International Journal of Applied Earth Observations and Geoinformation 117 (2023) 103212

Contents lists available at ScienceDirect

International Journal of Applied Earth Observations and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Application of geospatial and remote sensing data to support locust management

Igor Klein [a,*], Soner Uereyen [a], Christina Eisfelder [a], Vladimir Pankov [b], Natascha Oppelt [c], Claudia Kuenzer [a,d]

[a] German Remote Sensing Data Center (DFD), German Aerospace Center (DLR), 82234 Wessling, Germany
[b] Pavlodar Regional Branch of SD Republican Methodological Center of Phytosanitary Diagnostics and Forecasts, Pavlodar 140000, Kazakhstan
[c] Department of Geography, Kiel University, 24118 Kiel, Germany
[d] Julius-Maximilians-Universität Würzburg , Institute of Geography and Geology, 97074 Würzburg, Germany

ARTICLE INFO

Keywords:
Locust
Earth observation
Remote sensing
Insect pests
Plague
Outbreak
Risk assessment
GIS
Calliptamus italicus
Food security

ABSTRACT

Negative impacts on agricultural activities by different locust species are well documented and have always been one of the major threats to food security and livelihoods, especially for local communities. Locust management and control have led to less frequent and intense plagues and outbreaks worldwide. However, political insecurity and armed conflicts affect locust management, and can as well as changing climate, and land use management contribute to new outbreaks. In the context of the increasing world population and higher demand for agricultural production, locust pests will remain of high concern. Geospatial and remote sensing data have become an important source of information for different applications within locust research and management. However, there is still a gap between available information and actual practical usage. In this study, we demonstrate the importance of geospatial and remote sensing data and how this information can be prepared for a straightforward application for stakeholders. For this purpose, we use the h3-hexagonal hierarchical geospatial indexing system to simplify and structure spatial information into standardized hexagon units. The presented concept provides decision makers and ground teams with a simplified information database that contains area-wide information over time and space and can be used without detailed geospatial knowledge and background. The concept is designed for the use case of Italian locust management in the Pavlodar region (Kazakhstan) and based on actual practices. It can be extrapolated to any other study area or species of interest. Our results underline the importance of actual land management on locust presence. Up-to-date land management information can be derived from time-series analyses of remote sensing data. Furthermore, essential meteorological data are used to generate locust-specific climatic characteristics within the h3-system. Within this system, areal prioritizing for locust management can be achieved based on the included spatial information and experience from ongoing practices.

1. Introduction

Locust plagues, upsurges and outbreaks around the world have always been one of the major threats to agriculture and food security (Gay et al., 2021; Kietzka et al., 2021). The history of reported damages affecting humans from large-scale, long-lasting plagues and upsurges of desert locust (*Schistocerca gregaria*) in Africa and Asia to country-wide and regional outbreaks of many other locust species (e.g. Australian plague locust (*Chortoicetes terminifera*), migratory locust (*Locusta migratoria*), Italian locust (*Calliptamus italicus*), South American locust (*Schistocerca cancellata*), Moroccan locust (*Dociostaurus maroccanus*)) is long and goes back to ancient times (Cullen et al., 2017; Latchininsky, 1998; Trumper et al., 2022; Zhang et al., 2019).

Since the 1960 s, the development of preventive locust control strategies and usage of chemical treatments has enabled handling of outbreaks and plagues more effectively (Gay et al., 2021). Within these preventive locust control strategies satellite remote sensing has become an important data source for forecasting and monitoring favorable ecological conditions for locust development, as well as for mapping and assessment of locust habitat states (Cressman, 2013; Deveson, 2013;

* Corresponding author.
E-mail address: igor.klein@dlr.de (I. Klein).

https://doi.org/10.1016/j.jag.2023.103212
Received 8 September 2022; Received in revised form 6 January 2023; Accepted 24 January 2023
Available online 30 January 2023

Hunter et al., 2008; Klein et al., 2021; Latchininsky, 2013; Piou et al., 2019; Zhang et al., 2019). Nowadays, different satellite sensors provide a tremendous amount of data which offer cost-effective options to derive geospatial information and use them to describe environmental changes and their causes. They are also used as input data for modelling in earth and environmental sciences (Chaminé et al., 2021). Especially the recent improvements in remote sensing (e.g., open access, increased spatial and temporal resolution, analysis-ready data, and big data applications) allow continuous and more detailed monitoring of complex environmental systems such as habitats of locust species and their dynamics in relation to environmental changes. Estimation of spatial distribution and habitat suitability has become possible by coupling geospatial data (e.g. remote sensing, climate, soil, relief data) with presence and absence in situ information (Aragón et al., 2013; Gómez et al., 2021; Klein et al., 2022; Malakhov and Zlatanov, 2020; Piou et al., 2013). Additionally, geospatial and remote sensing data are highly essential for locust management and for analyzing the impact of climate change on locust spatial distribution and potential future outbreaks (Meynard et al., 2020, 2017; Popova et al., 2016; Tratalos et al., 2010; Wang et al., 2019). One of the main goals of locust management is the assessment of outbreak risk, by continuous monitoring of affected regions and state of the locust population, and the prioritization of exposed areas in terms of required measurements.

Despite increased usage in applied geoscience and growing business services (e.g., agriculture, forestry, rapid mapping), there is still a gap between academic state of the art, technical possibilities and actual application of remote sensing and geospatial data with respect to locust management. The activities of the Australian Plague Locust Commission (APLC) and Food and Agriculture Organization of the United Nations (FAO) in the context of Australian plague and desert locusts, are two prominent examples demonstrating that the utilization of geospatial and remote sensing data effectively support locust management (FAO, 2022; Mangeon et al., 2020; Matthews, 2021). Managing various geoscientific data and understanding the corresponding specifications including data format, projection, spatial and temporal resolution, as well as data accuracy and limitations, usually requires several years of practice and experience. Since locust ground teams and decision makers undergo a different education compared to geospatial data analysts, there is often a discrepancy between available information from geoscientific data and possibilities and "real-life" practice of locust management. At the same time, a lack of ground data or poorly collected information affects locust management decisions and might even seize up the whole management chain (Gay et al., 2021). Therefore, it is of significant importance to prepare spatial information in a way that enables a straightforward application for a targeted group of users within locust management.

In this study, we use locust management, which requires knowledge of multiple environmental disciplines (e.g., entomology, meteorology, agronomy) as a use case to demonstrate how geospatial information can be processed to allow for an improved implementation and provide additional information sources. For this purpose, we use the h3-system to simplify spatial information, and prioritize areas by means of decision trees and thus support decision making (Bousquin, 2021; Kang et al., 2021; Uber Technologies Inc., 2018). The h3-system has been proven to be of advantage when combining a complex set of information in the framework of a regular Discrete Global Grid (DGG) which is unbiased concerning spatial patterns and allows the development of simple and efficient algorithms (Li, et al., 2022; Sahr et al., 2003). In this study, different spatial information relevant for locust management are processed and presented in a stepwise approach to provide additional information for decision-making and field monitoring. Within the presented approach, complex information derived from various geoscientific datasets, including remote sensing imagery and climatic variables, are summarized at simplified hexagon levels which can be exploited by diverse set of rules according to current situation and severity of increase in locust population.

This paper is structured as follows. First, we provide background information on the typical life cycle of locusts. In addition, fundamental details with respect to the monitoring and management of the Italian locust are illustrated using the example of Pavlodar region, located in north-eastern Kazakhstan. Second, we recap which kind of information can be derived or is available from remote sensing data and other geospatial information sources. In the third and fourth section, we introduce how these datasets are pre-processed using the h3-system and how they can be used by ground teams to receive relevant and understandable information, thus allowing them to take fast decisions on a spatially aggregated level. Finally, the importance of geoscientific data for locust management is discussed in the light of climate change and applied control measurements.

2. Background information

2.1. Italian locust ecology and life cycle

Locusts are grasshoppers in the family *Acrididae* which are characterized by the so-called phase polyphenism (Trumper et al., 2022). At low density, the locusts behave as solitarious individuals and are an important part of their ecosystem (Cullen et al., 2017; Latchininsky et al., 2011). The phase change is initiated by a combination of different ecological conditions which benefit increasing locust population. During this, so-called gregarious phase, locusts behave in groups which leads to band formation of nymphs and later migrating swarms of adults (Trumper et al., 2022). Also, many locust species appear even in different colors and sizes during gregarious phase (Uvarov, 1957).

