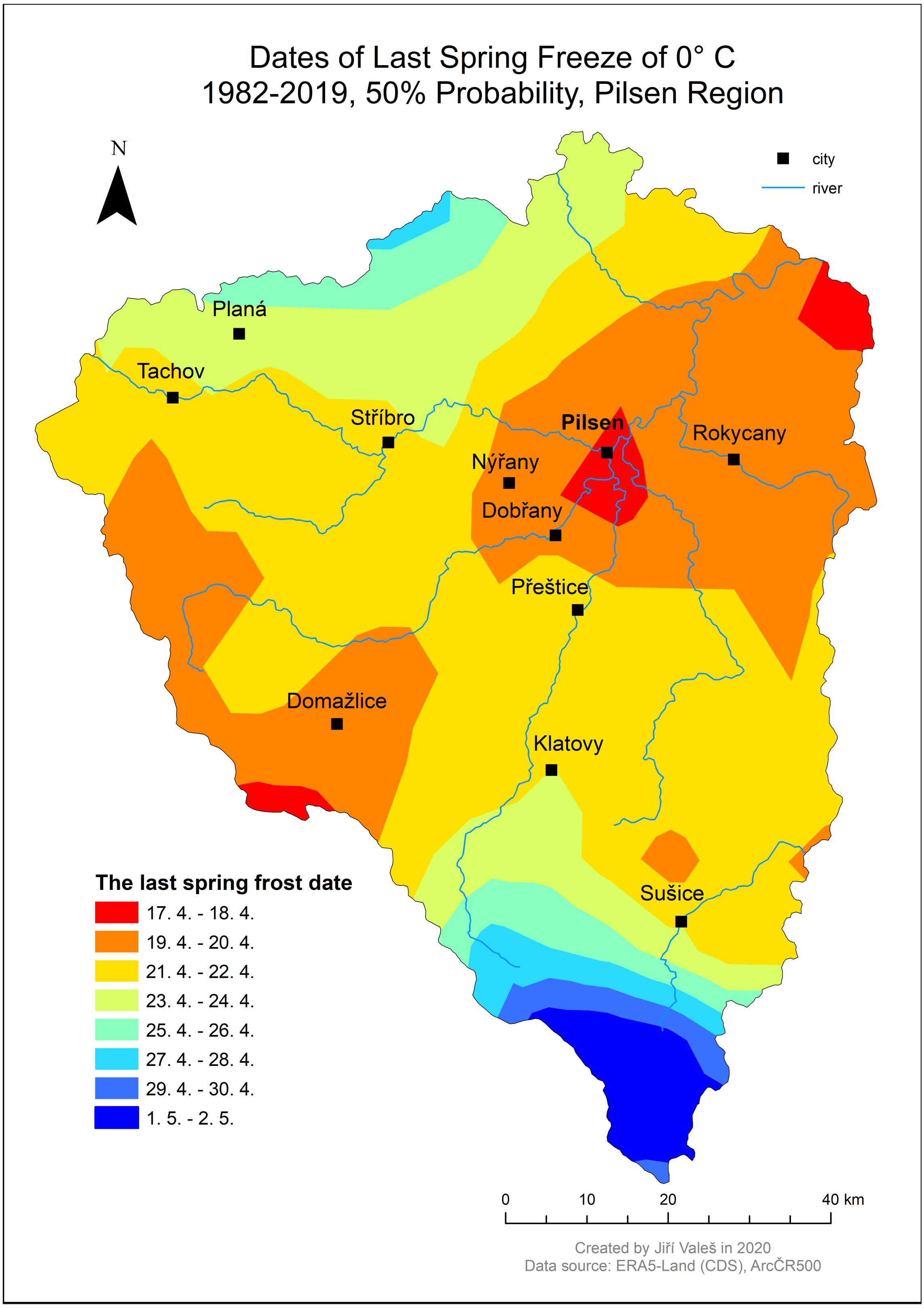
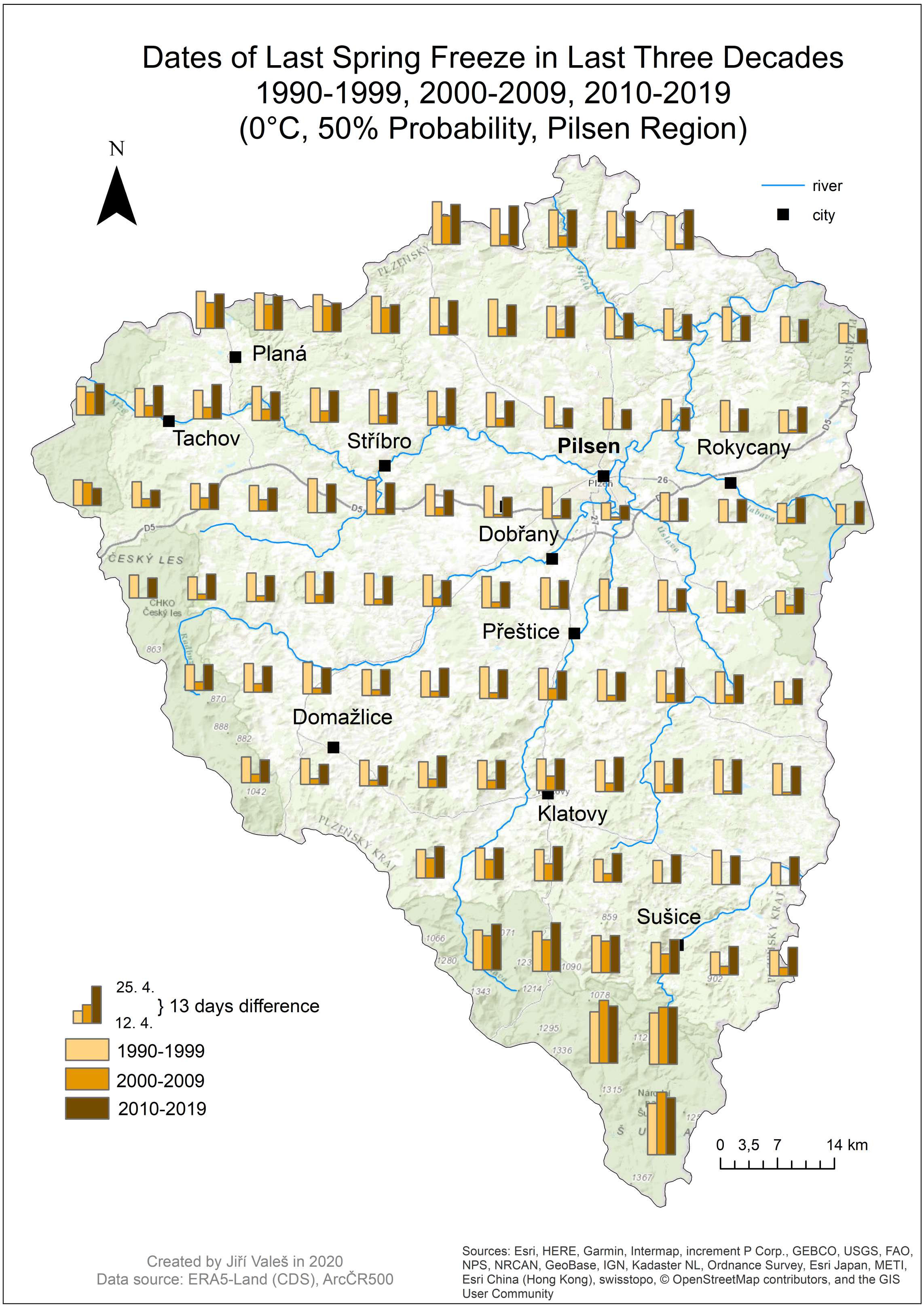

Dates of Last Spring Freeze of 0° C
1982-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last spring frost date
17. 4. - 18. 4.
19. 4. - 20. 4.
21. 4. - 22. 4.
23. 4. - 24. 4.
25. 4. - 26. 4.
27. 4. - 28. 4.
29. 4. - 30. 4.
1. 5. - 2. 5.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 62: Map 5



Dates of Last Spring Freeze in Last Three Decades
1990-1999, 2000-2009, 2010-2019
(0°C, 50% Probability, Pilsen Region)
N
river
city
Planá
Tachov
Stříbro
Pilsen
Rokycany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
ČESKÝ LES
CHKO Český les
PLZENSKÝ KRAJ
25. 4.
} 13 days difference
12. 4.
1990-1999
2000-2009
2010-2019
0 3,5 7 14 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 63: Map 6

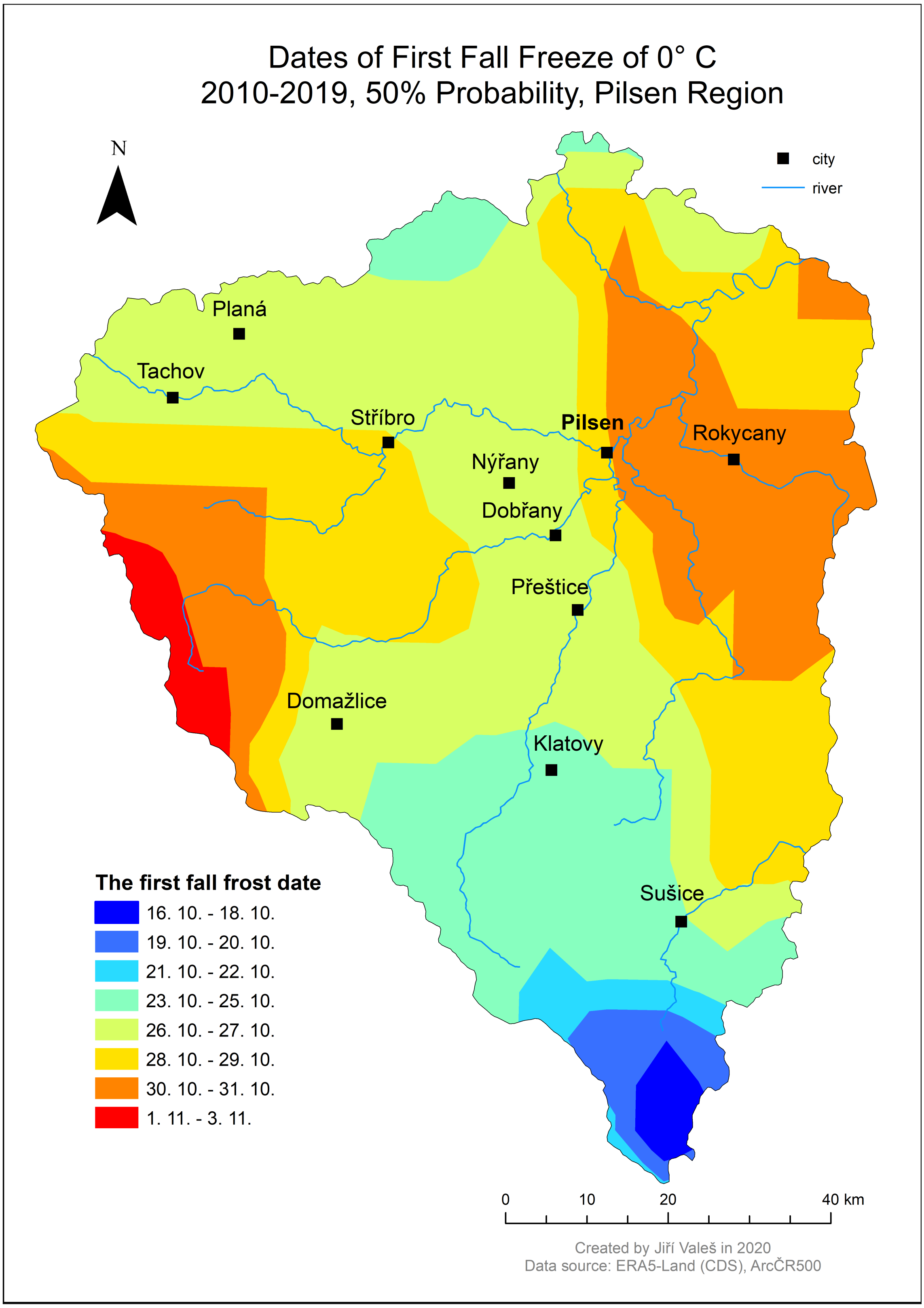

Dates of First Fall Freeze of 0° C
2010-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The first fall frost date
16. 10. - 18. 10.
19. 10. - 20. 10.
21. 10. - 22. 10.
23. 10. - 25. 10.
26. 10. - 27. 10.
28. 10. - 29. 10.
30. 10. - 31. 10.
1. 11. - 3. 11.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 64: Map 7

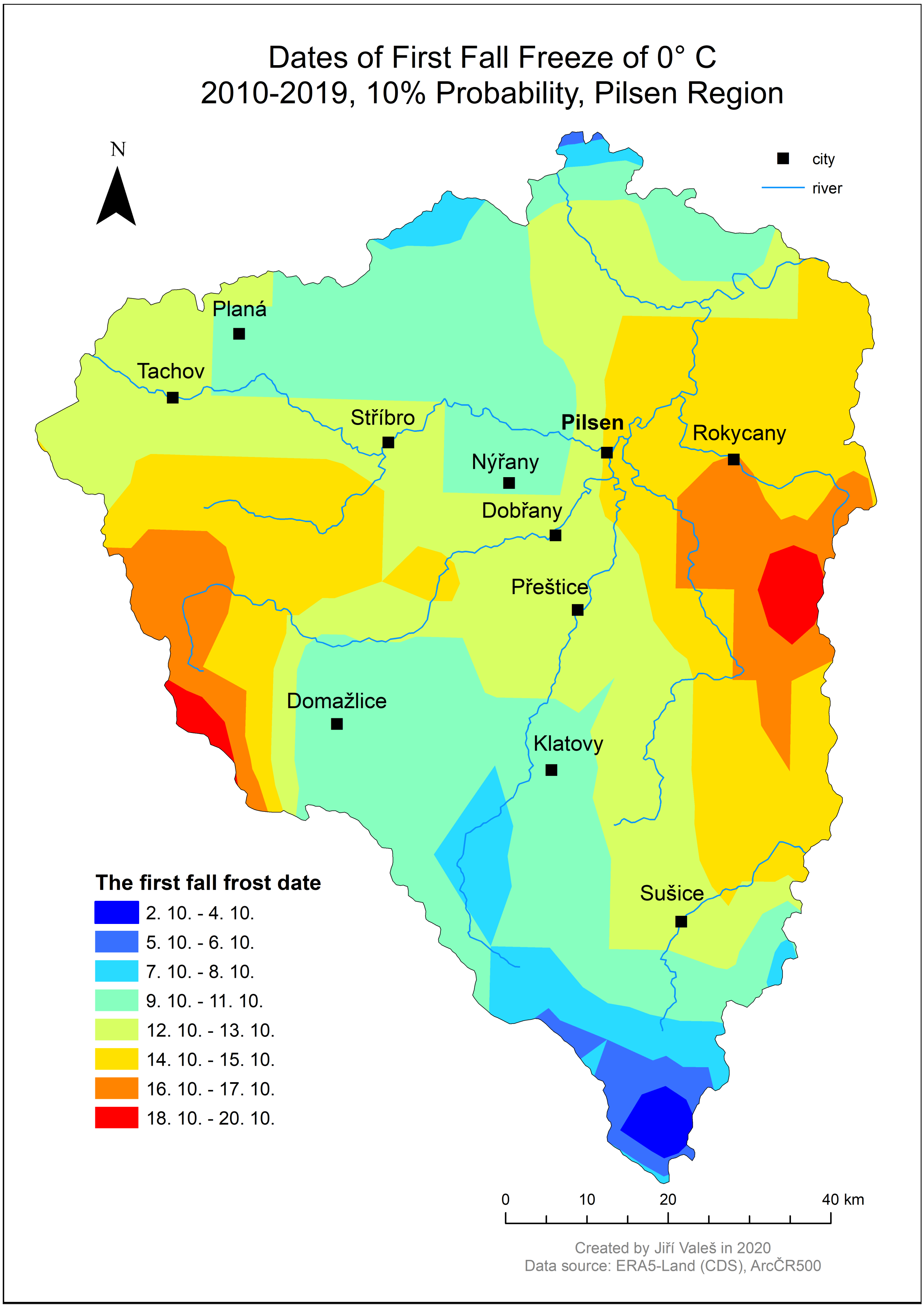
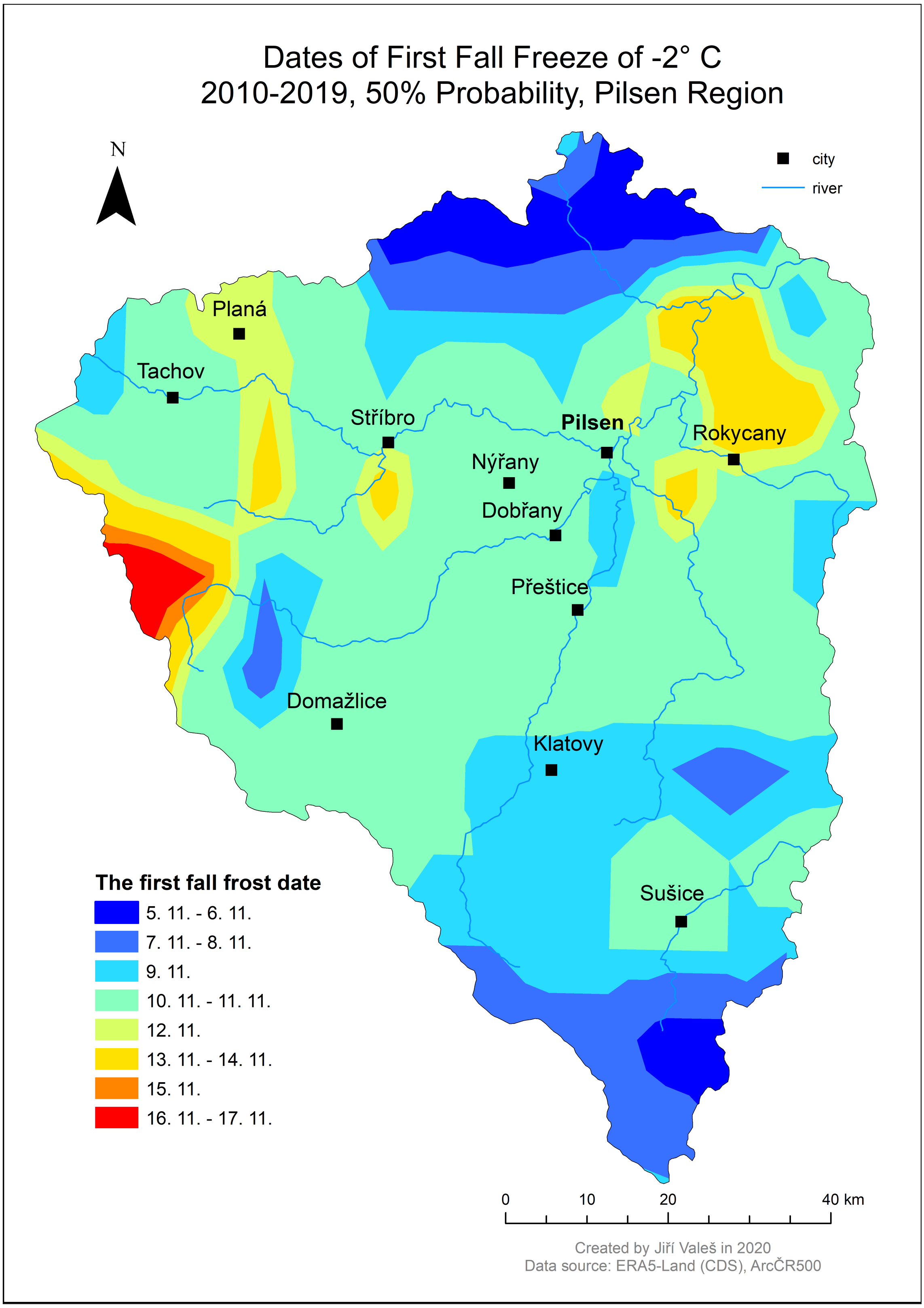