The CIT is an intermediate form between typical gregarious and solitarious acridid species (Sergeev, 2021). It is a univoltine species with egg diapause during autumn and winter. Its habitats are found in dry steppes and semi-desserts with preferable plants such as wormwood and sage-brushes (*Artemisia spp.*) and moderately compact, sandy soils (Sergeev, 2021). Potentially, CIT can be found up to 2700 m altitude and prefers abandoned or fallow land, pasture, active agricultural field borders and is also found along infrastructure tracks such as roads and railways (Kambulin, 2018; Sergeev et al., 2022). Generally, CIT is a highly elastic species and tolerates a wide range of semi-arid climate and soil types (Sergeev et al., 2022). After winter diapause, the hatching starts in late spring depending on local meteorological conditions. Higher air temperatures and less precipitation, which affect local edaphic situation lead to an earlier hatching start. On the contrary, cool temperatures and unnormal high rain amounts, at the location of egg-pods, lead to a later start as well as decreased population due to higher egg mortality. Once the nymphs hatch, they undergo five instar states whereas each state lasts for 3–7 days. The duration and population size, is again, controlled by meteorological conditions and food availability. Higher temperatures favor a faster development (Sergeev et al., 2022). Nymph bands of CIT can move up to 155 m per day. Once the locusts reach adult state and are capable to fly, their location is less predictable. With wind, large CIT swarms are capable of flying>200 km per day, while smaller swarms fly up to 20–40 km (FAO, 2021). After the pairing period which takes place around July and August (Fig. 1), the female locusts lay up to six egg-pods (containing 20–60 eggs, mostly 30–35) and a new life cycle of the next locust generation begins (Sergeev et al., 2022).

2.2. Locust management in Pavlodar region, Kazakhstan

The major CIT outbreak in 1999/2000 caused a total damage of 220,000 ha grain crops and an estimated economic cost of 15 Mio. US$ (Latchininsky, 2013). Within this period almost 10 Mio. ha land (approx. 8 Mio. in Kazakhstan) were treated with pesticide (Kambulin, 2018). The reason for such a large-scale and intense outbreak was a lack of preventive locust management at that time combined with a change of land use practices during the 1990 s (Kambulin, 2018; Sivanpillai et al., 2009). Vast areas of former agricultural and pasture land were

Fig. 1. Italian locust (left: mating, middle: oviposition, right: egg-pod). Photos from 27. July 2022, 50.3 N 75.44 E.

abandoned and developed into a perfect habitat for CIT which led to an increasing locust population over several years. Land management can change very fast due to different driving factors (e.g. political programs, economic profits, security, climate change) and can create perfect conditions for locusts breeding and population increase (Zhao et al., 2020). Therefore, up-to-date information on land cover and land use considering different locust pests have a high potential to support locust management.

After this outbreak, preventive management has been reestablished and has become a key component in controlling and avoiding locust outbreaks and related damages. In Kazakhstan, preventive management is done by regional offices under the coordination of a state inspection committee in the agricultural sector of the ministry of agriculture. The "Pavlodar regional branch of SD Republican Methodological Center of phytosanitary diagnostics and forecasts" is responsible for field monitoring, reporting and forecast of the CIT development in Pavlodar region (Fig. 2). This branch provides forecasts and assessments which are the base for annual preventive area treatment to avoid an increase in locust population and keep it under control. Field officers are using Global Positioning System (GPS) and standardized protocols to monitor qualitative and quantitative parameters of locusts four times a year (spring egg-pods control, spring nymphs hatching, summer pairing and egg-laying, autumn egg-pods control). For this study, a total of of 1515 presence locations indicating CIT breeding spots collected between 2016 and 2021 was used to analyse favourable LCLU situation where egg-pods were laid and hatching occurred.

3. Methods

3.1. Remote sensing data and geospatial information for locust management

Since locust development is highly dependent on the state of its ecosystem, meteorological conditions and land use practices, there is a vast number of existing datasets which can be used for locust management. First of all, locust presence and abundance locations from field data in combination with spatial information data can be applied to analyze and estimate species richness and spatial distribution as well as potential habitats and their suitability (Klein et al., 2021; Lazar et al., 2015; Piou et al., 2017; Youngblood et al., 2022; Zhang et al., 2019).

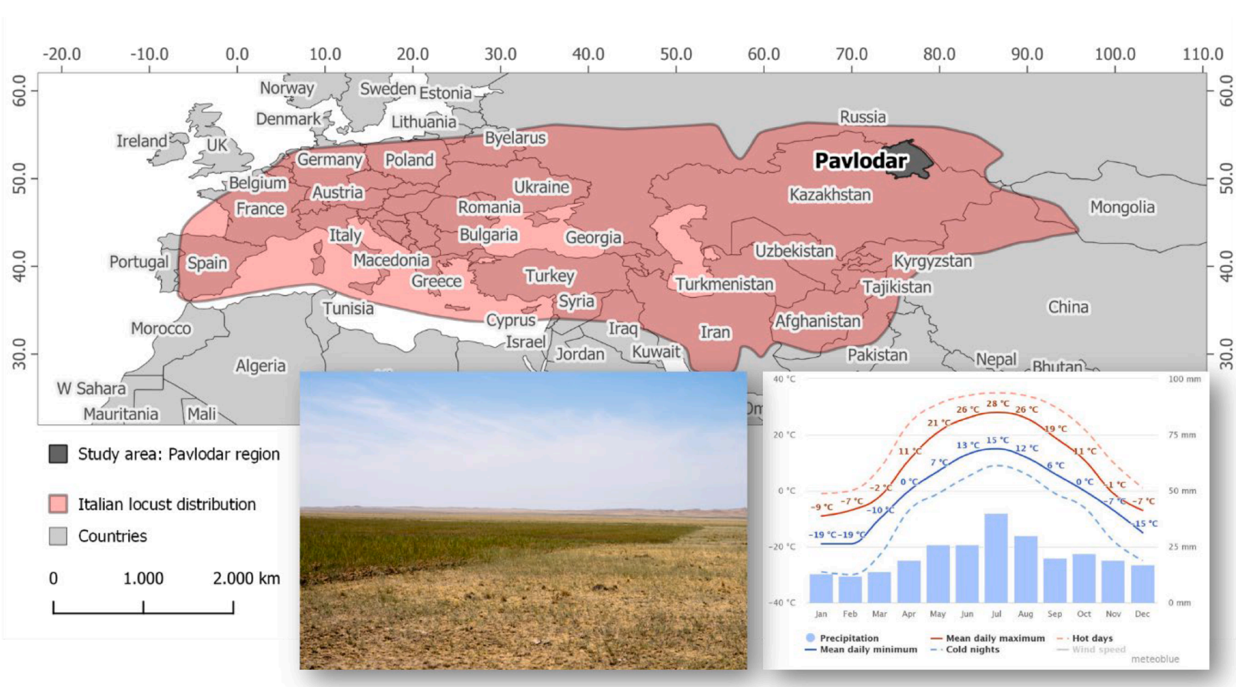

Fig. 2. Overview of study area and Italian locust distribution (based on Fig. 14 from Sergeev et al., 2022). Photo: Typical habitat (from 27. July 2022, 50.3 N 75.44 E). Climate diagram for Pavlodar ().
Source: meteoblue.com

Second, the monitoring of the actual situation and the forecast of the hatching begin and possible outbreaks which are based on meteorological data, soil conditions as well as vegetation state are the most important components for early warning (Cressman, 2016, 2013; Lecoq, 1995; Lecoq and Cease, 2022; Liu et al., 2008). Based on a literature review of relevant studies, we use a selection of the most important variables for CIT presence and development which are summarized in Table 1.

In detail, we used Sentinel-2 and Landsat imagery to derive a land cover and land use map (Fig. 3). The processing and classification of remote sensing imagery was conducted on the Google Earth Engine (Gorelick et al., 2017). Due to the limited availability of Landsat imagery over this region, we generated median composites covering a 5 year period between 1984 and 2020 (i.e. 1984–1989, 1990–1994, 1995–1999). Besides the spectral bands, the spectral indices normalized difference vegetation index (NDVI), modified normalized difference water index (MNDWI), salinity index (SI), and normalized difference built-up index (NDBI) were included. Using the Random Forest classifier (Breiman, 2001), agricultural areas were mapped in each of the Landsat composites. Likewise, a median composite was created using Sentinel-2 imagery for the year 2021. Here, all Sentinel-2 bands were resampled to 10 m spatial resolution. The resulting classification map covers the classes agricultural land use, bare soil, sparse as well as dense vegetation, and for completeness built-up areas. At this, agricultural and built-up areas were extracted from the ESA WorldCover classification (Zanaga et al., 2021). Based on the temporal evolution of agricultural land use from the Landsat composites and the recent classification of agricultural land use in 2021 from the Sentinel-2 imagery an intersection was performed to retrieve abandoned land. Next, the Landsat-based abandoned land class is resampled to 10 m spatial resolution to match the Sentinel-2 classification.

Furthermore, the employed meteorological variables are gathered from the ERA5-Land reanalysis (Hersbach et al., 2020; Muñoz-Sabater et al., 2021) and the TerraClimate dataset (Abatzoglou et al., 2018). Temperature data at daily temporal resolution was required to calculate the sum of effective temperature (SET). In this regard, hourly ERA5-Land temperature was aggregated to daily temporal resolution (Fig. 3). In addition, precipitation, soil moisture, and temperature at monthly temporal resolution were retrieved from TerraClimate due to its comparatively high spatial resolution. In the context of Central Asia, both ERA5 and TerraClimate data are widely applied (e.g. Hao et al., 2022; Hou et al., 2022; Hu and Han, 2022; Li et al., 2021; Shi et al., 2020; Zheng et al., 2021).

Table 1
Important variables for CIT and used open source geospatial and remote sensing datasets.

Variable	Spatial res.	Temporal res.	Source/Reference
Abandoned land, Agriculture, bare soil, natural vegetation (sparse, dense)	10 *m*	Annual	Classified based on annual Sentinel-2 time-series phenology analyses of the year 2021 compared to long-term phenology of 1984–2020 (Landsat archive)
Temperature	10 km	Hourly	ERA5-Land (Hersbach et al., 2020; Muñoz-Sabater et al., 2021)
Temperature	4.6 km	Monthly	TerraClimate (Abatzoglou et al., 2018)
Precipitation	4.6 km	Monthly	TerraClimate (Abatzoglou et al., 2018)
Soil Moisture	4.6 km	Monthly	TerraClimate (Abatzoglou et al., 2018)
CIT nymph presence	Lat, Lon	Annual (2016–21)	Pavlodar regional branch

3.2. Data harmonization workflow

In order to enable a joint analysis of the collocated geospatial data, a harmonization in terms of their spatial resolution is required. In this section, we demonstrate the spatial aggregation based on a hexagon-system and how it can simplify the interpretation and decision-making without detailed background knowledge of each individual dataset characteristics (e.g. data formats, temporal or spatial aggregations, reprojections, etc.). Nevertheless, despite introduced simplification of handling geospatial datasets, all potential users shall be informed and aware about existing range of uncertainties and possible errors coming along with geospatial and remote sensing datasets. DGGs such as the hierarchical geospatial index *h3-system* allow simplified and effective data combination and spatial interpretation (Sahr et al., 2003; Uber Technologies Inc., 2018). In this study, we apply the *h3-system* which offers a quick aggregation at different levels across disparate datasets independent from precision and data specification (spatio-temporal resolution, projection, format). Furthermore, the hexagon system enables grid-based algorithm development focusing on spatial relation between grids. Compared to triangles or squares grid systems, hexagons have the same topological relation and are in equidistance between all neighbors (Uber Technologies Inc., 2018; Ma et al., 2021). In addition, due to the hexagonal shape, a smaller number of grids is required to represent the raster data, reducing the processing time and storage space (Duszak et al., 2021). Regarding locust management, which requires a lot of different parameters as described in the previous section, the application of such systems has three main advantages. First, different dataset characteristics and data pre-processing do not have to be done by ground teams and end users. Second, simple spatial analysis assessment and interpretation can be done straightforwardly based on defined conditions and expert knowledge for specific applications at different hierarchical levels. Third, existing spatial relationships between grid cells (e.g., distances- and nearest neighbors-based conditions) can be exploited for more complex assessment. Fig. 4 shows the *h3-system* for the Pavlodar region at three levels with moderate area size.

After the selection of an appropriate level and hexagon area for the use case based on the *h3-py python* software package, all geospatial data are spatially aggregated to the hexagons using the average function of zonal statistics. At this point, the geospatial and remote sensing datasets are harmonized to the same spatial unit and geographic projection. From here on the end-user and experts can apply their regular data analysis on large scales and entire territory of interest or define and develop new rulesets and algorithms by exploiting the full range of available geospatial information. In this study, we demonstrate an exemplary working process based on essential characteristics of CIT in the Pavlodar region. Fig. 5 presents a schematic stepwise workflow which combines different exemplary parameters to exclude areas of minor risk as well as prioritize hotspot regions based on highly favorable bio-climatic, edaphic and land surface conditions.

3.3. Use-case for Italian locust

As described in section 2, the development of CIT depends highly on four main influencing factors. First, the local meteorological conditions (temperature and precipitation) which determine egg mortality, survival of young nymphs within first locust instar phases, as well as the duration of development phases. Furthermore, meteorological conditions also determine the beginning of hatching and availability of green vegetation for feeding. Second, human land management directly affects the presence or absence of locusts. Active land management and ploughing lead to mechanical destruction of egg-pods and reduce the locust population (Latchininsky, 2013, 1998; Sergeev et al., 2022). On the other hand, fallow and abandoned land become an ideal habitat for further distribution and increase of locust population. The information on land cover land use (LCLU) can be derived by time-series analyses of remote sensing data and annual comparison of vegetation development

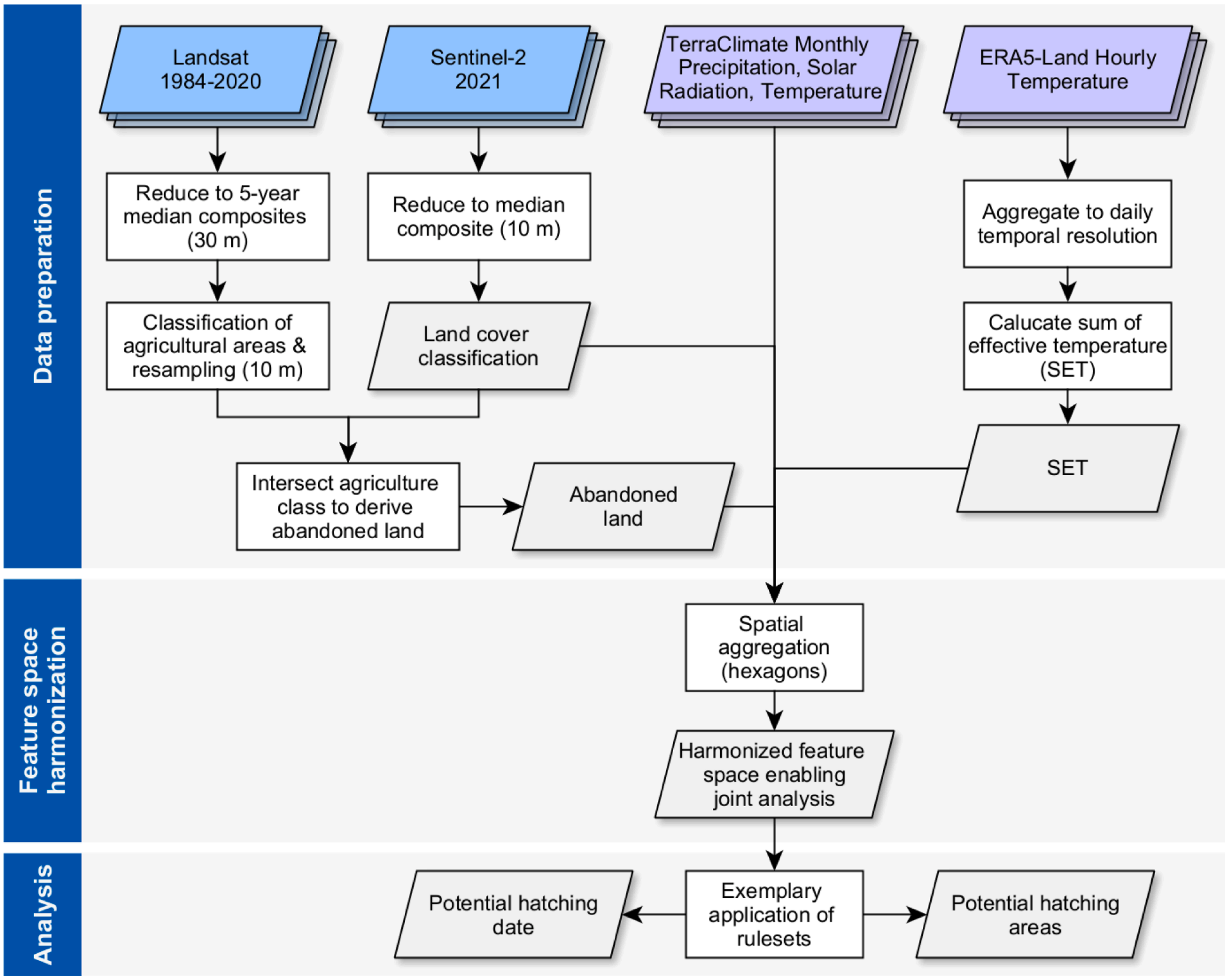

Fig. 3. Workflow including classification steps and spatial aggregation to achive harmonized data within hexagon grid system.

because most cultivations are characterized by distinct phenological cycles (sowing, growing, harvesting). Therefore, active agricultural fields differ from rangelands and natural vegetation. Third, the mid- and long-term climate conditions affect the biological increase or decrease of locust populations. Drought years (high temperature and low precipitations) usually favor the development resulting in population increase. Cold and wet years decrease the population (Kambulin, 2018; Tronin et al., 2014). Finally, static environmental conditions such as soil type and relief must be considered as well. All four influencing factors are independent of locust management and must be put in logical context for monitoring and forecast purposes. Furthermore, one has to keep in mind that the locust population dynamics are highly influenced by active ongoing control measurements and their effectiveness. Favorable meteorological conditions over several years can be counteracted by extensive monitoring and pesticide treatments to avoid exponential population increase.