Dates of First Fall Freeze of 0° C
2010-2019, 10% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The first fall frost date
2. 10. - 4. 10.
5. 10. - 6. 10.
7. 10. - 8. 10.
9. 10. - 11. 10.
12. 10. - 13. 10.
14. 10. - 15. 10.
16. 10. - 17. 10.
18. 10. - 20. 10.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 65: Map 8



Dates of First Fall Freeze of -2° C
2010-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The first fall frost date
5. 11. - 6. 11.
7. 11. - 8. 11.
9. 11.
10. 11. - 11. 11.
12. 11.
13. 11. - 14. 11.
15. 11.
16. 11. - 17. 11.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 66: Map 9

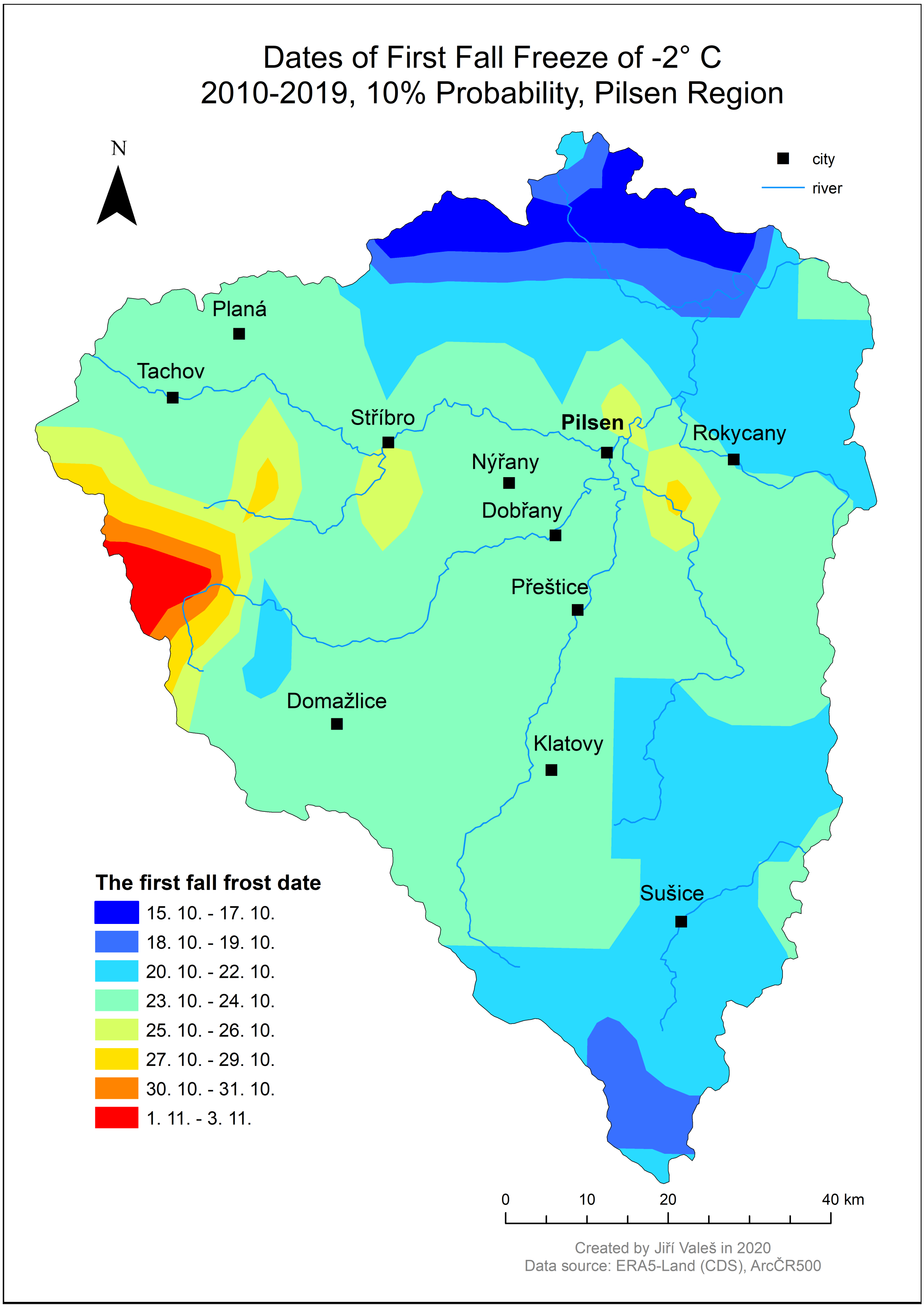

Dates of First Fall Freeze of -2° C
2010-2019, 10% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The first fall frost date
15. 10. - 17. 10.
18. 10. - 19. 10.
20. 10. - 22. 10.
23. 10. - 24. 10.
25. 10. - 26. 10.
27. 10. - 29. 10.
30. 10. - 31. 10.
1. 11. - 3. 11.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 67: Map 10

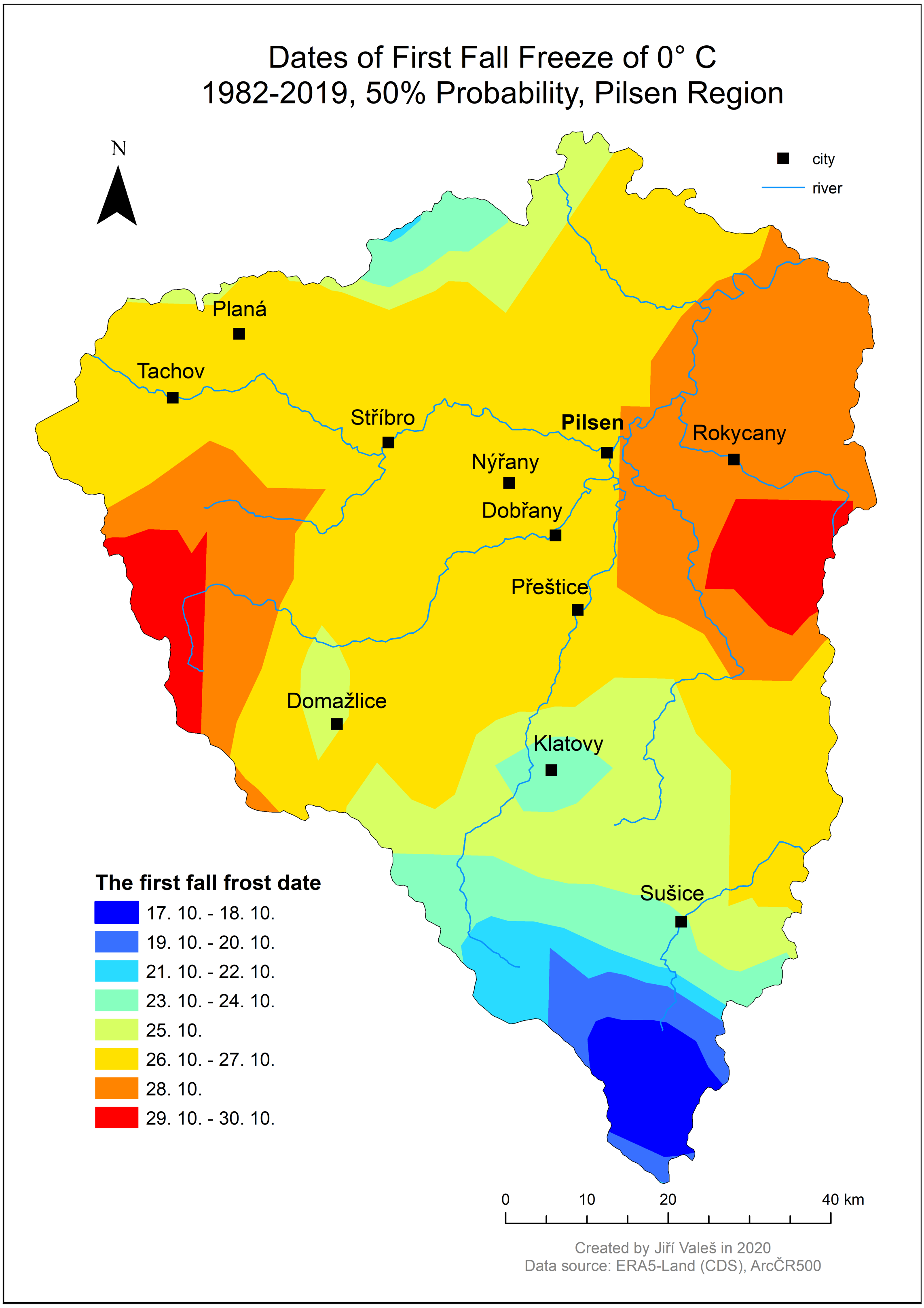

Dates of First Fall Freeze of 0° C
1982-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The first fall frost date
17. 10. - 18. 10.
19. 10. - 20. 10.
21. 10. - 22. 10.
23. 10. - 24. 10.
25. 10.
26. 10. - 27. 10.
28. 10.
29. 10. - 30. 10.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 68: Map 11

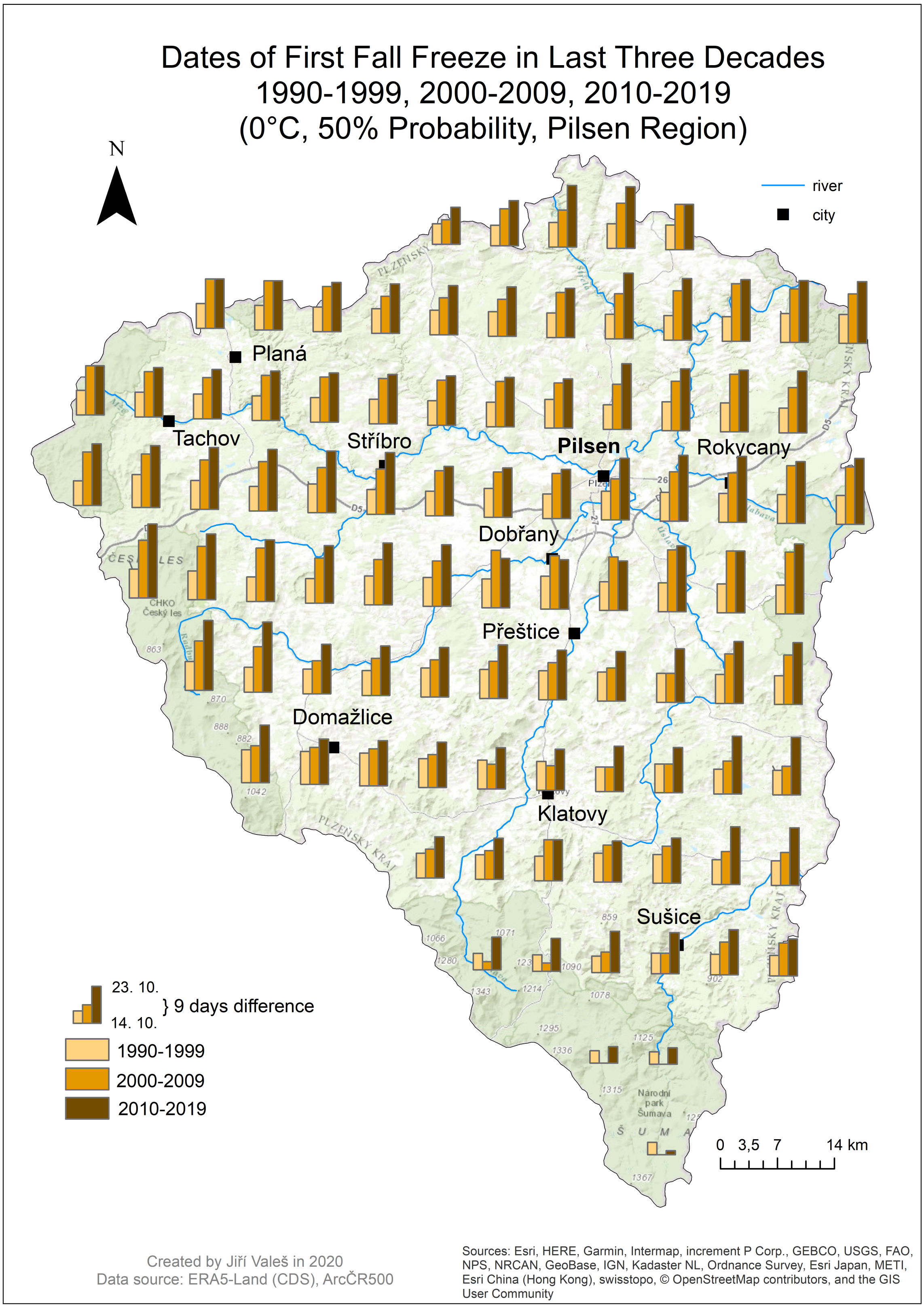

Dates of First Fall Freeze in Last Three Decades
1990-1999, 2000-2009, 2010-2019
(0°C, 50% Probability, Pilsen Region)
N
river
city
Planá
Tachov
Stříbro
Pilsen
Rokycany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
23. 10.
} 9 days difference
14. 10.
1990-1999
2000-2009
2010-2019
0 3,5 7 14 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 69: Map 12

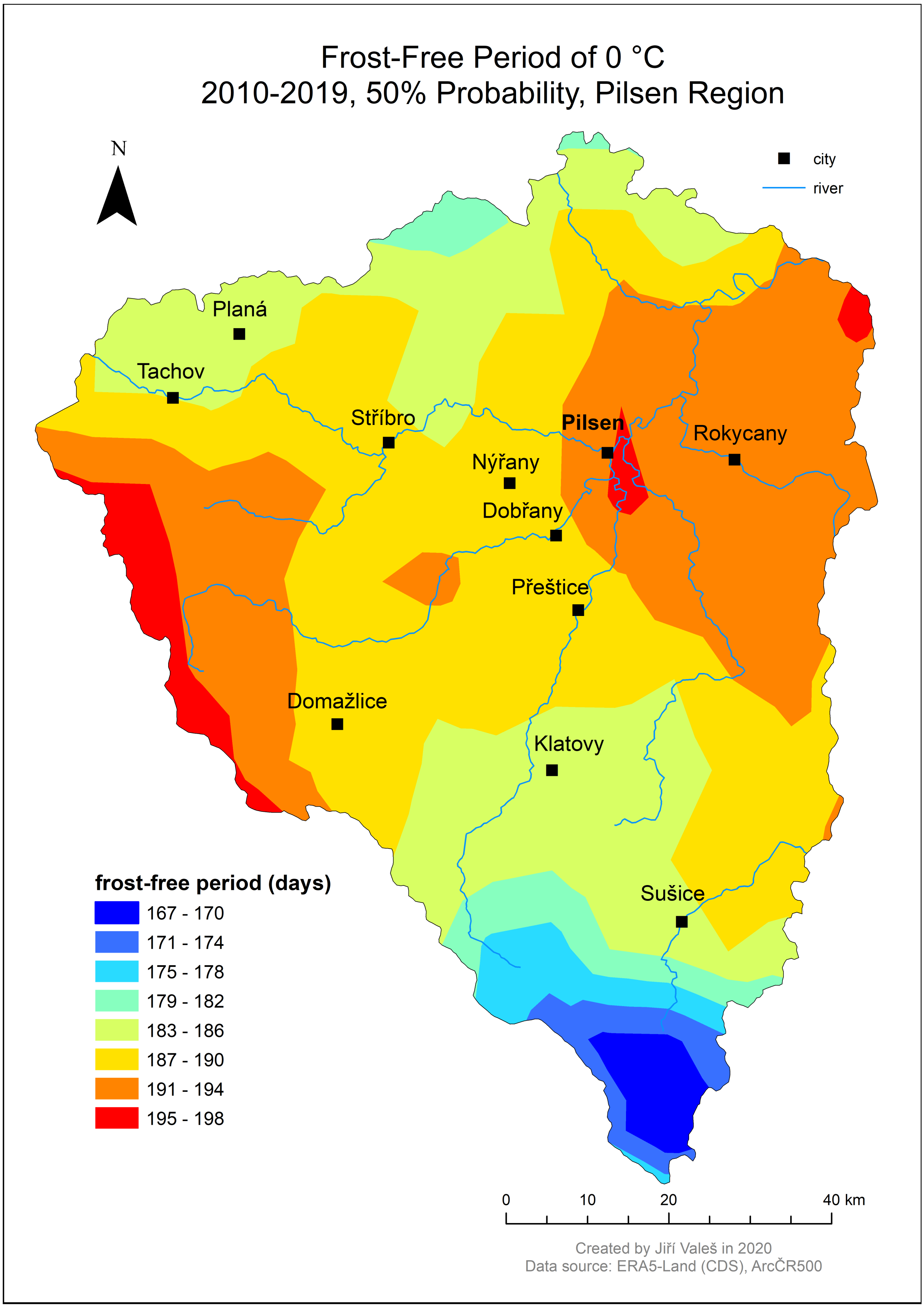

Frost-Free Period of 0 °C
2010-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
frost-free period (days)
167 - 170
171 - 174
175 - 178
179 - 182
183 - 186
187 - 190
191 - 194
195 - 198
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 70: Map 13