In the Pavlodar region, the meteorological conditions can be described based on Selyaninov's hydrothermal coefficient (HTC) (Selyaninov, 1928). The HTC has been applied in different studies related to drought determination (Dabrowska-Zielinska et al., 2020; Ryazanova and Voropay, 2019; Vlăduţ et al., 2017), as well as to assess the favorability of climate for the development of cultivations and natural plants (Evarte-Bundere and Evarts-Bunders, 2012). The HTC during vegetation period (HTC_{VP}) is calculated based on the following formula:

$$HTC = \frac{10\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} T_i}$$

where n is the length of the period (months) when mean temperatures exceed 10 °C, P_i is the precipitation amount (mm) of the ith month, and T_i is the average air temperature (°C) for the ith month.

Furthermore, the SET is another important indicator to access meteorological conditions which influence locust population increases or decreases. The SET is calculated based on the following formula:

$$SET = \sum_{i}^{n} T > 10^{\circ} C$$

where i - n is the period between January 1st to December 31st and T > 10 °C mean daily temperature above 10 °C.

A population increase of CIT is expected to be favored in dry and hot years without exceptionally high precipitation amounts in spring. We summarized optimal conditions and logical rules based on (Kambulin, 2018; Sergeev et al., 2022) (Table 2, Fig. 6).

In conclusion, a population increase begins with hot and dry years and its progression depends on the meteorological conditions of the following years. In this context, (Tronin et al., 2014) presented the dependency on drought years for CIT in West Siberia. Comparable assumptions are also formulated for Northern and Western Kazakhstan (Kambulin, 2018). In this regard, it has to be mentioned that different authors postulate that drought years and locust outbreaks are related to the solar cycle (Cheke et al., 2020; Kambulin, 2018; Sergeev et al., 2022; Tronin et al., 2014).

Additionally, based on SET during the spring and early summer period, the start of hatching (SoH) can be estimated. Here, the accumulation of SET starts after the daily mean temperature reaches above

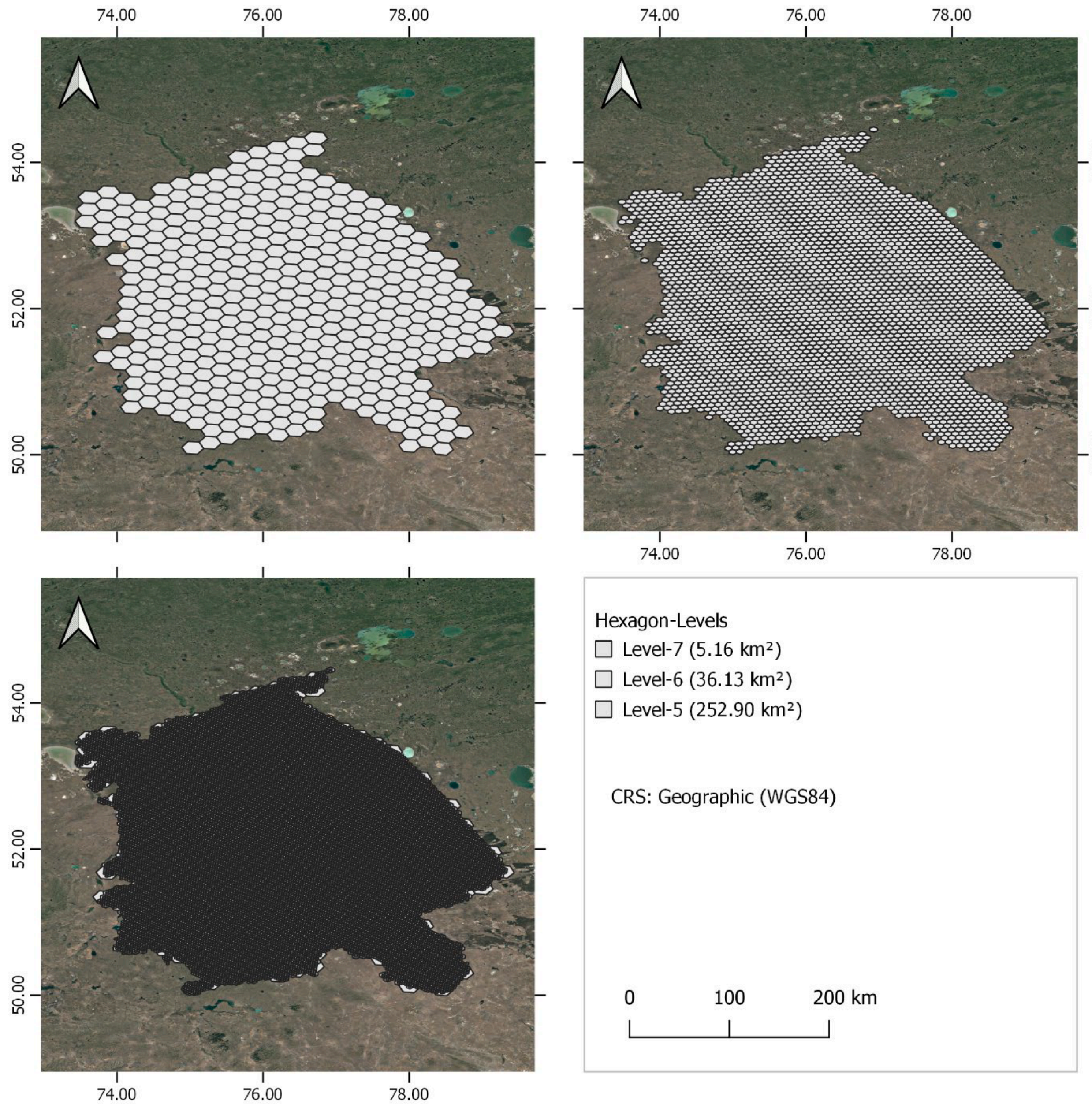

Fig. 4. Pavlodar region in three different spatial resolutions with approximate individual hexagon areas of: level-5 (top left), level-6 (top right), and level-7 (bottom left).

0 °C in five consecutive days, whereas only those temperature values are summed up which are above 10 °C. The hatching is assumed to begin once the SET threshold reaches 90 °C. In praxis, the field officers already start monitoring the egg-pods when the threshold reaches 70 °C. Around that time the embryonal state of eggs is examined by field experts which enables more accurate start of hatching estimation.

$$SoH_{CIT} = \sum_{i}^{n} if T > 10^{\circ} C then + T - 10$$

The population dynamics correspond to the effects of seasonal meteorological conditions on the life cycle of CIT. During rainy and cold springs, the egg mortality is high, and hatching is delayed. In contrast, dry and hot conditions secure egg survival and accelerate hatching. During long, hot, and dry summers multiple mating is favored which also contributes to population increase. On the other hand, high precipitation during autumn in combination with low temperatures endanger newly laid eggs by fungi and mold (Kambulin, 2018).

Usually, the field officers receive weather information from local stations and plan their monitoring according to the actual situation which varies from year to year in terms of timing as well as region. The defined conditions are based on experts' knowledge and their daily practices from the "*Pavlodar regional branch of SD Republican Methodological Center of phytosanitary diagnostics and forecasts*" and detailed information from the FAO report which was written by leading entomologists and CIT experts (Sergeev et al., 2022). The ruleset can be adjusted in any way and extended by additional parameters and conditions.

4. Results

4.1. The importance of land cover for breeding locations

The CIT ecology is more complicated compared to other locust species (Latchininsky, 2013; Sergeev, 2021; Tronin et al., 2014). There are

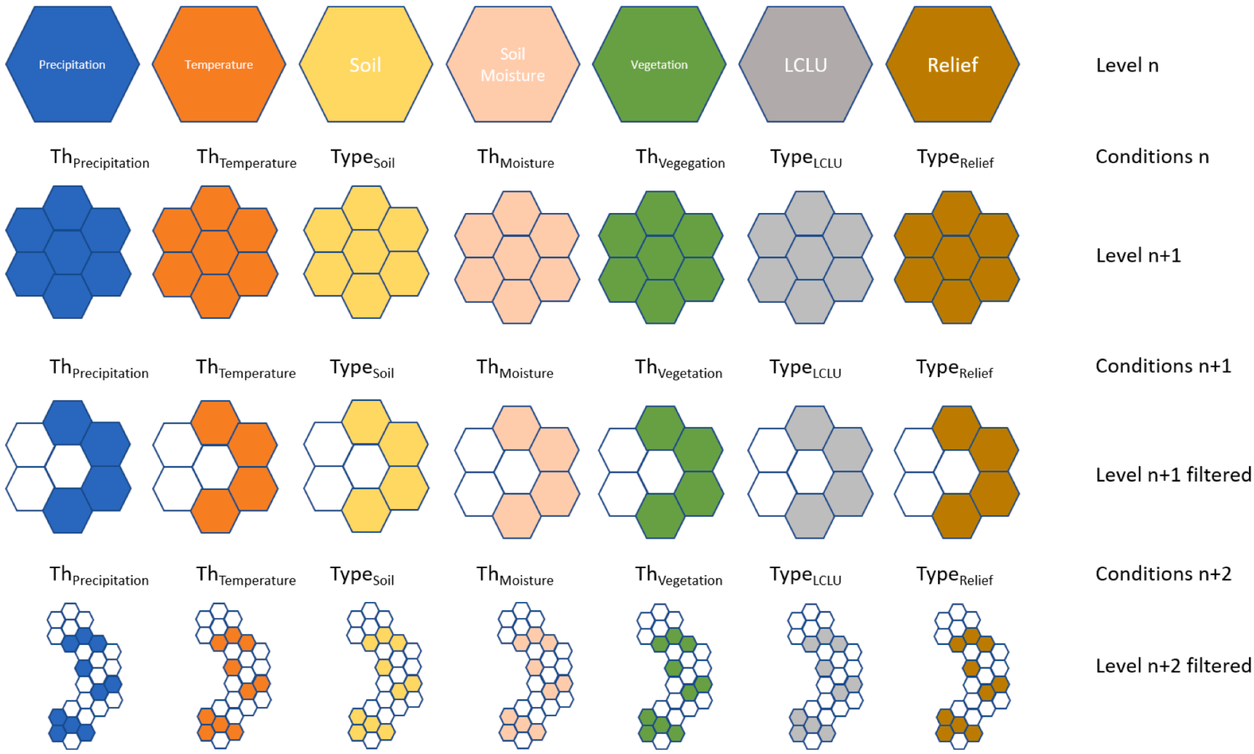

Fig. 5. Schematic exemplary stepwise workflow to use h3-polygons at various levels to prioritize hotspot areas (T_h = threshold). Variables, appropriate levels, and conditions shall be defined based on individual specifications of species and application tasks.

Table 2
Logical rules for CIT population dynamics in the Pavlodar region based on ongoing meteorological conditions (LTA = long-term average based on 1991–2021 data). Conditions should be considered within a logical "&" function.

Conclusion	HTC_{VP}	SET	Annual Precipitation	Seasonal Condition
Highly favorable years	0.3–0.5	2800–3100 °C	150–200 mm	spring precipitation is within LTA
Generally favorable years	0.5–0.7	2250–2800 °C	< 250 mm	spring precipitation is within LTA
Population decreasing years	> 0.7	< 2800 °C	> LTA	exceptionally wet and cold years, especially during springtime as it negatively affects the survival of the eggs and nymphs, spring precipitation > LTA, spring temperature < LTA

no specific ecosystems which represent the natural habitat of CIT and this is one of the main reasons why remote sensing-based monitoring of spatial distribution and locust population density is more difficult. However, one of the most crucial factors for CIT breeding sites and population increase are the state of the land surface and its management. It is well documented that different locust species, especially CIT, find perfect conditions on abandoned land or fallow fields (Kambulin, 2018; Latchininsky, 2013; Sergeev et al., 2022; Sivanpillai et al., 2009; Zhao et al., 2020). In this study, we quantified the relationship between the occurrence of abandoned land and the presence of CIT based on time-series analyses using Landsat and Sentinel-2 data. An up-to-date land cover and land use map of 2021 was generated (Fig. 7a). Besides the actual state of the land surface in 2021, Fig. 7 includes spatial and temporal information on abandoned land and fallow fields evolution (Fig. 7b) and indicates the transformation of these areas (Fig. 7c). In combination, the derived infomration provide, whether an areas was used for agricultural purposas in the past and the time when agriculture activity stooped, as well as its recent land cover situation. The generated LCLU map based on Sentinel-2 imagery for the year 2021 resulted in an overall accuracy of 86.02% and a Kappa coefficient of 0.824. The binary cropland classification has an overall accuracy of 96.48% and a Kappa coefficient of 0.877.

The intersection of field data locations with derived LCLU information shows that 63% of CIT presence data were found on land which was classified as formerly or recently used for agriculture (36% abandoned land; 27% cropland). Another 36% are distributed across bare to sparse vegetation mosaics (13% sparse; 23% bare). Most breeding locations found on abandoned land were detected in areas which became abandoned or fallow in the period 2016–2020 (62%) and 2011–2015 (15%). This underlines the hypothesis that annual changes in land use and land cover directly influence locust population dynamics because of changes in nutrient availabilities (Cease et al., 2012; Le Gall et al., 2019; Youngblood et al., 2022). Furthermore, it is not only important to derive the age of abandoned land to assess its succession state but also the present land surface situation which means, whether the fields have turned to bare soils, sparse or dense vegetation mosaics. In this regard, 38% of CIT breeding locations were found in sparse vegetation and 62% in bare soil mosaics. These results are in line with descriptions from literature about preferable land cover and bare soil-vegetation mosaics for egg laying of CIT and young fallow fields (Sergeev et al., 2022).

4.2. The importance of meteorological conditions for breeding locations and population dynamics

As discussed in the previous section meteorological conditions are the most important variables which define the timing of the life cycle as well as locust population dynamics. Therefore, climatic conditions