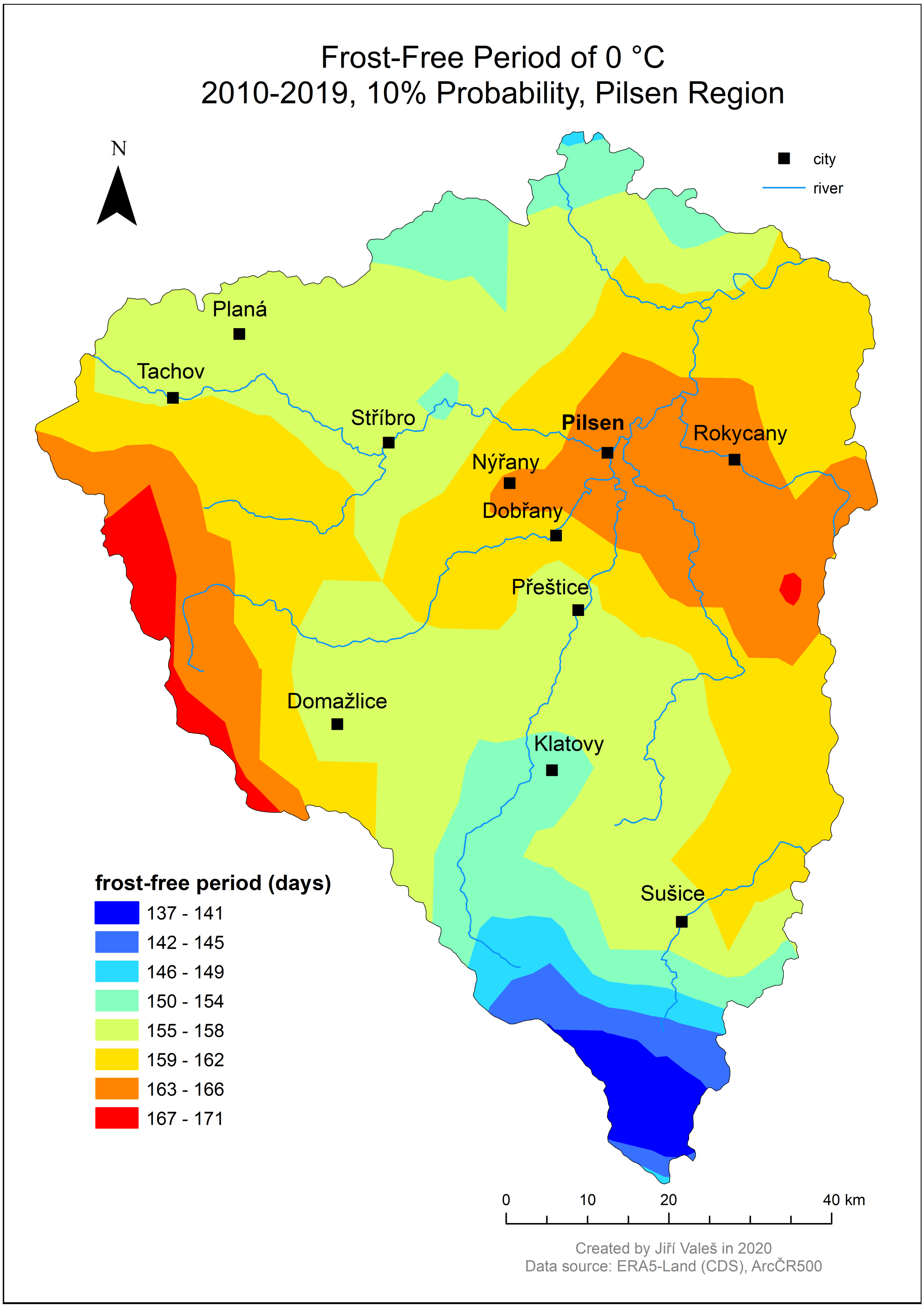

Frost-Free Period of 0 °C
2010-2019, 10% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
frost-free period (days)
137 - 141
142 - 145
146 - 149
150 - 154
155 - 158
159 - 162
163 - 166
167 - 171
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 71: Map 14

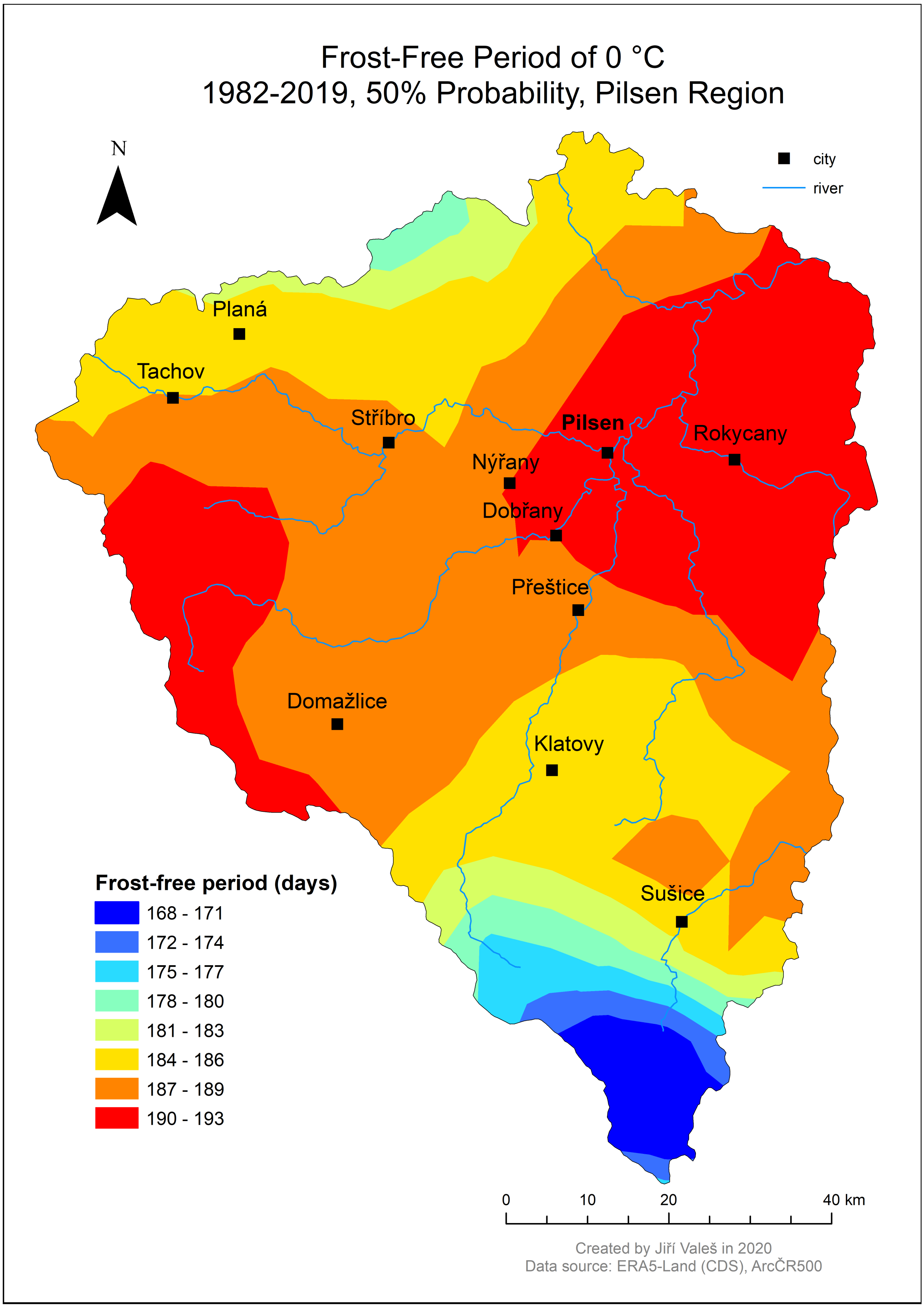

Frost-Free Period of 0 °C
1982-2019, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Frost-free period (days)
168 - 171
172 - 174
175 - 177
178 - 180
181 - 183
184 - 186
187 - 189
190 - 193
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 72: Map 15

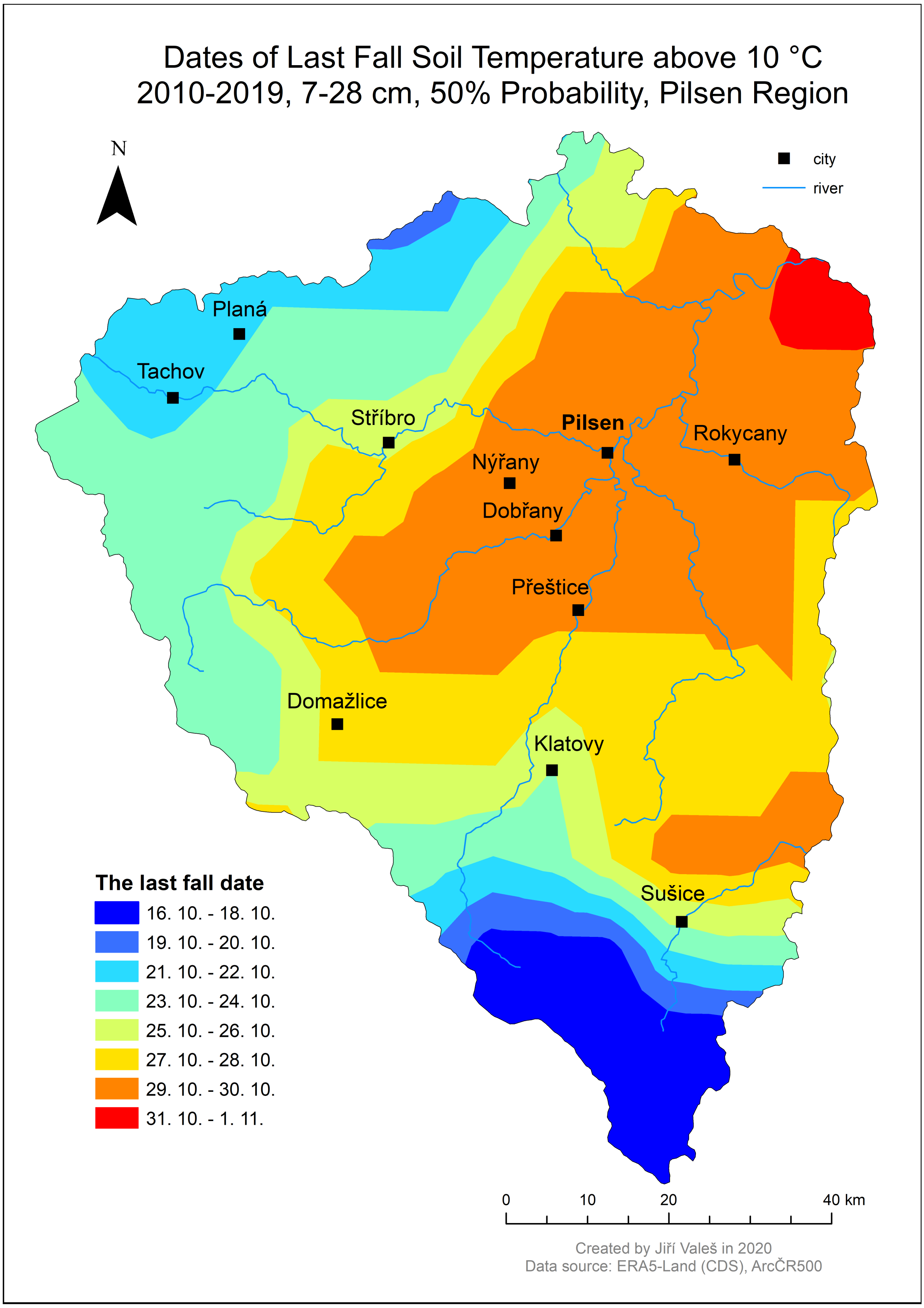

Dates of Last Fall Soil Temperature above 10 °C
2010-2019, 7-28 cm, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last fall date
16. 10. - 18. 10.
19. 10. - 20. 10.
21. 10. - 22. 10.
23. 10. - 24. 10.
25. 10. - 26. 10.
27. 10. - 28. 10.
29. 10. - 30. 10.
31. 10. - 1. 11.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 73: Map 16

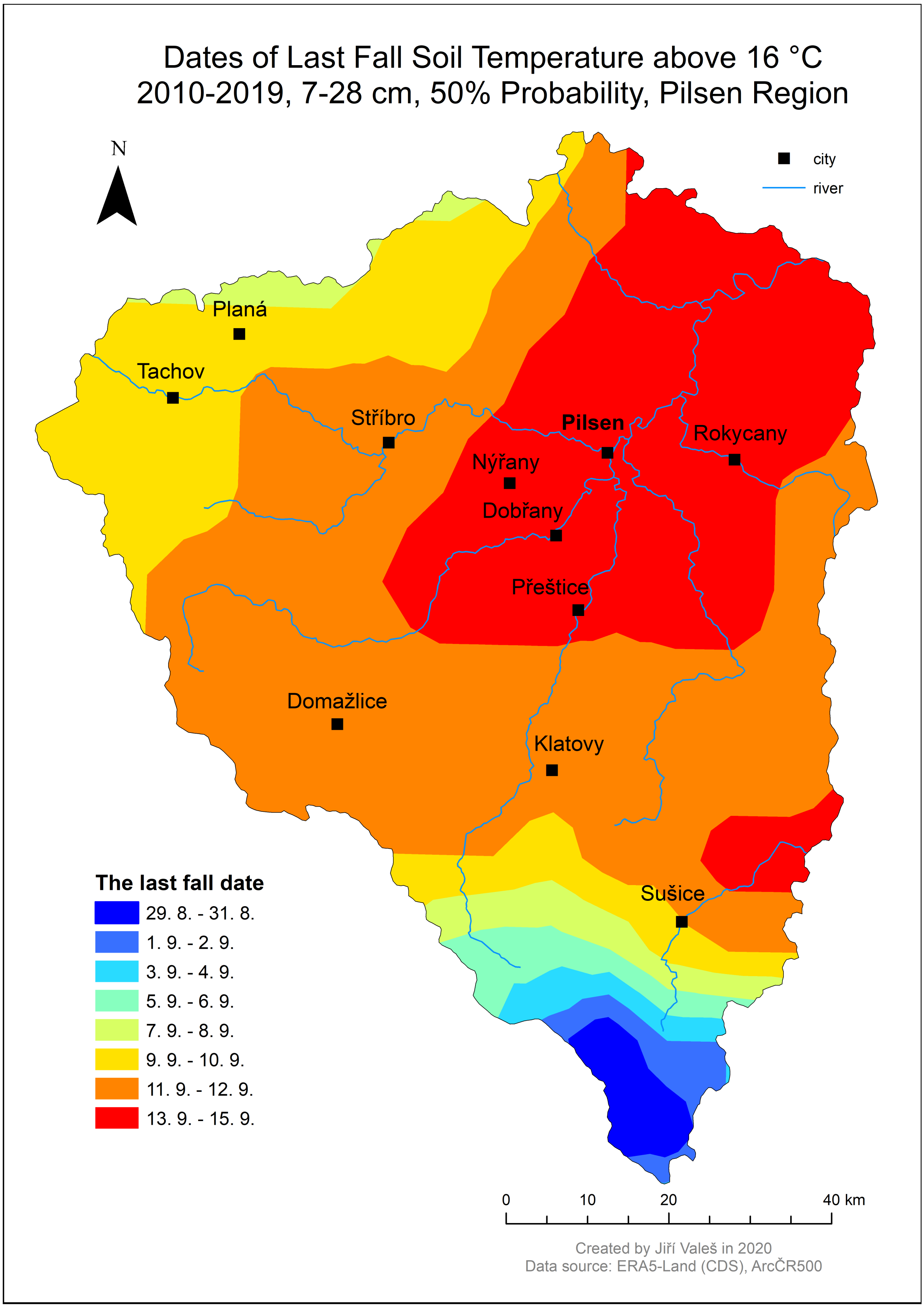

Dates of Last Fall Soil Temperature above 16 °C
2010-2019, 7-28 cm, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last fall date
29. 8. - 31. 8.
1. 9. - 2. 9.
3. 9. - 4. 9.
5. 9. - 6. 9.
7. 9. - 8. 9.
9. 9. - 10. 9.
11. 9. - 12. 9.
13. 9. - 15. 9.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 74: Map 17