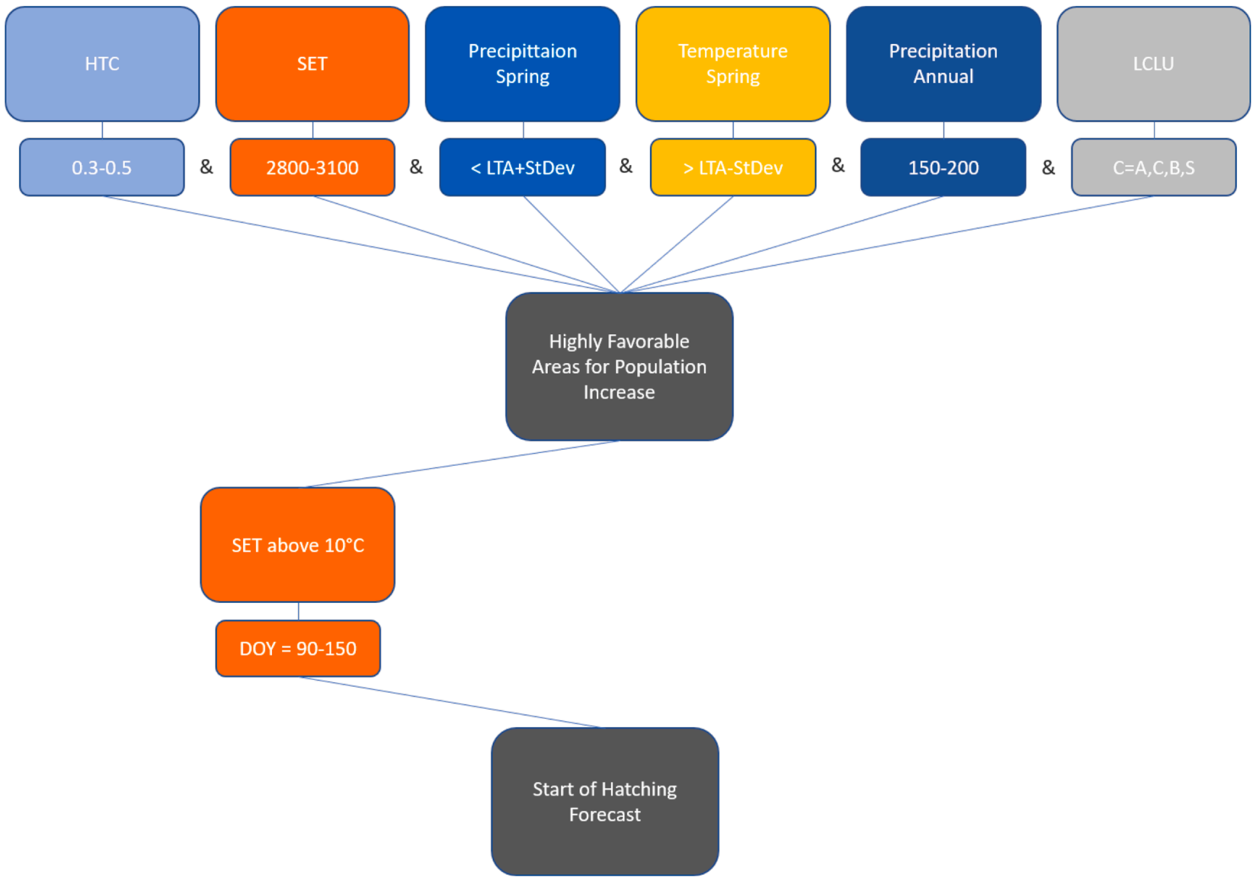

Fig. 6. Highly favorable meteorological conditions for potential CIT population increase in the Pavlodar region based on (Kambulin, 2018; Sergeev et al., 2022), including SoH forecast. (LTA = long-term average based on 1991–2021 data, A = abandoned land, C = recently or currently used for agriculture, B + S = bare soil and sparse vegetation mosaics).

detectmines whether locusts are in the solitarious or gregarious phase. Fig. 8 illustrates the results of relevant meteorological variables at h3 hexagon level-7 for the year 2021. The annual SET provides valuable information about which areas have experienced ideal thermal conditions over the year of interest (Table 2). Therefore, the dark orange areas (Fig. 8a) experiences highly favourable thermal conditions to promote locust population increase over the year 2021. In 2021 central and south Pavlodar regions as well as the region east of Irtysh river show higher spring temperature (Fig. 8b) and dryer conditions (Fig. 8d). This is critical especially for the areas east of Irtysh river which are well known contain hotspots for CIT breeding (Kambulin, 2018; Sergeev et al., 2022). Despite the conditions during spring period, the annual precipitation (Fig. 8c) also affects the development of locust. Furthermore, extreme rain events negatively affect young nymphs. Additionally, each hexagon contains both, the climatic history and ongoing conditions which enable a comprehensive view in terms of locust situation in the past. Fig. 9 presents climatic characteristics over the past 30 years for four selected hexagons with regards to CIT-relevant parameters. In fact, recent population increases within the study area are also mirrored by climatological variables. For example, there was drier period with significantly less annual precepitation (9e) and HTC (9a) lower than 0.5 the years before the 1999–2001 outbreak, as well as before 2011–2012 and 2018 population upsurges in Pavlodar. These actual years with higher locust population are charactirized by higher than avergae spring temperature (9f) slighly above avergae soil moisture and spring precipitation (9c, 9 h).

In general, locust managers are monitoring all relevant variables in combination to assess whether the situation based on recent climate, ongoing meteorological conditions and actual land cover situation provide higher risk for population increase. Spatial data preprocessing within presented h3 hexagonal system provides an easy to use database at different spatial levels. Based on hexagonal units, locust managers can access and assess all necessary information in a standardized way. The different variables are spatially harmonized so that current areas with favourable or less favourbale conditions can be easily identified.

5. Discussion

5.1. Importance of prioritization and hotspots

Gay et al. (2021) stated that the knowledge and prioritization of hotspot breeding sites is highly important to improve the capability to maintain plagues or outbreaks. In this way, attention and efforts shall be concentrated in time and space to enable highly effective preventive locust management. Therefore, it is crucial to reduce the area which has to be monitored by excluding areas where locust breeding and hatching are unlikely and to prioritize areas with different levels of urgency to allow stepwise actions and urgent intervention. Gay et al. (2021) conclude that any tool which supports guidance in this regard is helpful to reduce plagues and outbreaks. Besides historical ground data collection, consistent monitoring of ecological and meteorological conditions with remote sensing and geospatial datasets is inevitable. The presented approach demonstrates, how different geospatial and remote sensing datasets can be pre-processed for end-users so that they are simply applicable for locust management in a straightforward way. This allows assumptions from daily practices and fast decisions to either exclude or prioritize areas when time and resources are critical.

In this context, Boedeker et al. (2020) estimated that worldwide

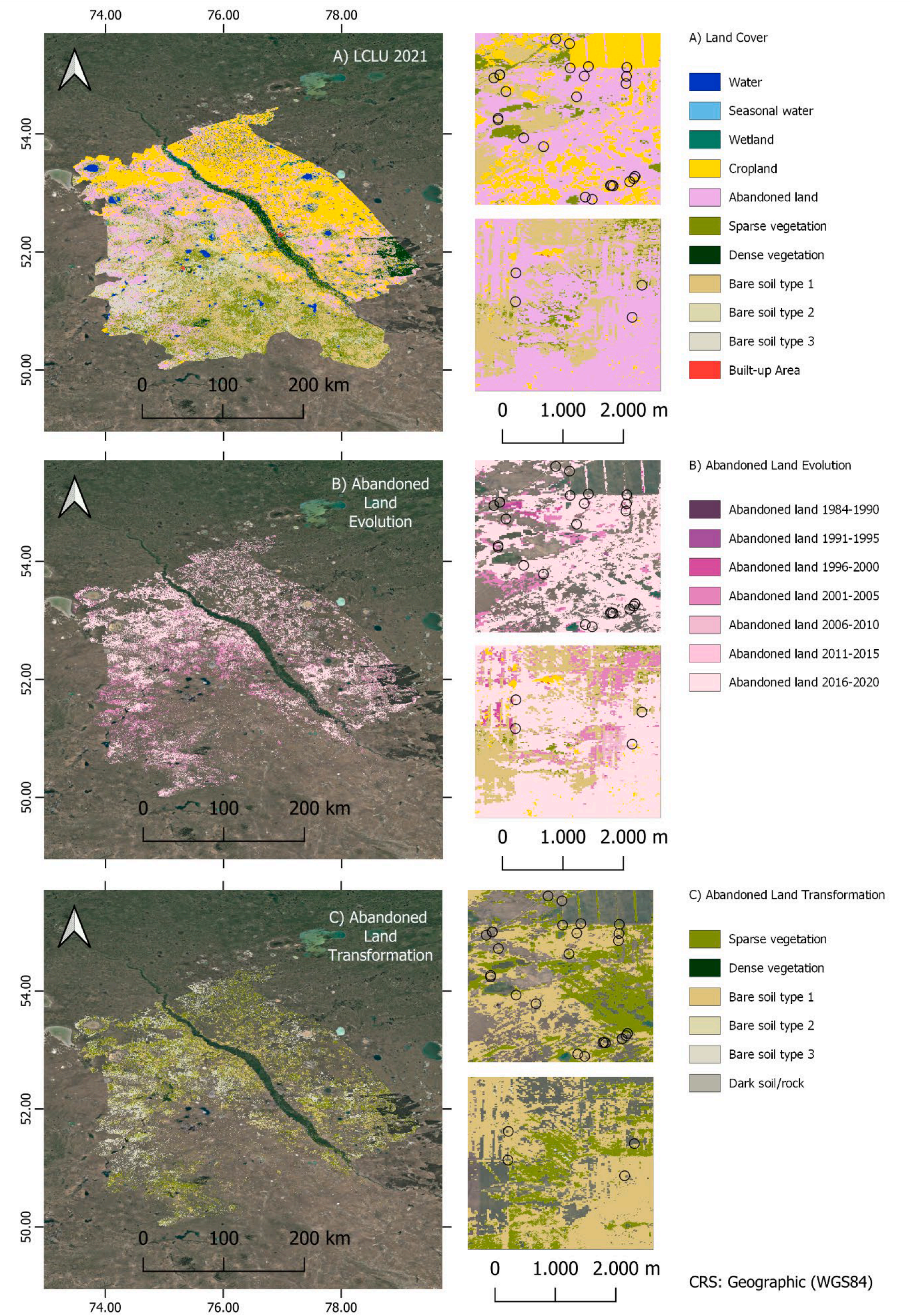

Fig. 7. LCLU classification and derived parameters for abandoned land evolution and transformation. Including two detailed views and detected nymph locations 2016–2021 (circles).