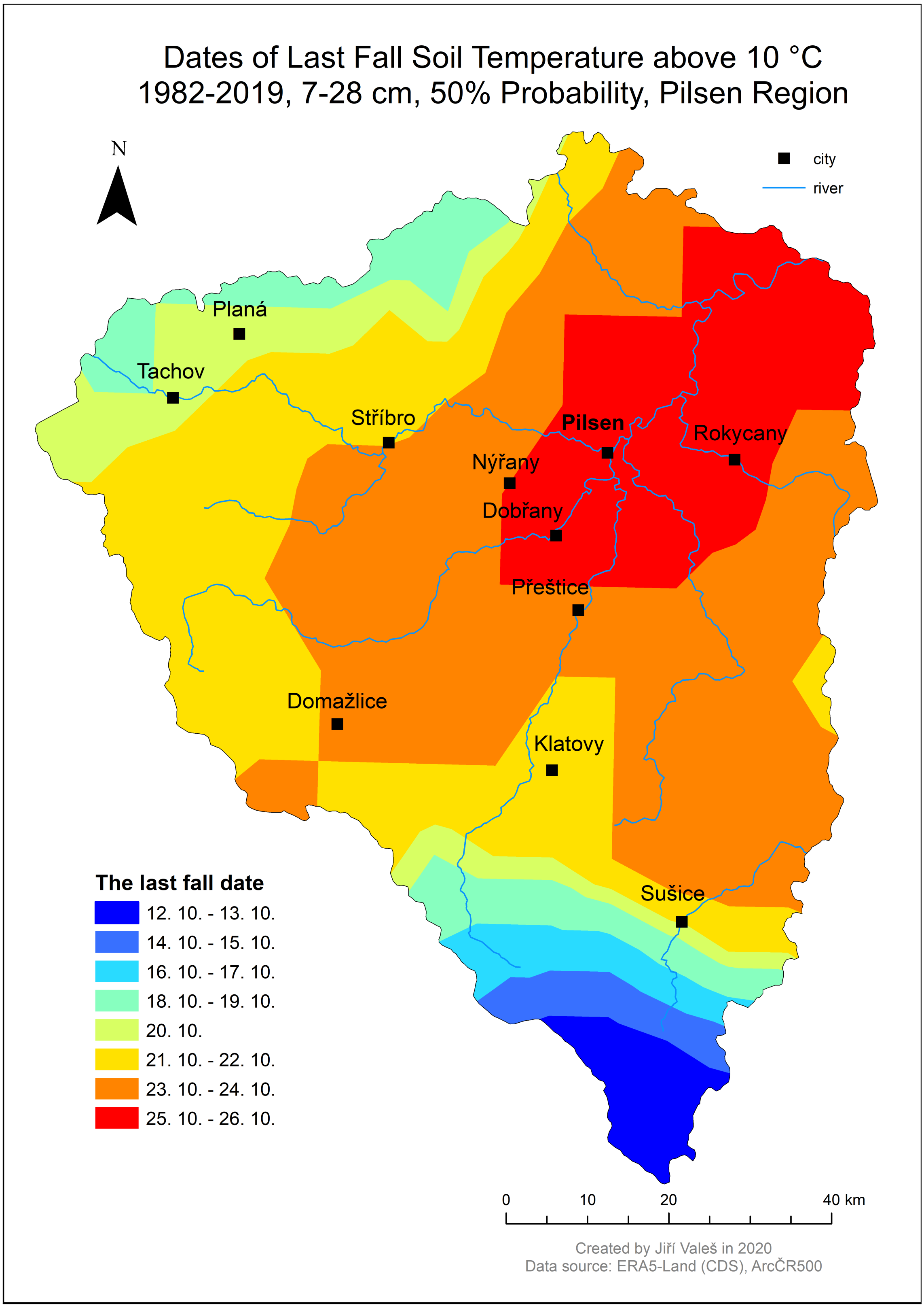

Dates of Last Fall Soil Temperature above 10 °C
1982-2019, 7-28 cm, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last fall date
12. 10. - 13. 10.
14. 10. - 15. 10.
16. 10. - 17. 10.
18. 10. - 19. 10.
20. 10.
21. 10. - 22. 10.
23. 10. - 24. 10.
25. 10. - 26. 10.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 75: Map 18

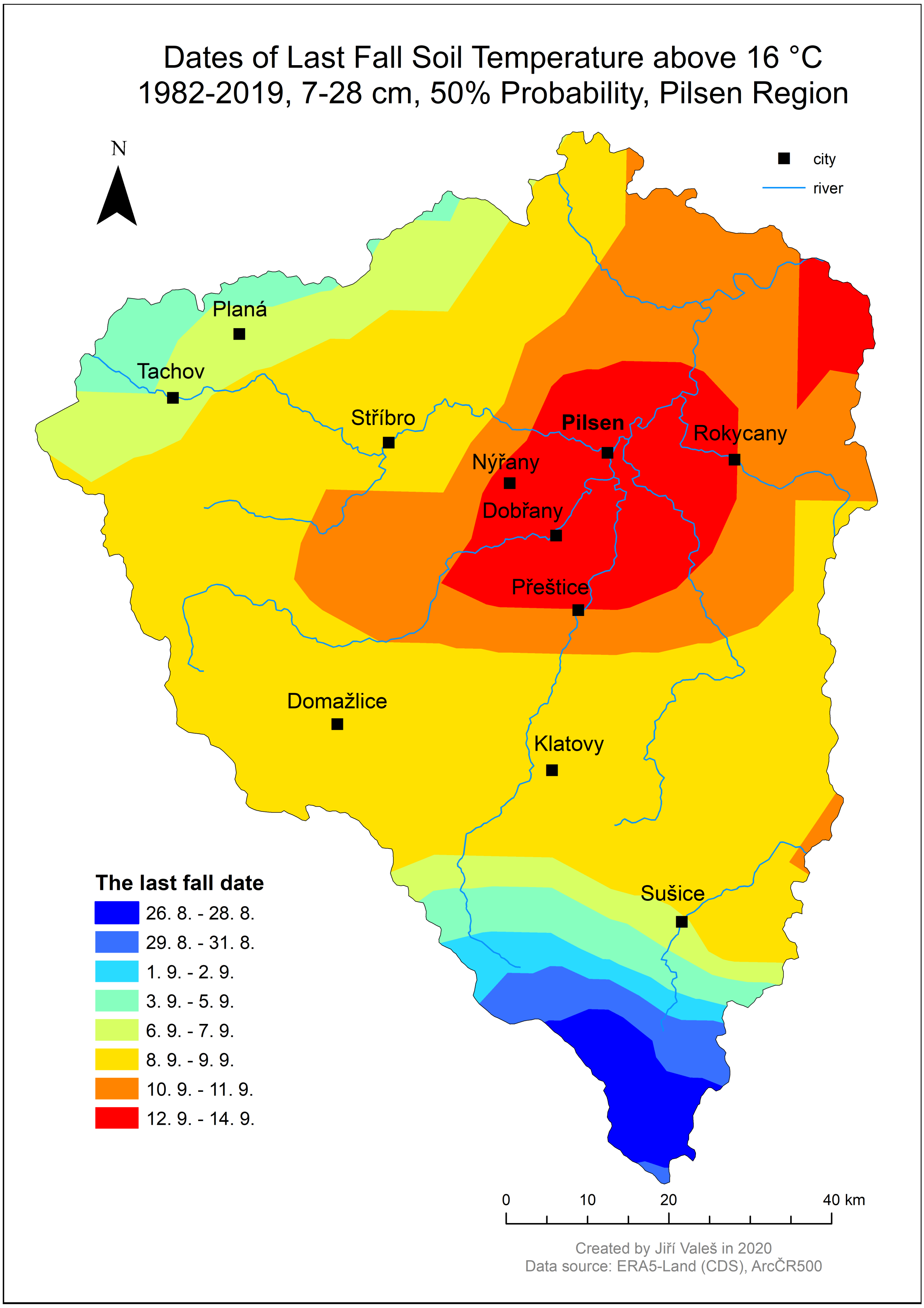

Dates of Last Fall Soil Temperature above 16 °C
1982-2019, 7-28 cm, 50% Probability, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
The last fall date
26. 8. - 28. 8.
29. 8. - 31. 8.
1. 9. - 2. 9.
3. 9. - 5. 9.
6. 9. - 7. 9.
8. 9. - 9. 9.
10. 9. - 11. 9.
12. 9. - 14. 9.
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 76: Map 19

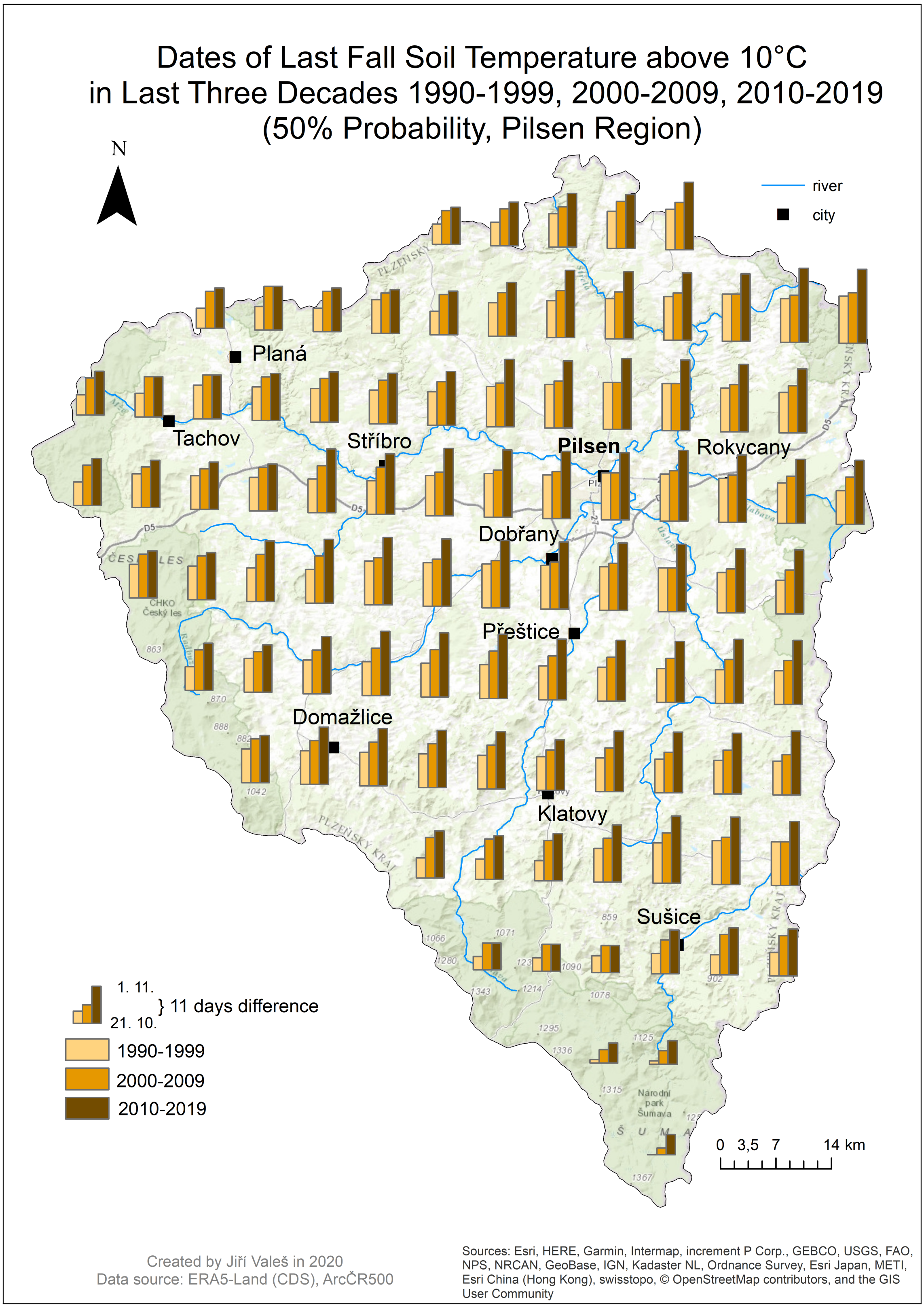
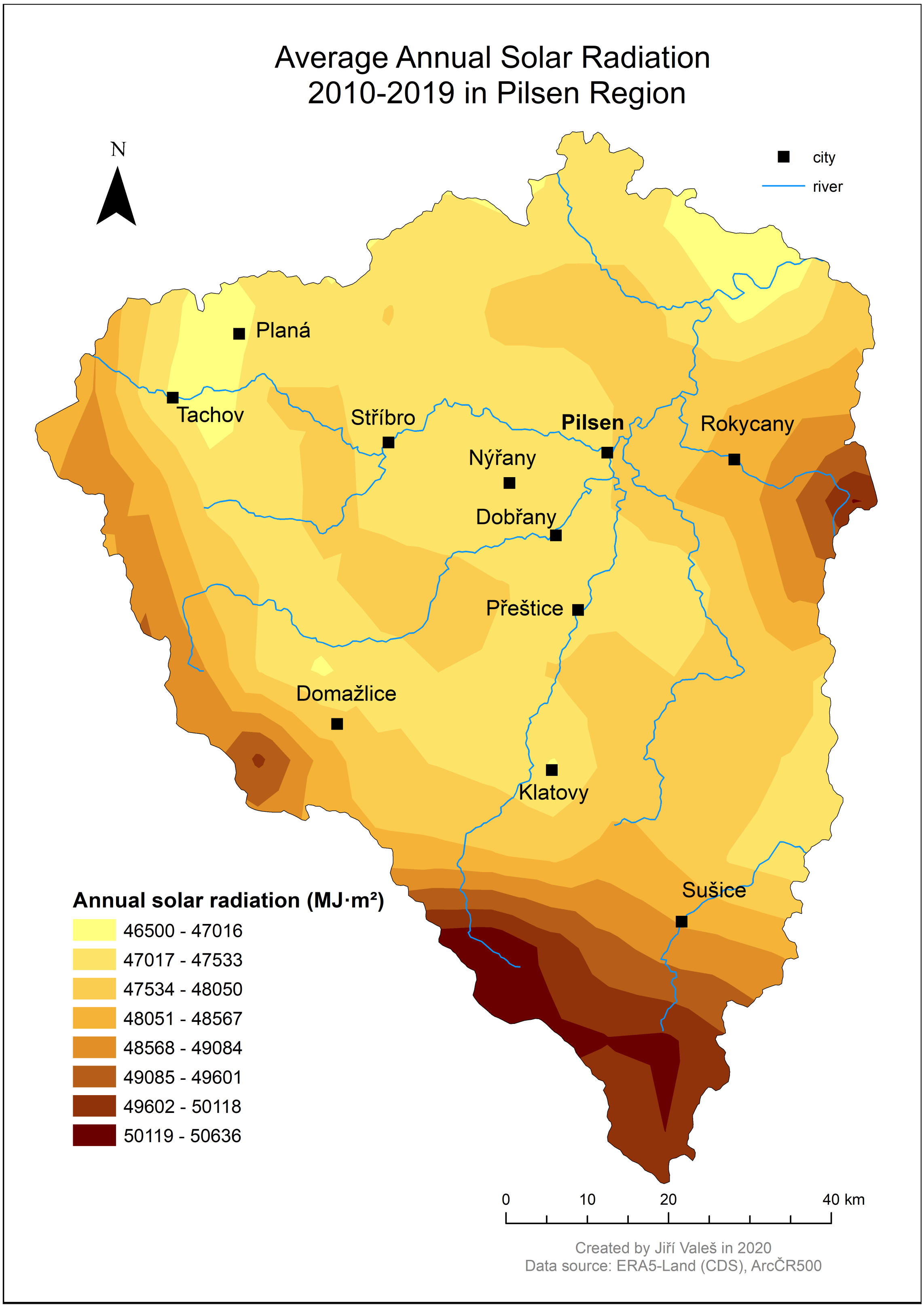

Dates of Last Fall Soil Temperature above 10°C
in Last Three Decades 1990-1999, 2000-2009, 2010-2019
(50% Probability, Pilsen Region)
N
river
city
Planá
Tachov
Stříbro
Pilsen
Rokycany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
1. 11.
} 11 days difference
21. 10.
1990-1999
2000-2009
2010-2019
0 3,5 7 14 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 77: Map 20



Average Annual Solar Radiation
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Annual solar radiation (MJ·m²)
46500 - 47016
47017 - 47533
47534 - 48050
48051 - 48567
48568 - 49084
49085 - 49601
49602 - 50118
50119 - 50636
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 78: Map 21

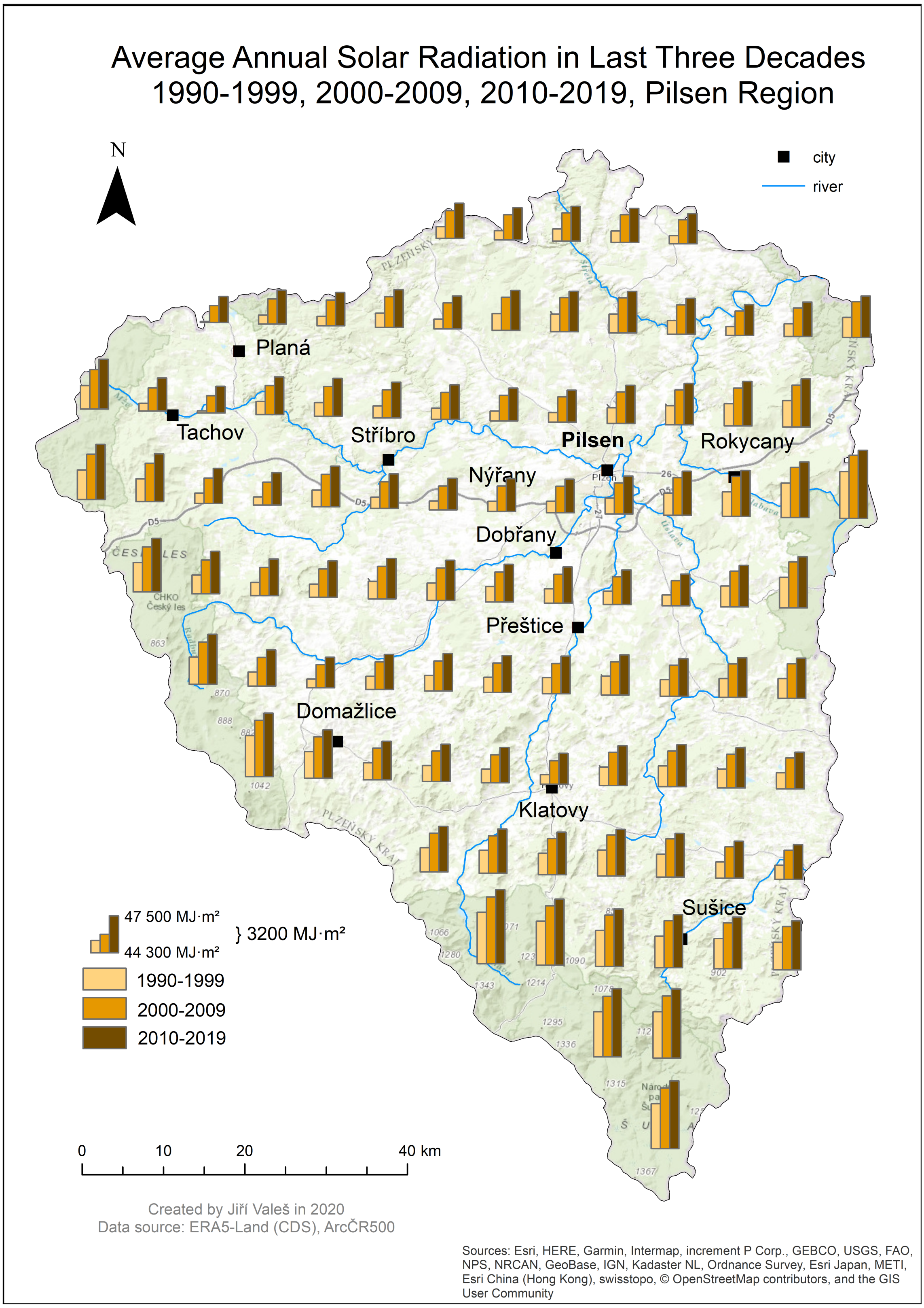
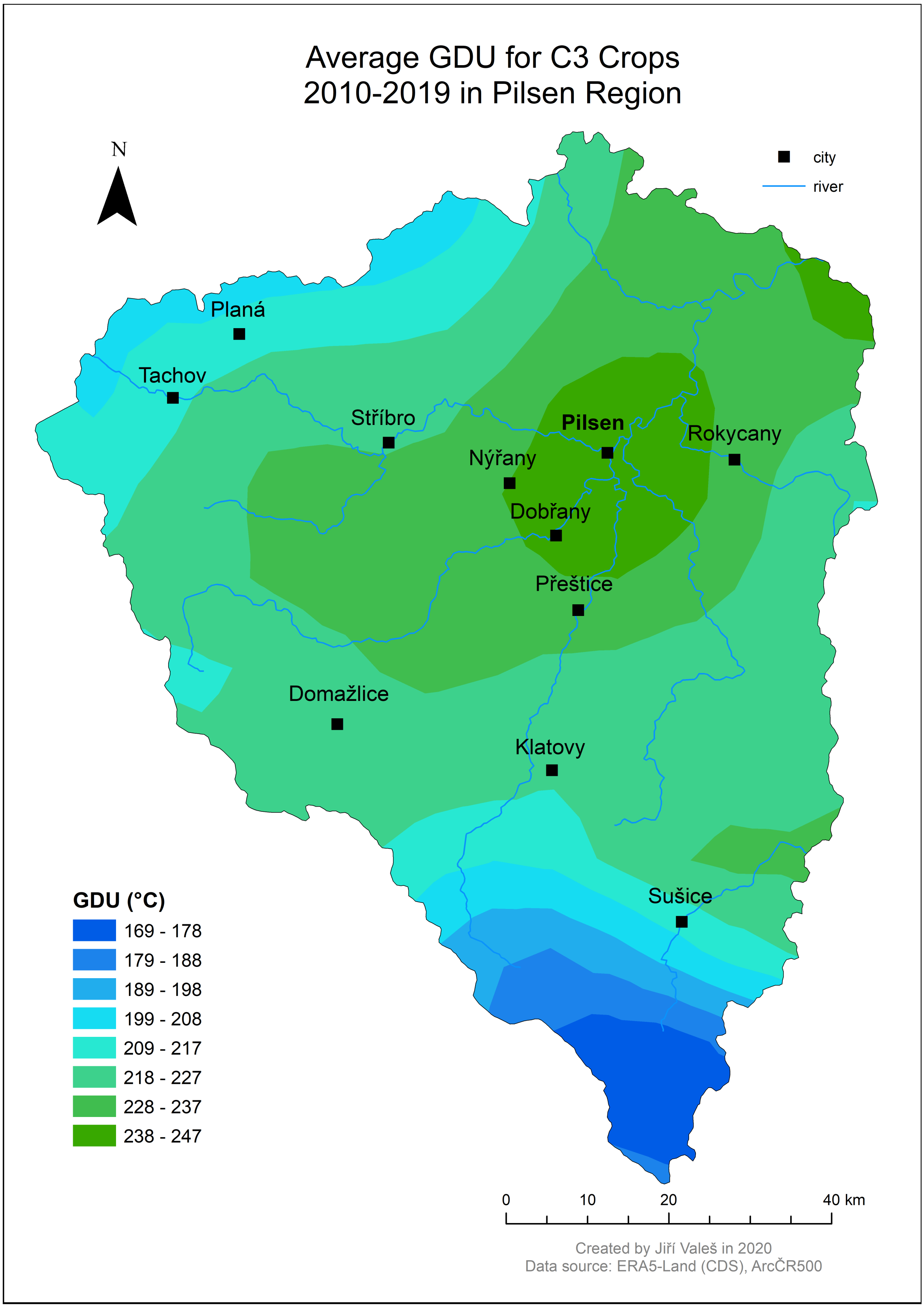
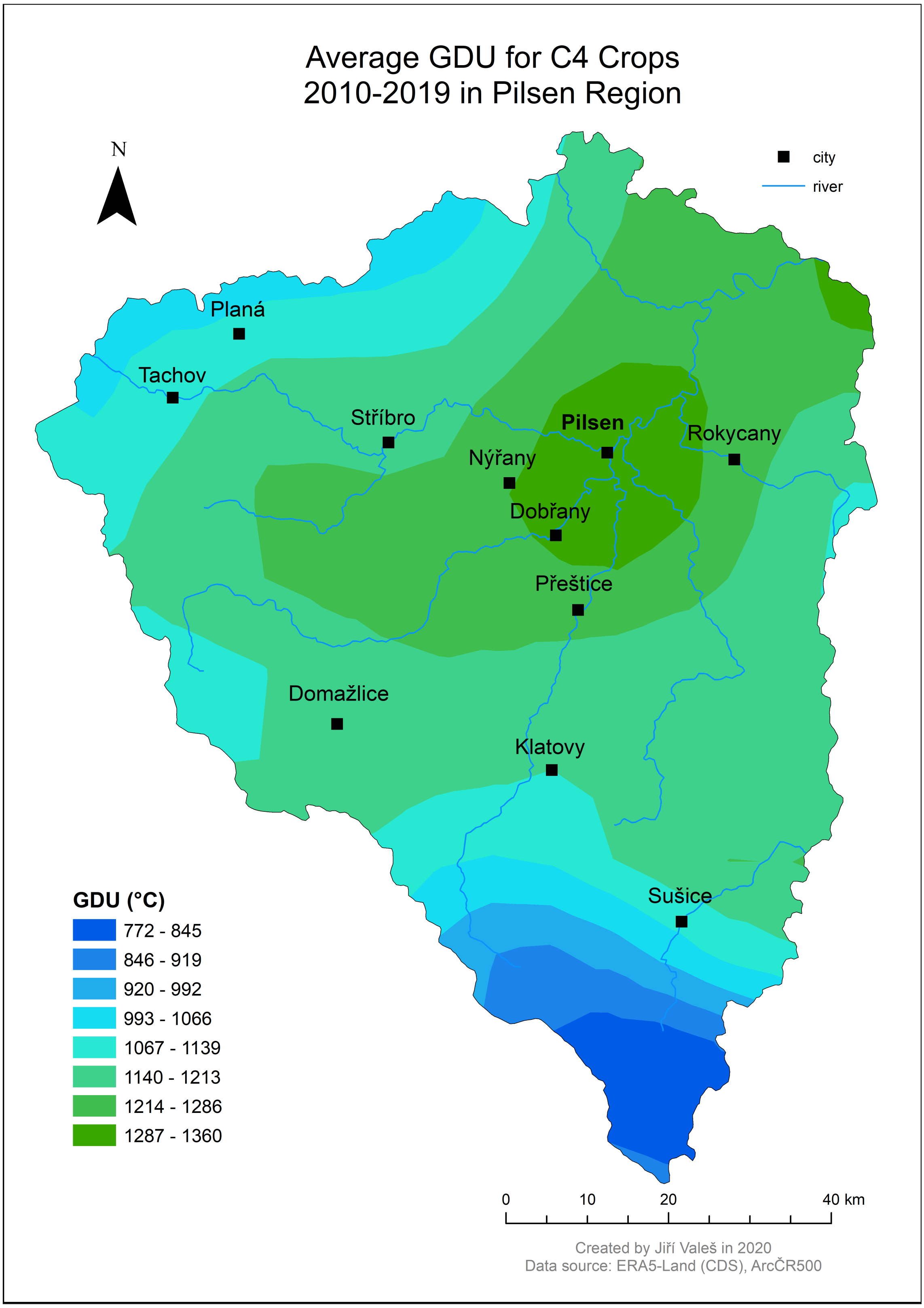

Average Annual Solar Radiation in Last Three Decades
1990-1999, 2000-2009, 2010-2019, Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
47 500 MJ·m²
} 3200 MJ·m²
44 300 MJ·m²
1990-1999
2000-2009
2010-2019
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 79: Map 22



Average GDU for C3 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
GDU (°C)
169 - 178
179 - 188
189 - 198
199 - 208
209 - 217
218 - 227
228 - 237
238 - 247
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 80: Map 23



Average GDU for C4 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
GDU (°C)
772 - 845
846 - 919
920 - 992
993 - 1066
1067 - 1139
1140 - 1213
1214 - 1286
1287 - 1360
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 81: Map 24

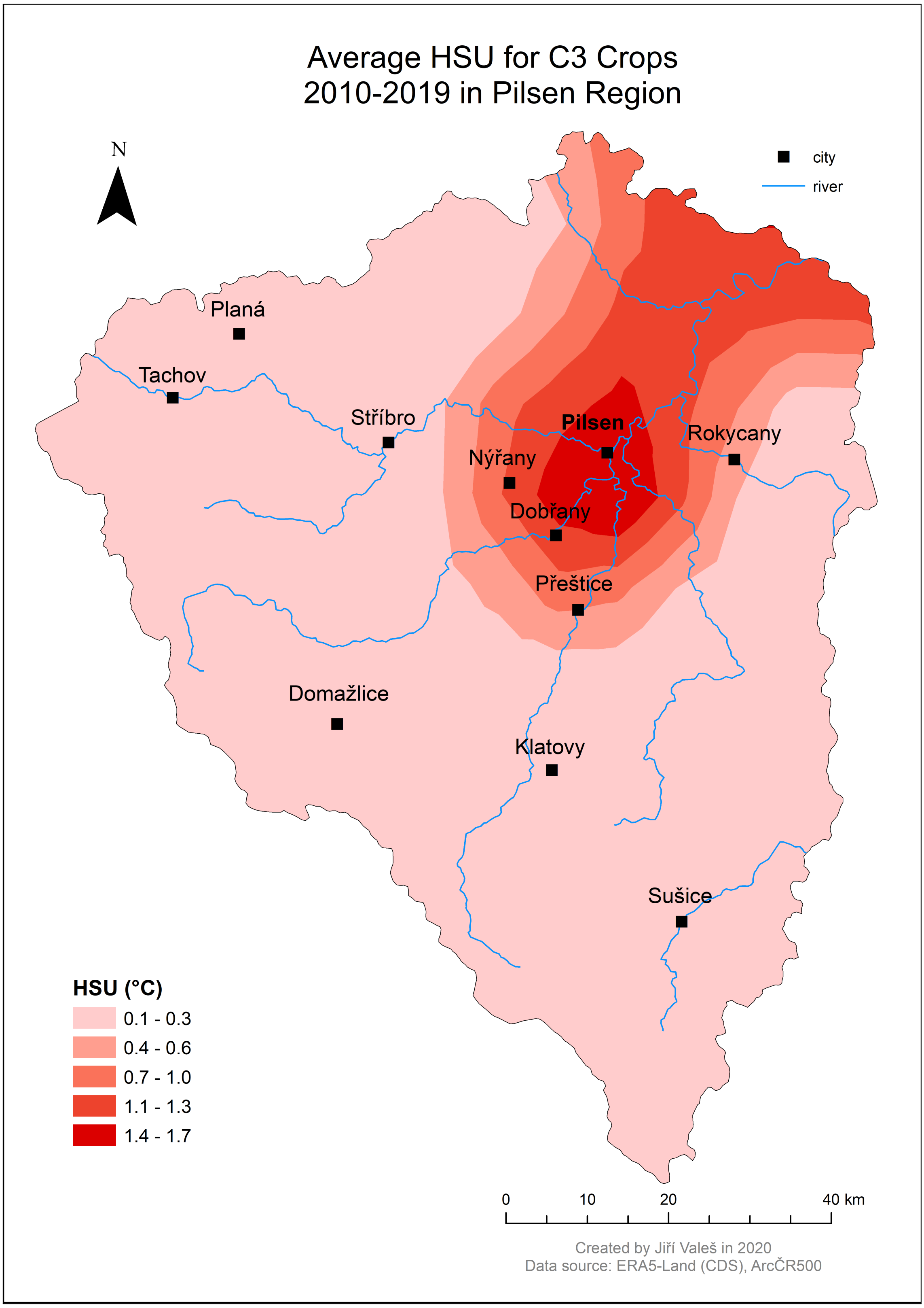

Average HSU for C3 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
HSU (°C)
0.1 - 0.3
0.4 - 0.6
0.7 - 1.0
1.1 - 1.3
1.4 - 1.7
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 82: Map 25

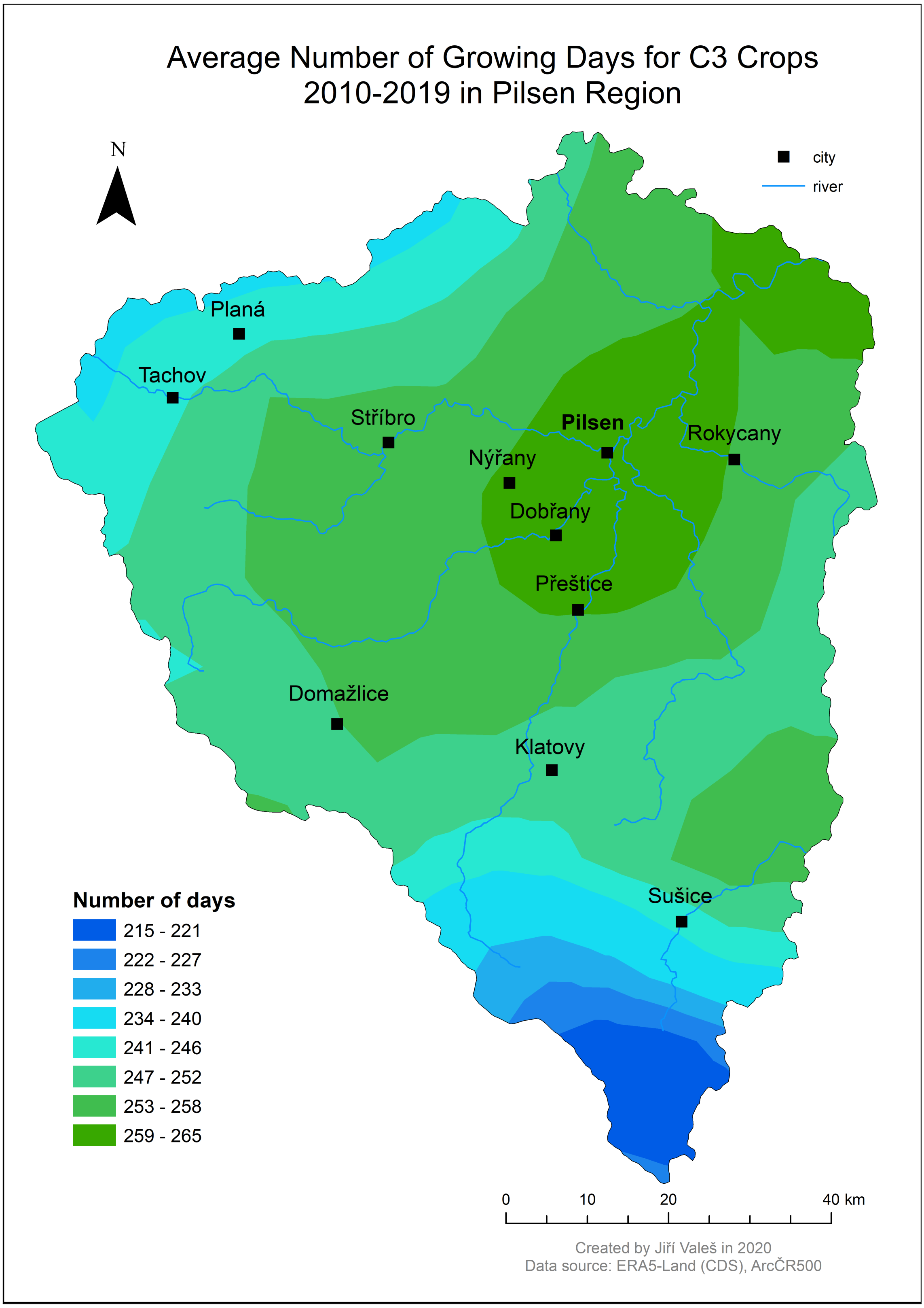

Average Number of Growing Days for C3 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Number of days
215 - 221
222 - 227
228 - 233
234 - 240
241 - 246
247 - 252
253 - 258
259 - 265
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 83: Map 26