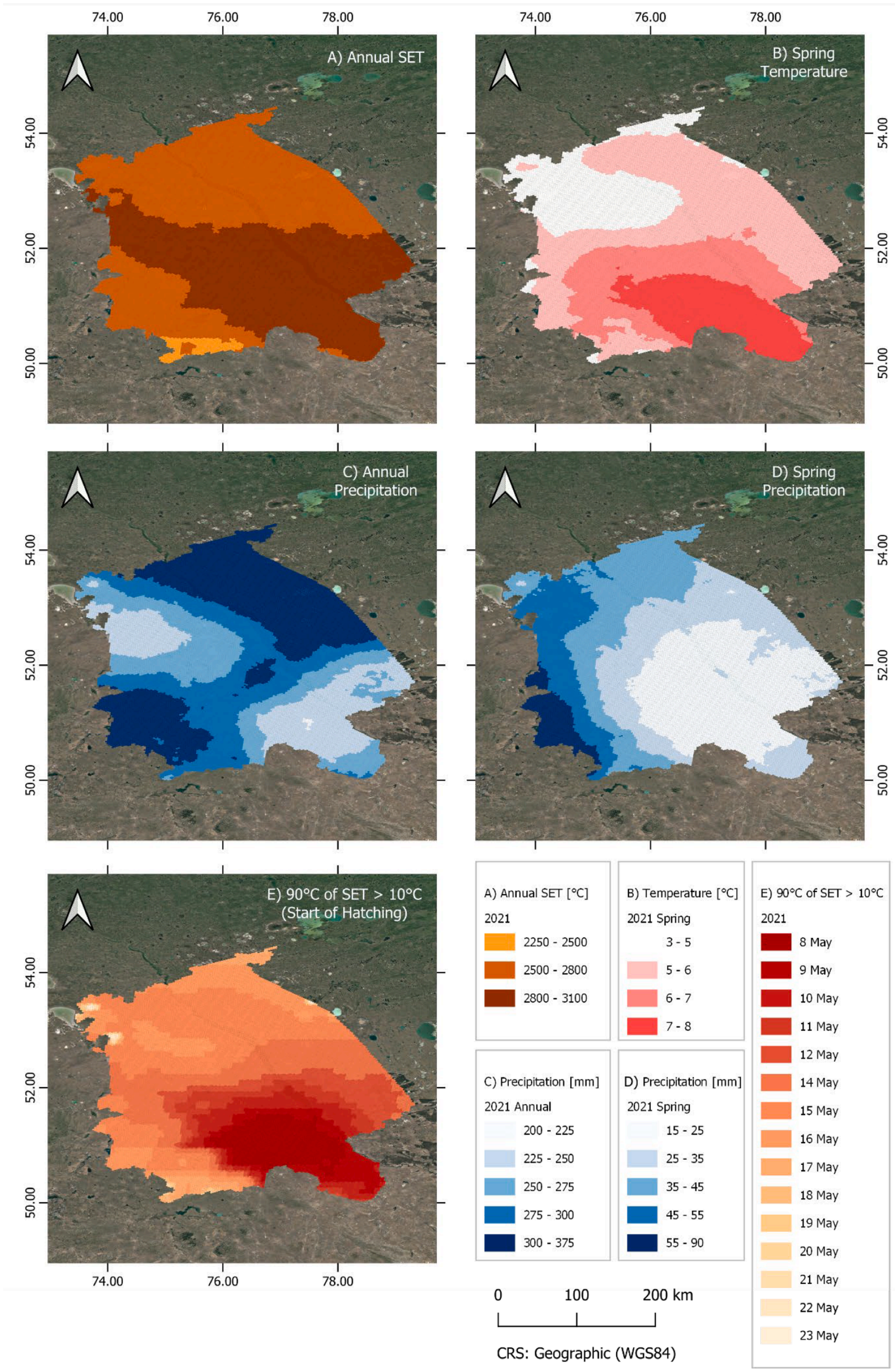

Fig. 8. Climatic characteristics with regards to CIT relevant information aggregated at level-7 hexagons (5.16 km^2).

there are approx. 385 Mio. annual accidental poisoning cases including around 11.000 mortal cases related to pesticide usage. Despite improved practices and guidelines for pesticide treatment for locust control and outbreak fighting, the risk of poisoning is always present. Therefore, if preventive locust management works effective in terms of time and space, less pesticides under lower time pressure will be used during recessions and depressions phases to keep the locust population low and in its solitarious form. However, if locusts are already in gregarious phase the control measurements should occur during the nymph development phase before it is capable to fly and migrate. During this phase, locusts are in groups and bands and can be localized according to the positions of egg-laying from previous field monitoring. If locust management is functioning well, the ground teams are aware of locations with potential increasing locust density and the state of the locust

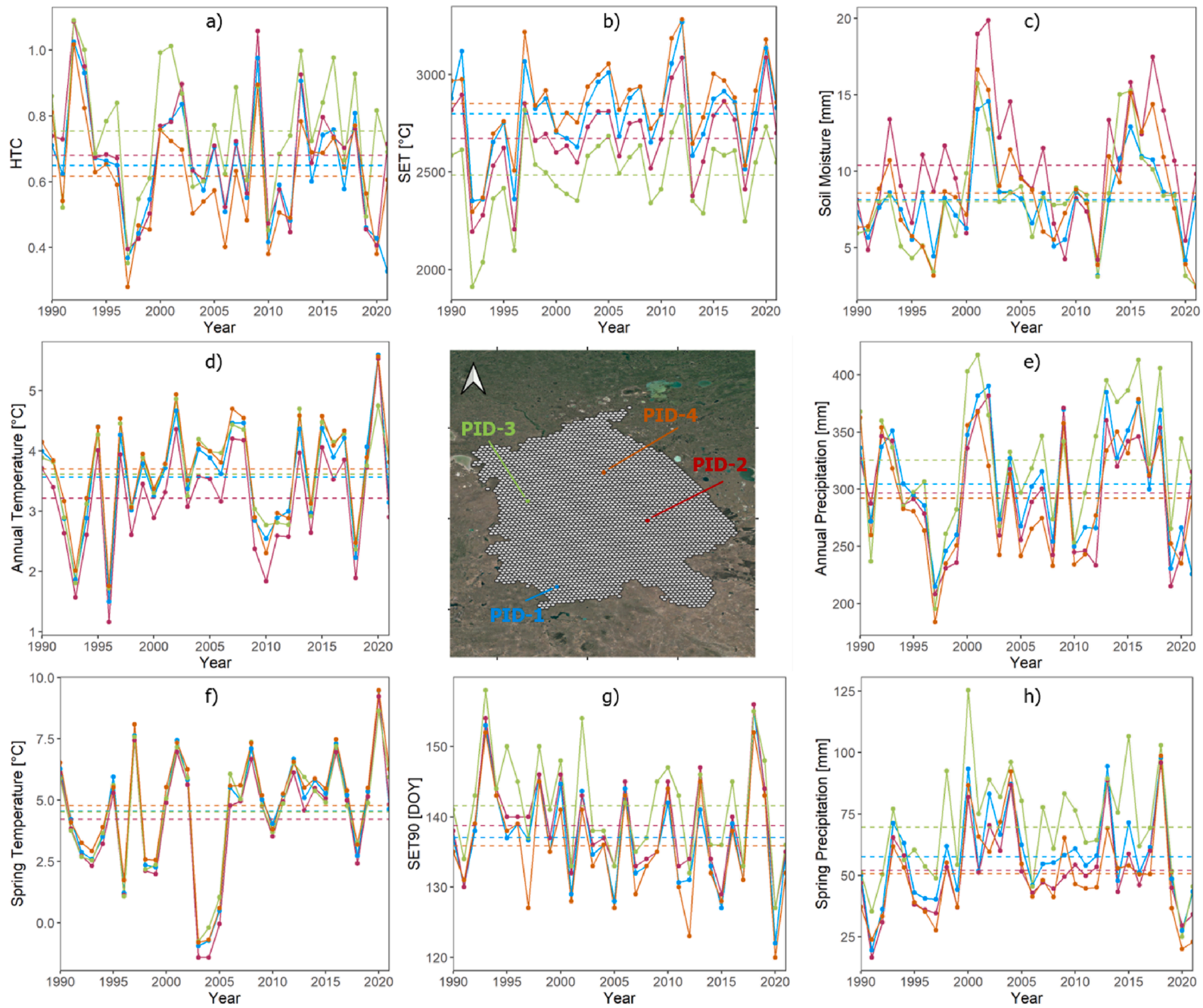

Fig. 9. Exemplary climatic characteristics for four selected hexagons (polygon identification, PID) with regards to CIT relevant information (dashed lines = long-term average for 1990–2020).

life cycle (hatching, instar phase). Nevertheless, the treated areas against locust nymphs can be still exceptionally large (Fig. 10). Despite ongoing research projects and developments for applying bio-pesticides, the ground control teams often use chemical pesticides which proved to be effective and affordable. The presented approach of identifying areas of high risk and prioritizing them for monitoring and treatment could thus contribute to an areal assessment of ecological conditions and in this way improve health safety and reduce the usage of pesticides. This becomes of higher relevance when active locust management does not exist (e.g., due to insufficient funding, insecurity due to political conflicts, absence of locust outbreaks over decades) or locust swarms reach regions which usually are not affected and therefore not prepared. The most important component of preventive locust management is a functioning system with locust field officers operating in the field on daily basis (Gay et al., 2021). This is also of high importance for future efforts to improve modelling and remote sensing based locust breeding mapping and damage assessment as it depends on availability and accuracy of ground data (e.g., correct species identification, precise geolocation, abundance and absence). However, this depends highly on the existing budget, accessibility to affected areas and security (Showler and Lecoq, 2021). Meynard et al. (2020) concluded that socio-political instability in the Middle East and East Africa contributed to the 2019–2021 outbreak of desert locusts. Lecoq and Cease (2022) summarized that the locust problem, associated measurements and research are a cycle of repeated events with increased interest of media and opportunistic scientific publications during and shortly after major outbreaks.