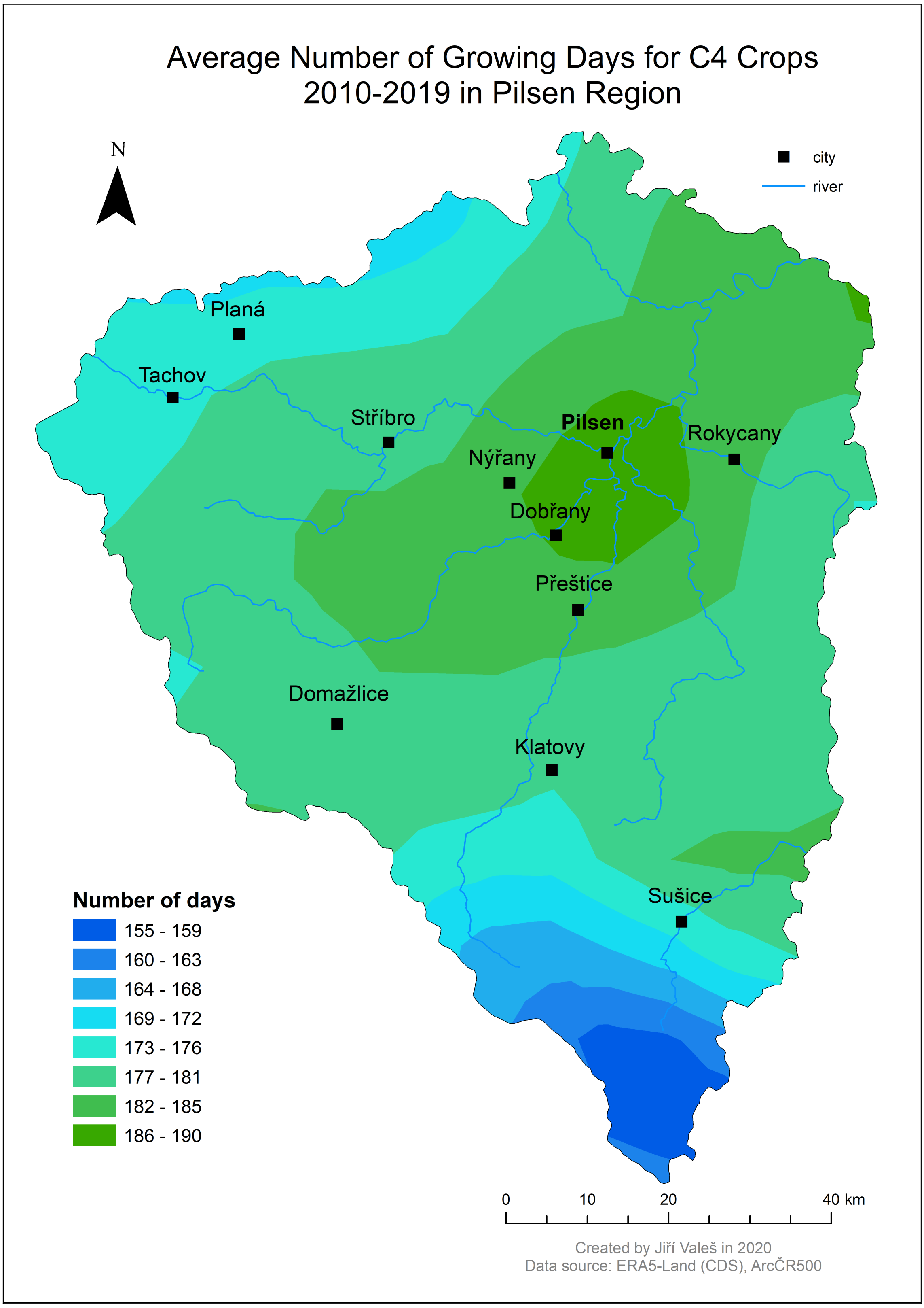

Average Number of Growing Days for C4 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Number of days
155 - 159
160 - 163
164 - 168
169 - 172
173 - 176
177 - 181
182 - 185
186 - 190
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 84: Map 27

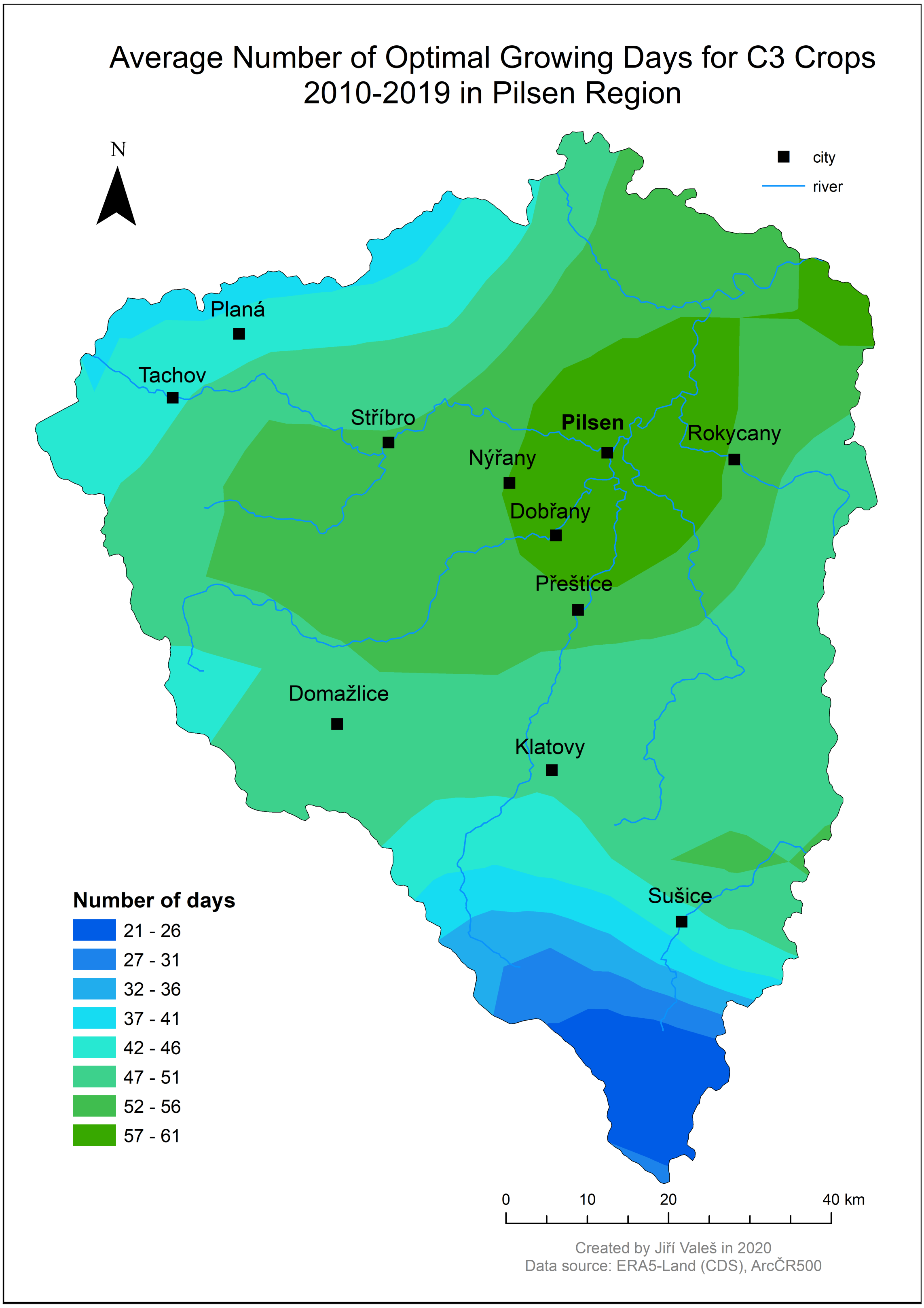

Average Number of Optimal Growing Days for C3 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Number of days
21 - 26
27 - 31
32 - 36
37 - 41
42 - 46
47 - 51
52 - 56
57 - 61
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 85: Map 28

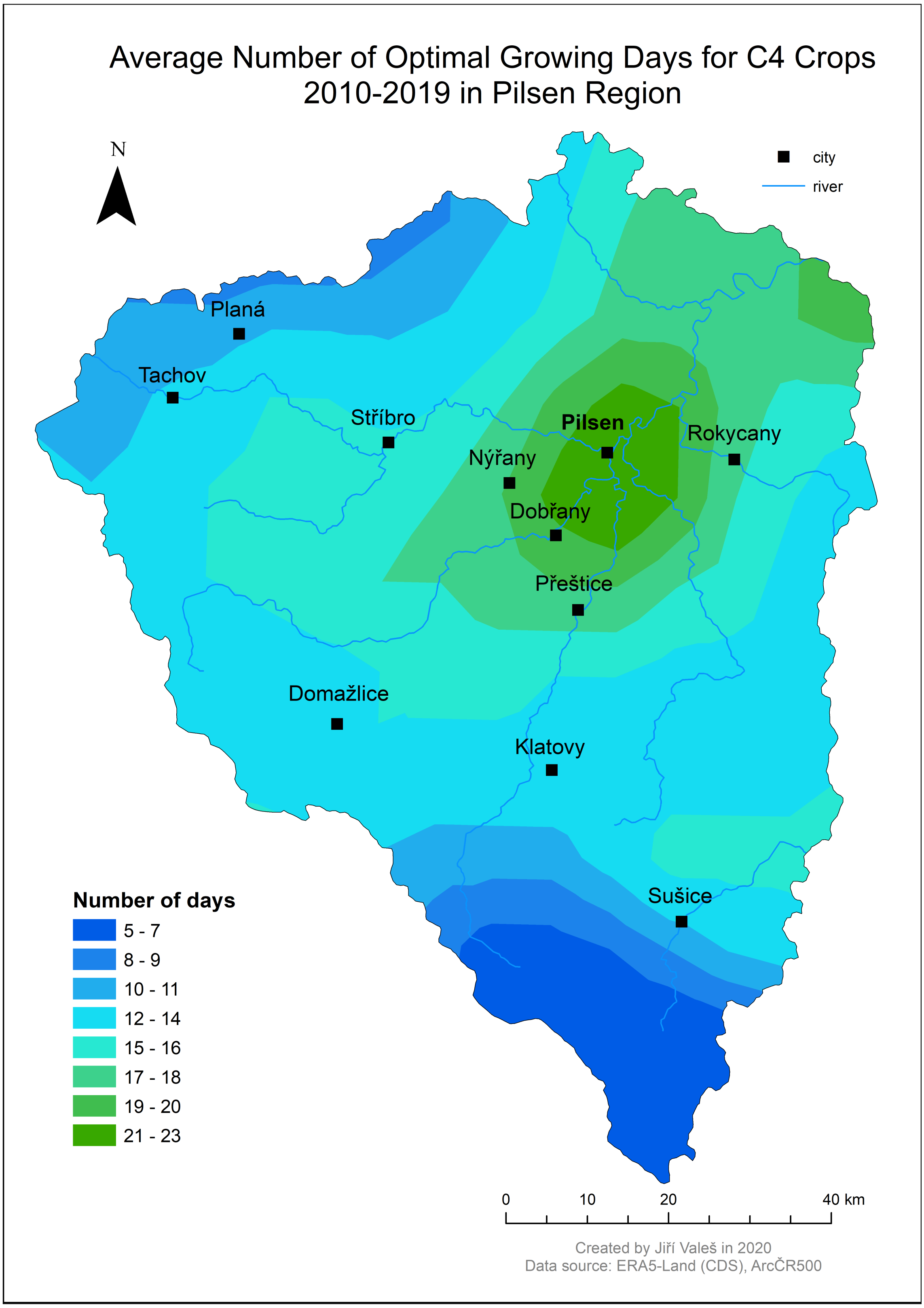

Average Number of Optimal Growing Days for C4 Crops
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Number of days
5 - 7
8 - 9
10 - 11
12 - 14
15 - 16
17 - 18
19 - 20
21 - 23
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 86: Map 29

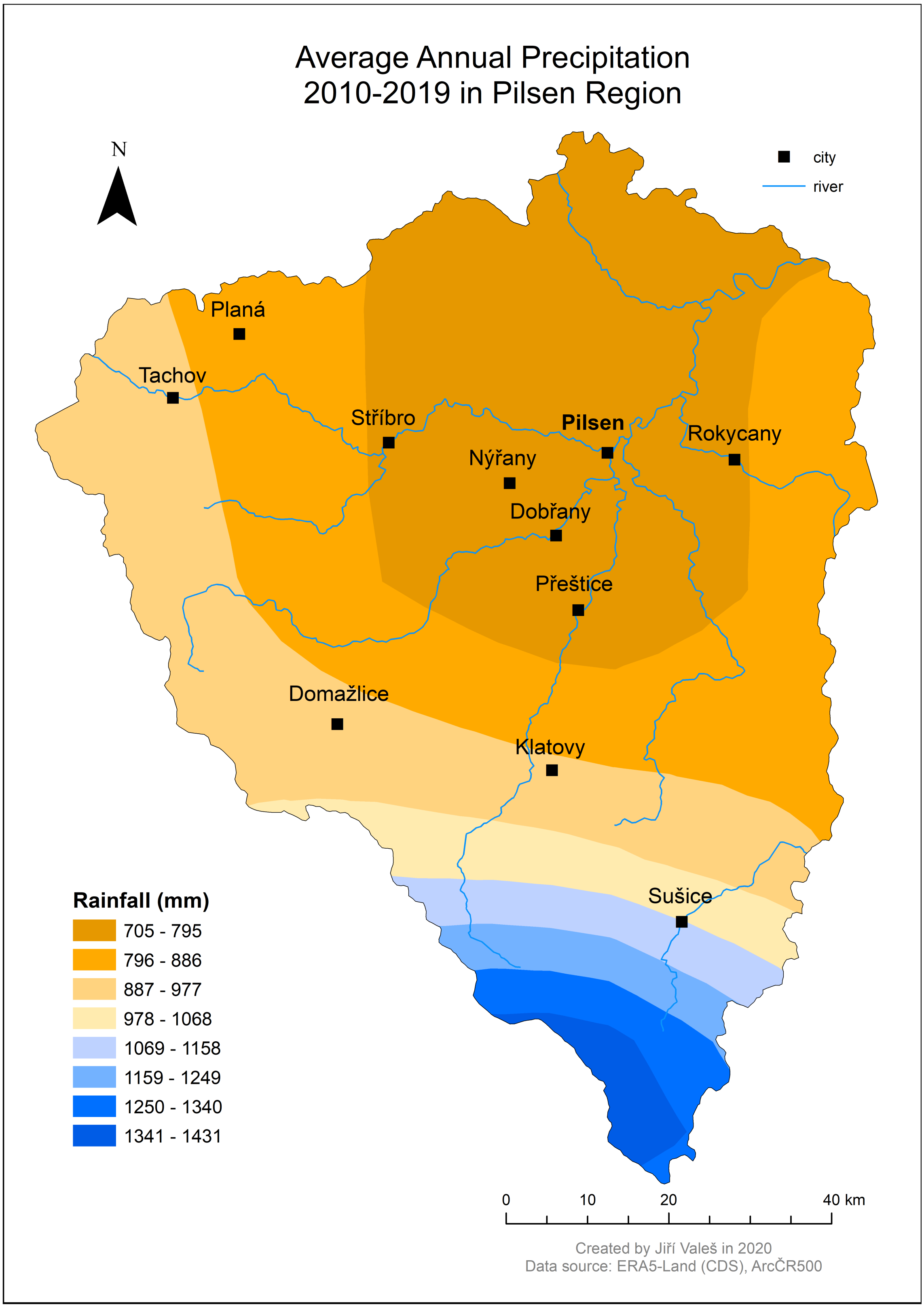

Average Annual Precipitation
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Rainfall (mm)
705 - 795
796 - 886
887 - 977
978 - 1068
1069 - 1158
1159 - 1249
1250 - 1340
1341 - 1431
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 87: Map 30

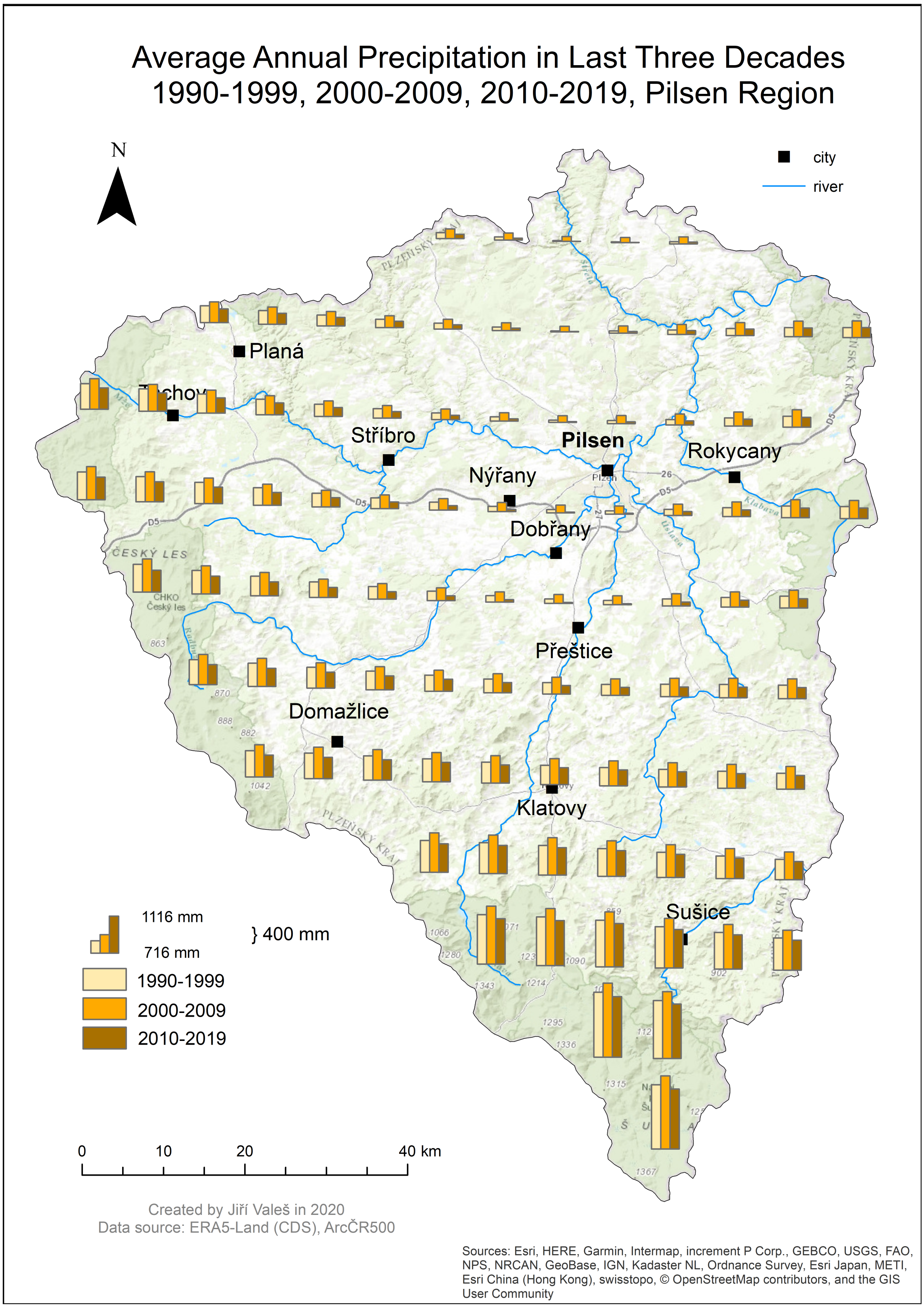

Average Annual Precipitation in Last Three Decades
1990-1999, 2000-2009, 2010-2019, Pilsen Region
N
city
river
Planá
Stříbro
Pilsen
Nýřany
Rokycany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
1116 mm
716 mm
} 400 mm
1990-1999
2000-2009
2010-2019
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 88: Map 31

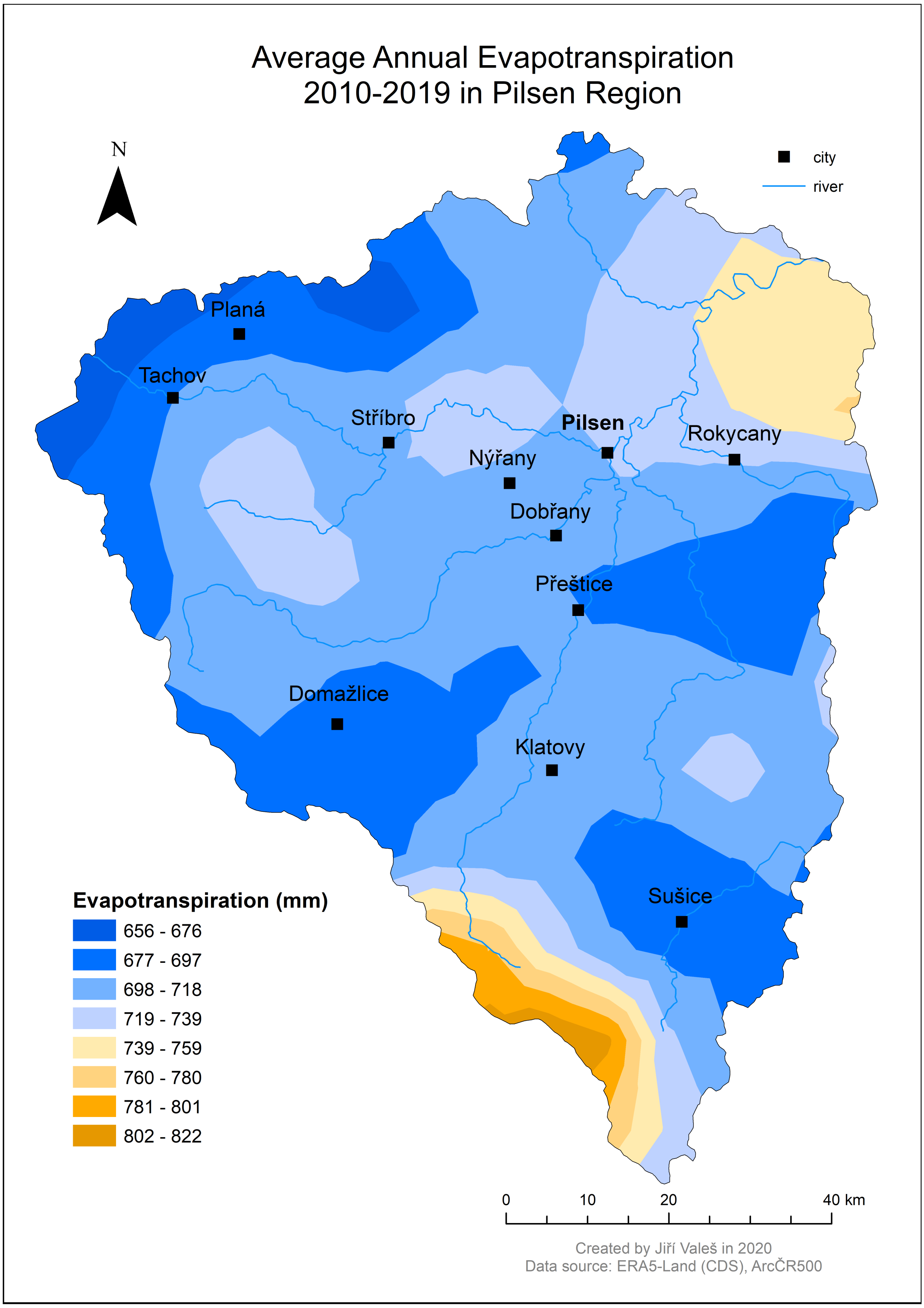

Average Annual Evapotranspiration
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Evapotranspiration (mm)
656 - 676
677 - 697
698 - 718
719 - 739
739 - 759
760 - 780
781 - 801
802 - 822
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 89: Map 32

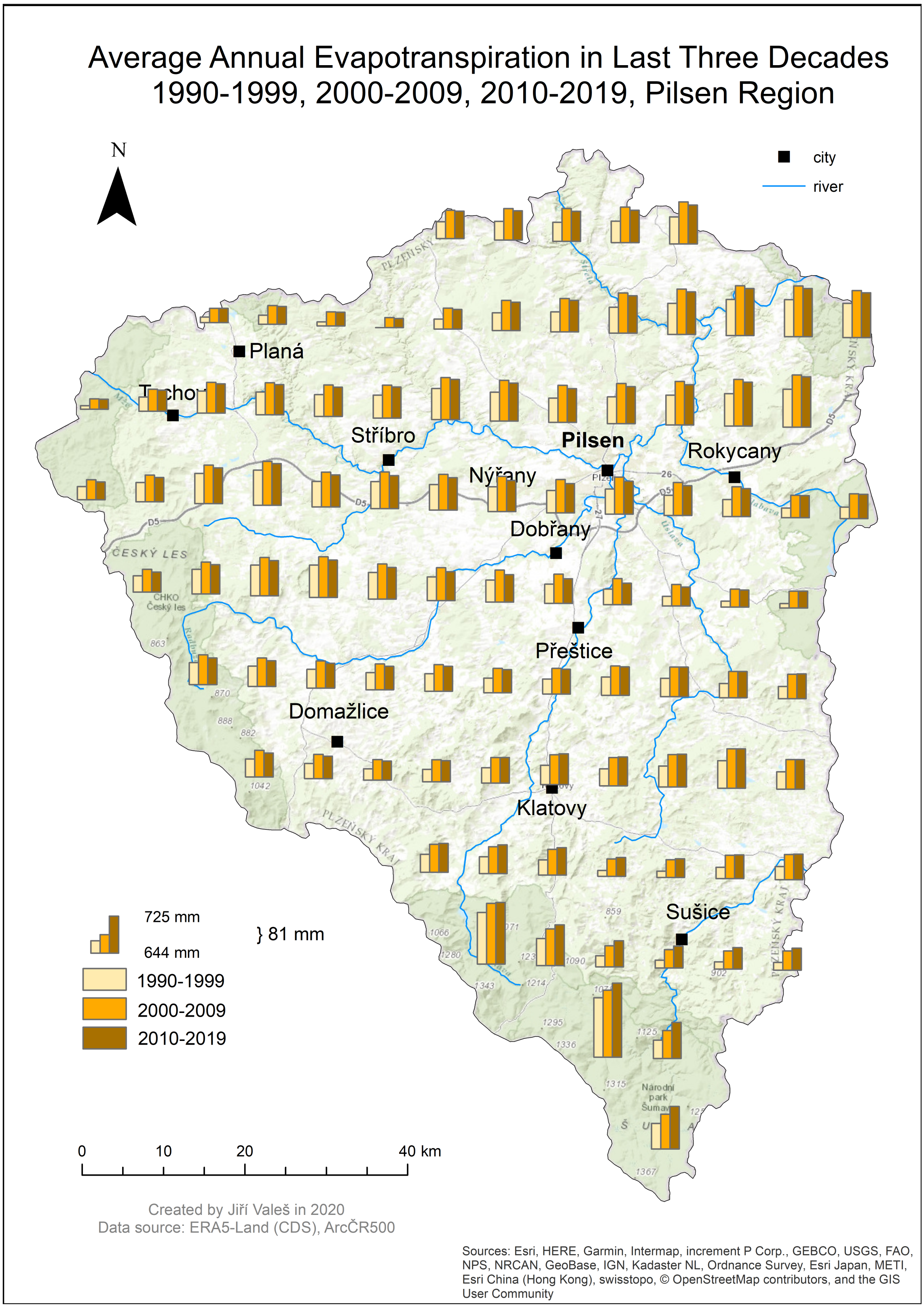

Average Annual Evapotranspiration in Last Three Decades
1990-1999, 2000-2009, 2010-2019, Pilsen Region
N
city
river
Planá
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
725 mm
644 mm
} 81 mm
1990-1999
2000-2009
2010-2019
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 90: Map 33

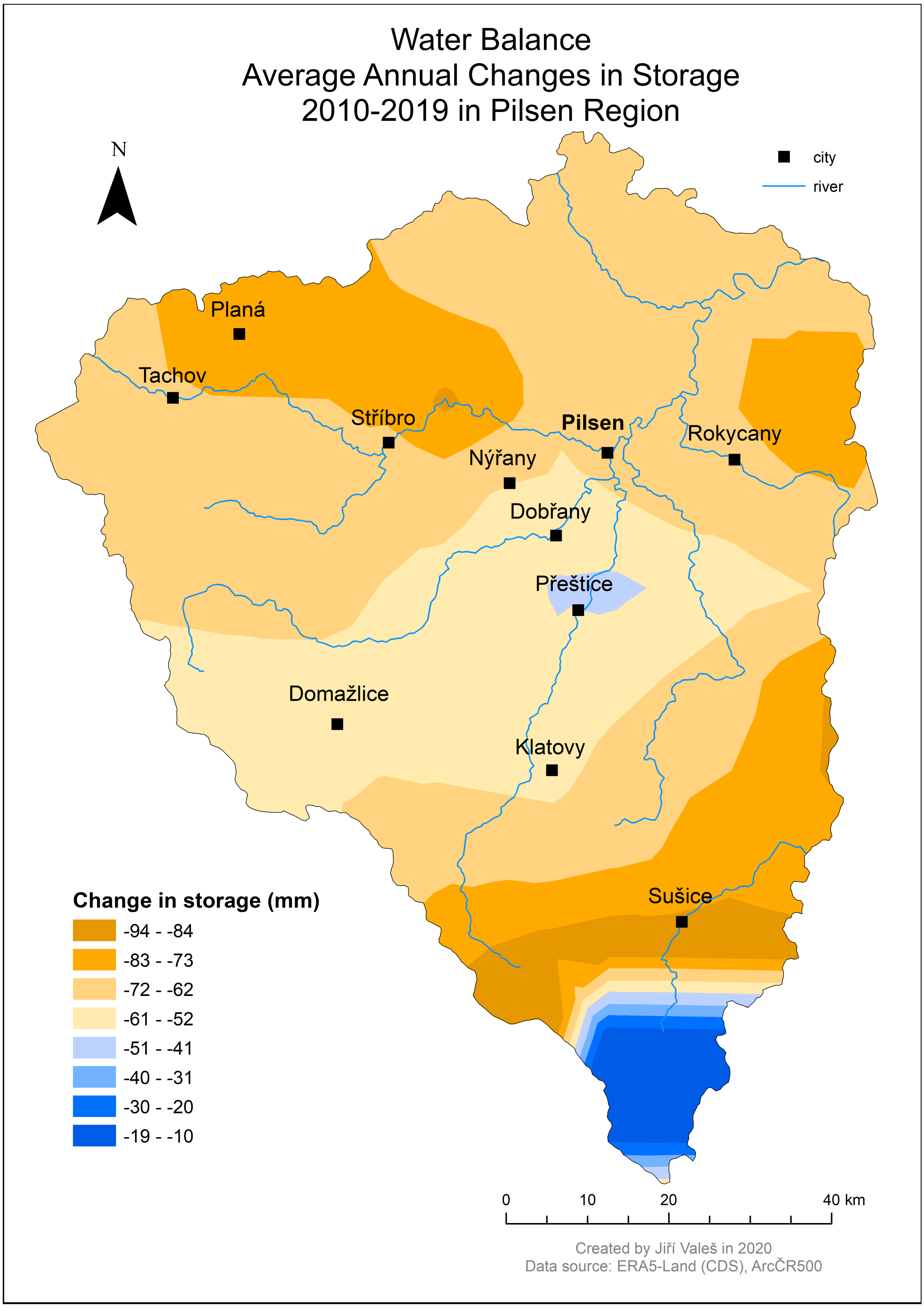

Water Balance
Average Annual Changes in Storage
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Change in storage (mm)
-94 - -84
-83 - -73
-72 - -62
-61 - -52
-51 - -41
-40 - -31
-30 - -20
-19 - -10
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 91: Map 34

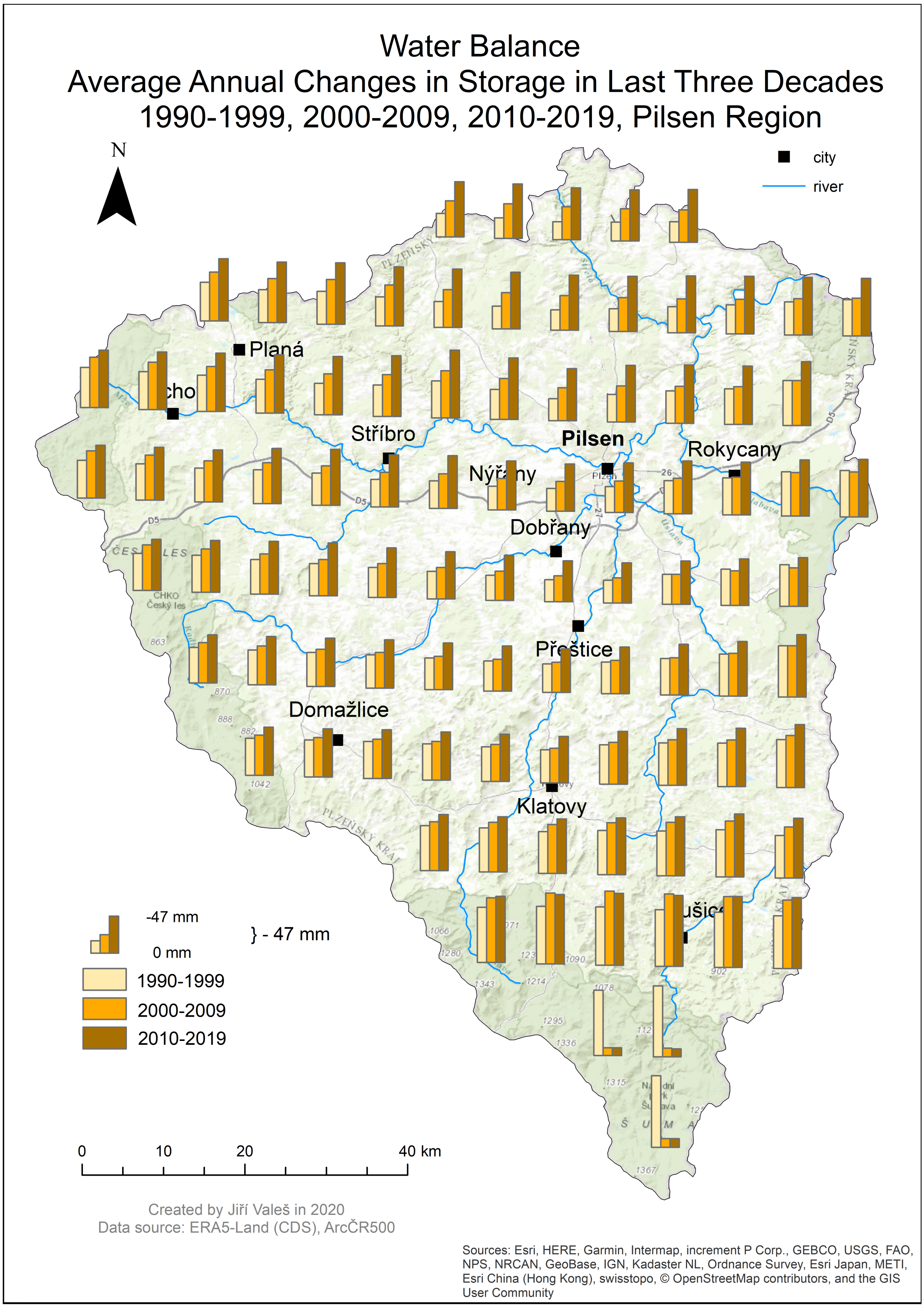
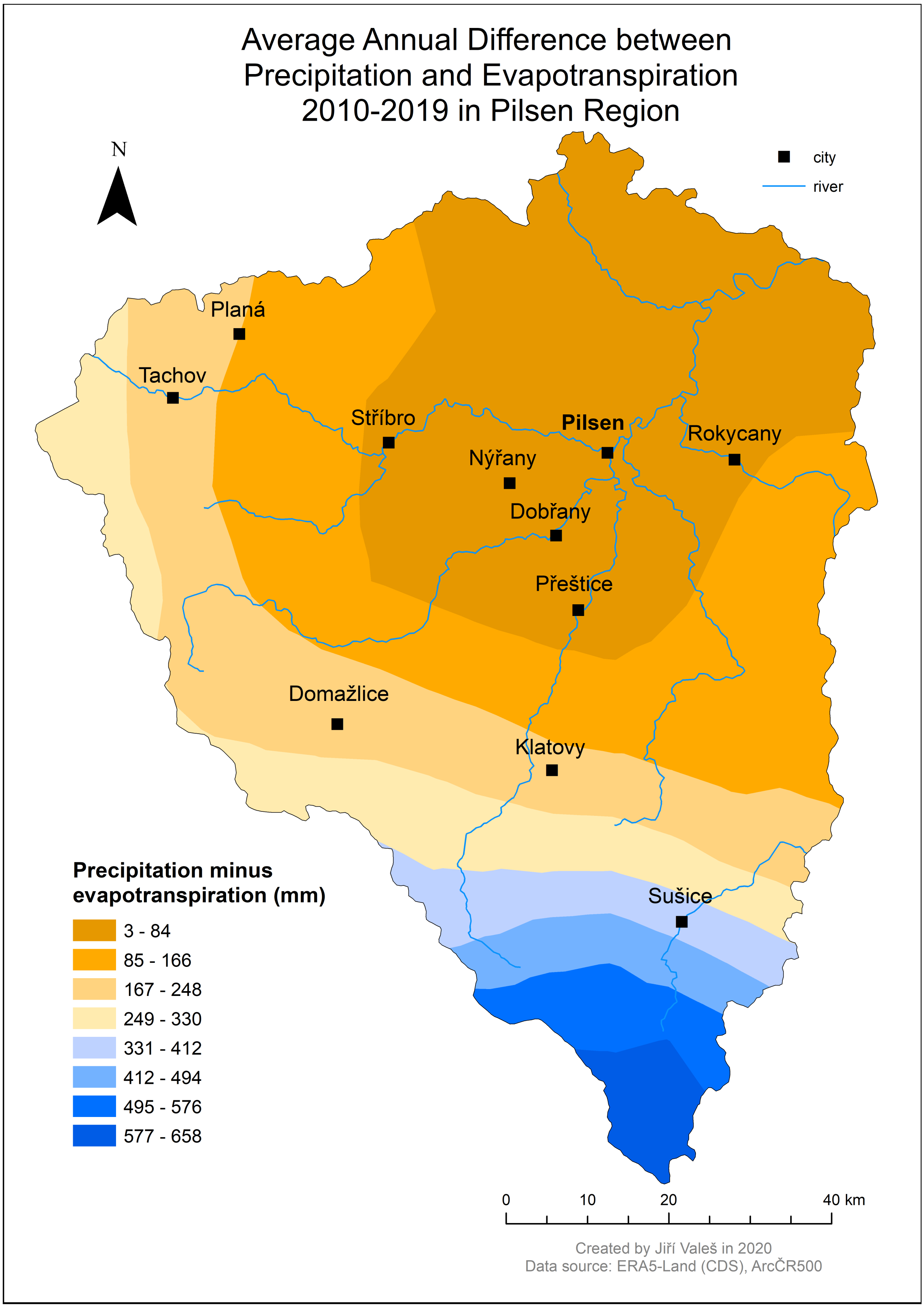

Water Balance
Average Annual Changes in Storage in Last Three Decades
1990-1999, 2000-2009, 2010-2019, Pilsen Region
N
city
river
Planá
Stříbro
Pilsen
Rokycany
Dobřany
Přeštice
Domažlice
Klatovy
-47 mm
0 mm
} - 47 mm
1990-1999
2000-2009
2010-2019
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 92: Map 35



Average Annual Difference between
Precipitation and Evapotranspiration
2010-2019 in Pilsen Region
N
city
river
Planá
Tachov
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Precipitation minus
evapotranspiration (mm)
3 - 84
85 - 166
167 - 248
249 - 330
331 - 412
412 - 494
495 - 576
577 - 658
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500

Fig. 93: Map 36

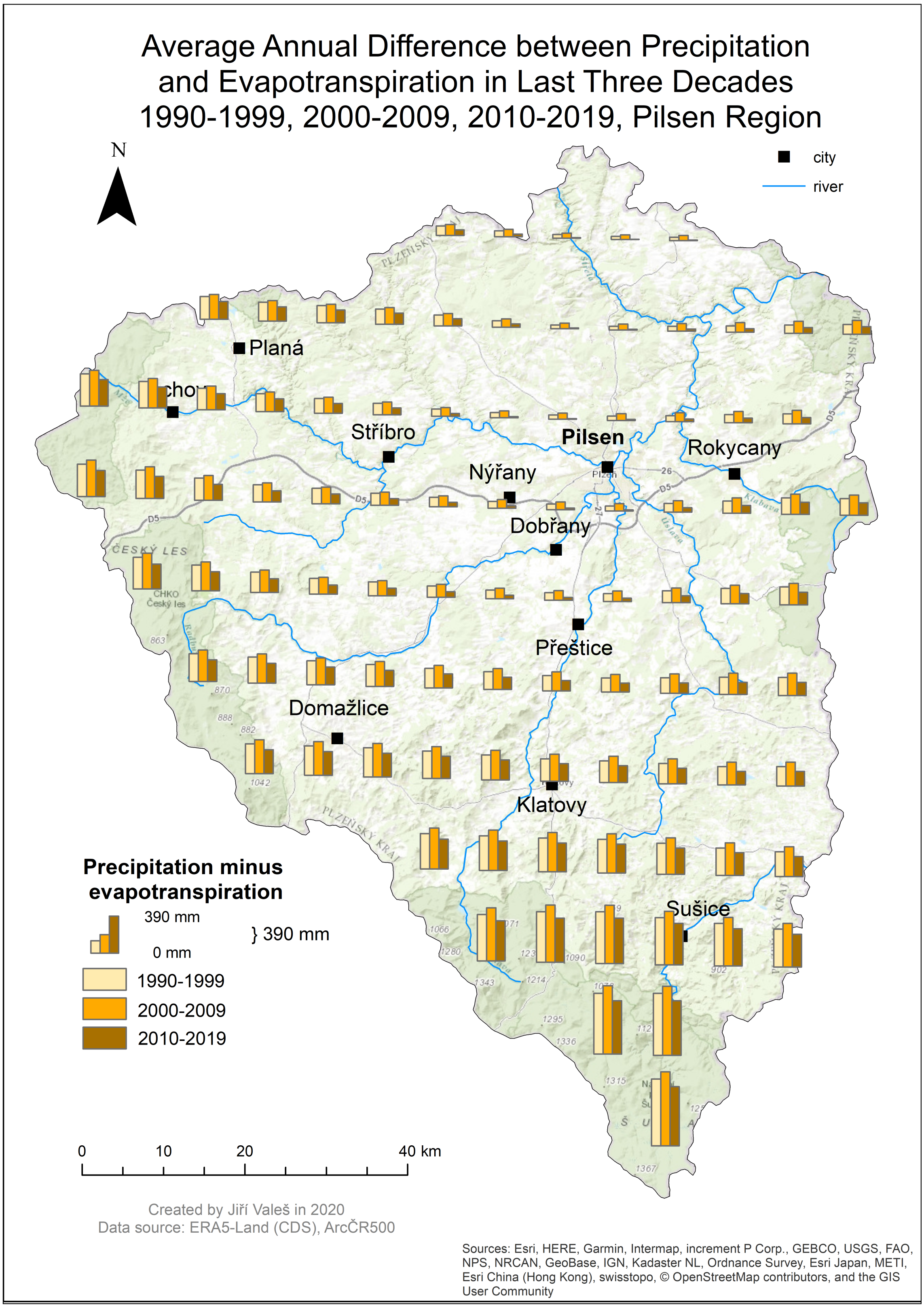

Average Annual Difference between Precipitation and Evapotranspiration in Last Three Decades 1990-1999, 2000-2009, 2010-2019, Pilsen Region
N
city
river
Planá
Stříbro
Pilsen
Rokycany
Nýřany
Dobřany
Přeštice
Domažlice
Klatovy
Sušice
Precipitation minus evapotranspiration
390 mm
0 mm
} 390 mm
1990-1999
2000-2009
2010-2019
0
10
20
40 km
Created by Jiří Valeš in 2020
Data source: ERA5-Land (CDS), ArcČR500
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Fig. 94: Map 37

EUXDAT: User interface of frost dates, frost-free period

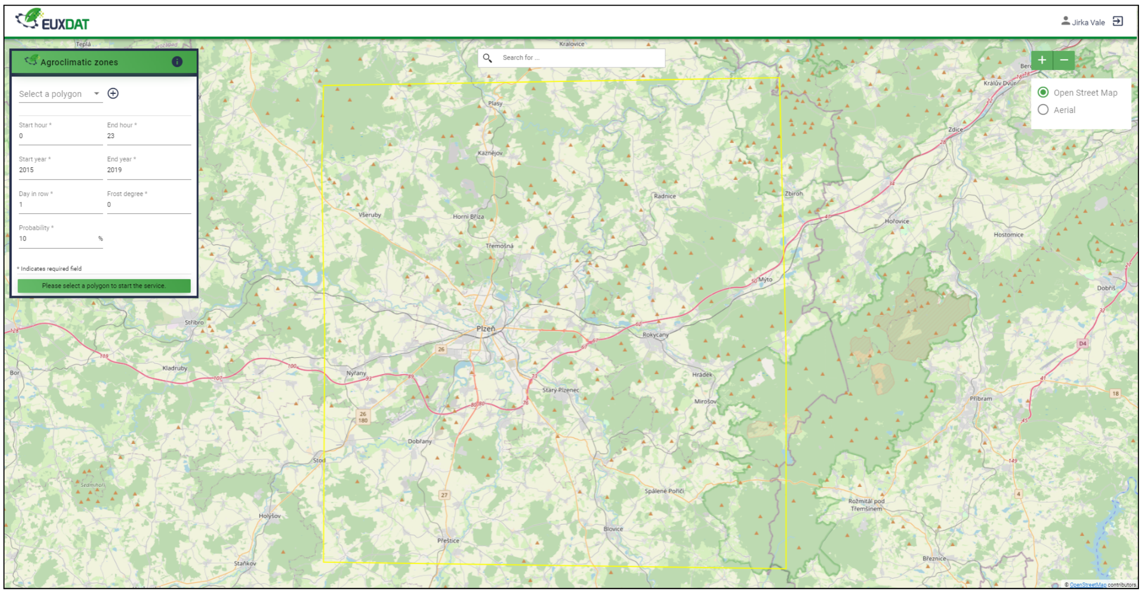


Fig. 95: The user interface of frost dates. Possibility to select an area using polygon and parameters of frost dates. (frostdates.test.euxdat.eu)

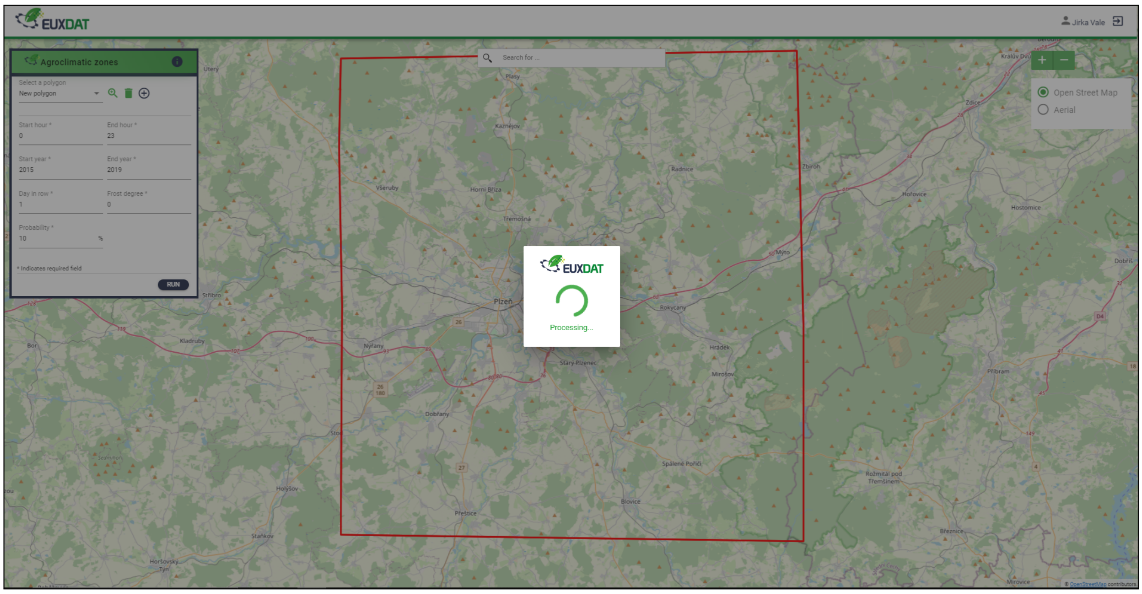


Fig. 96: The user interface of frost dates. Calculation. (frostdates.test.euxdat.eu)

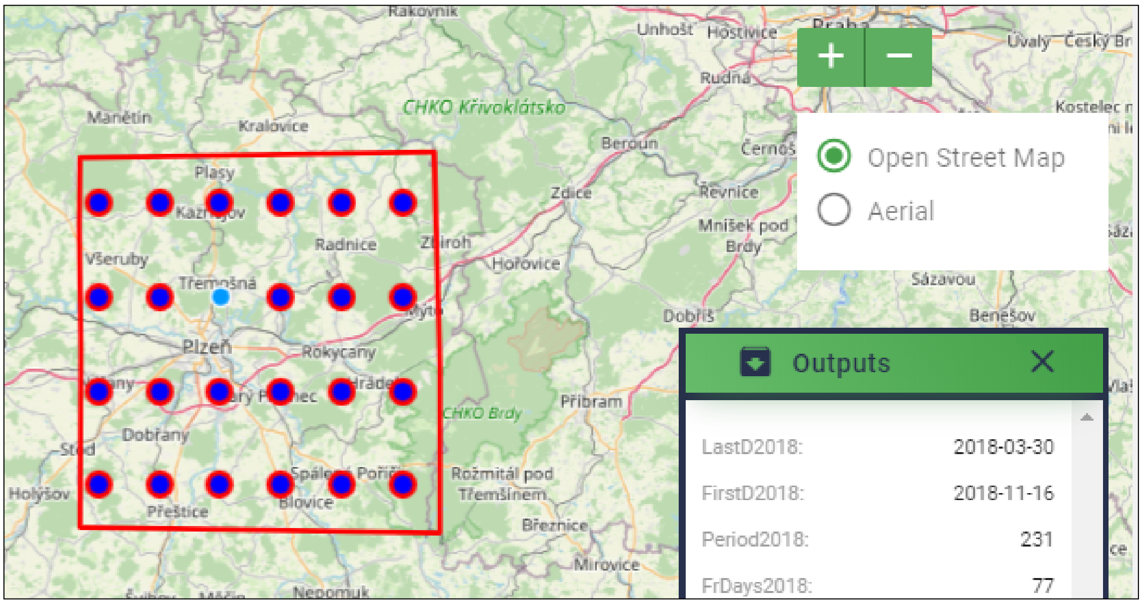


Fig. 97: The user interface of frost dates. Output: calculated points with attributes. (frostdates.test.euxdat.eu)