In regards to food security and the fact that locusts are a nutritious food source, historically and currently being consumed by humans (Kietzka et al., 2021), future outbreaks and plagues might become a valuable source of additional food as occurred during the last desert locust upsurge at a local scale (van Huis, 2021). However, in this case the insects for consumption should not be contaminated by pesticides.

5.2. Geospatial data and accuracy

An accuracy assessment is conducted to provide the user with information on the error and uncertainty of the resulting output products (Lyons et al., 2018). These accuracy measures are crucial for using and interpreting the data (Brovelli et al., 2015; Stehman and Foody, 2019). In this regard, it is important to keep in mind that geospatial datasets and outputs derived from remote sensing data are only a generalization of the reality (Foody, 2002) and might come along with uncertainties. Due to this fact, users and decision makers need to be aware and have to understand that the derived information have to be considered critically and carefully in the light of the provided accuracy measures.

5.3. Future studies for climate change effects on locust species

Insect pests might destroy 10–25% more crops due to climate change (Deutsch et al., 2018). This is partly because climate change reshuffles

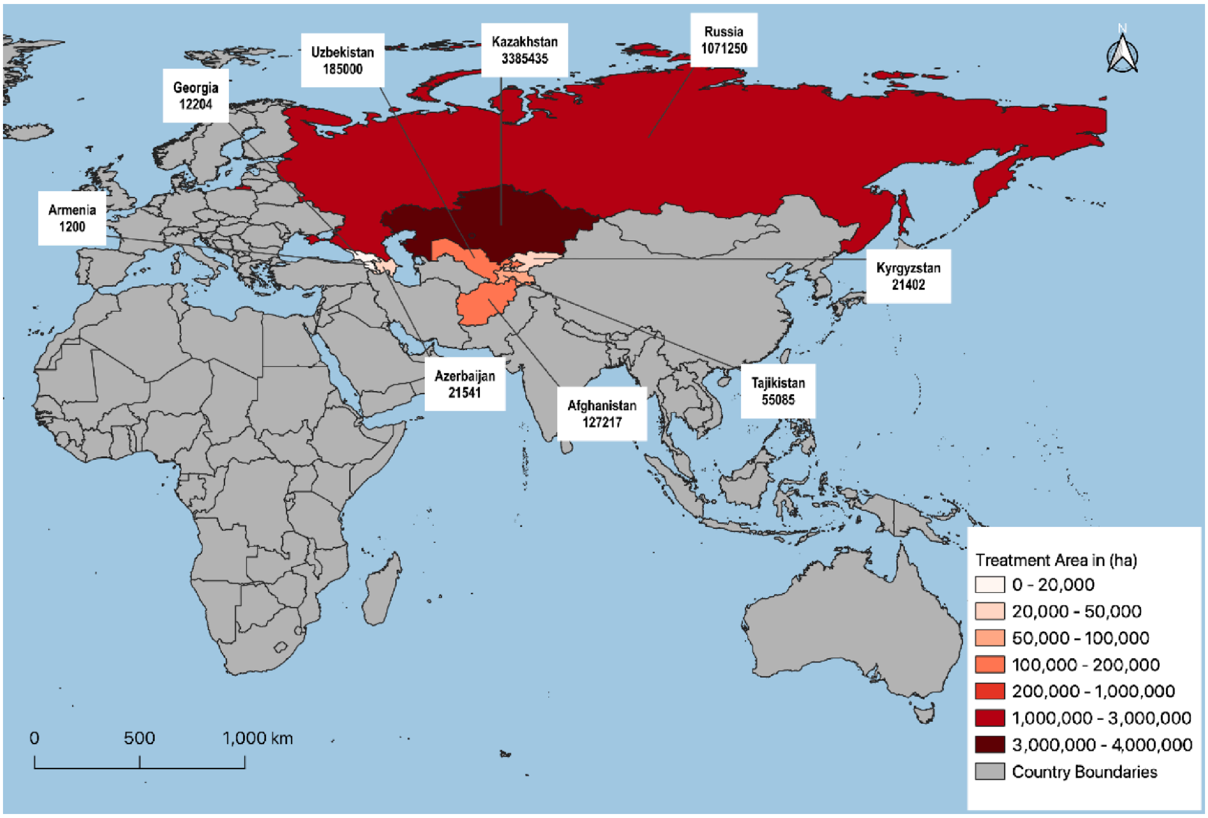

Fig. 10. Treated cumulative area between 2010 and 2021 against Moroccan locust (DMA), Italian locust (CIT) and Asian migratory locust (LMI) in Caucasus, Central Asia, and Russia (information extracted from monthly FAO reports).

northern and southern species within their niches (Antão et al., 2022; Çiplak, 2021; Youngblood et al., 2022). Apart from temperature changes, also the precipitation trends determine future occurrences of compound hot–dry events (Bevacqua et al., 2022) while increased frequency of global precipitation extremes with its influence on locust life cycles (Thackeray et al., 2022). For example, for desert locusts, the influence of climate change on tropical cyclone heavy rainfall is evident (Utsumi and Kim, 2022). As future climate will bring more droughts and more intense precipitation events (IPCC, 2019), it is also of high concern for many other locust species around the world (Cressman, 2016; Kimathi et al., 2020; Latchininsky, 2013; Meynard et al., 2020, 2017; Wang et al., 2019; Youngblood et al., 2022). However, as stated in Lecoq and Cease (2022) there is still a lack of detailed understanding of how different locust species will be affected by climate change. Therefore, further assessment of the impacts of climate change on locust habitats and population dynamics and adjustments to locust management and control are of high importance not only for the most dangerous species such as desert locust, migratory locust, or Australian plague locust but also for other species with regional or even local relevance. The recent outbreaks of Moroccan locust (*Dociostaurus maroccanus*) in Sardinia, Italy and Tajikistan, migratory locust (*Locusta migratoria*) in Romania, or brown locust (Locustana pardalina) in South Africa are only few of many examples that locust pests can become a devasting factor for rural population due to change in climate and land management.

Regarding the overall importance of locust impact all over the world, we propose to generate a standardized database for all locust pest species with special focus on species-relevant conditions. Such a database could support areal planning, includes all necessary information and may be an important backup for urgent interaction independent in the case that ground monitoring and management is missing or restricted. The variability of different climatic, edaphic and landscape parameters influence the population dynamics even of adjacent local CIT population in their long-term dynamics (Sergeev, 2021; Sergeev and Van'kova, 2008). Therefore, additional holistic research focusing on spatial and temporal variability of all parameters under consideration of local population dynamics within the habitats is necessary. Geospatial and remote sensing data provide an ideal base to conduct more complex spatial distribution modelling and contribute to further understanding of population upsurges which lead to locust outbreaks.

6. Conclusion

Locust management is a multi-disciplinary challenge and requires the understanding and handling of diverse information and datasets. Decision support systems for locust management at various levels using the interpretation of available geospatial and remote sensing data are still lacking for many dangerous locust pests. In this study, we introduce a concept towards a comprehensive usage of geospatial and remote sensing data. The concept simplifies complex datasets with different spatial and temporal characteristics into reasonable spatial units which can be used by stakeholders to improve monitoring, control efficiency and contribute to more sustainable planning practices. Furthermore, being aware of areas of higher or lower risk and being able to predict hatching and outbreak timing can contribute to timely sustainable control and minimize the "over-usage" of pesticides in large areas. The presented use case for Italian locusts in the Pavlodar region shows that spatial data can effectively be integrated for practical applications of locust management.

Furthermore, the application of geospatial and remote sensing datasets within a simplified h3-system may close the discrepancy between users experience and available information. Information within the h3-system can be easily exploited by locust experts without the need for additional pre-processing steps and detailed knowledge of data formats and specifications. Meteorological variables were calculated in standardized hexagons, containing CIT-relevant climatic and land cover characteristics and can be utilized for expert-defined rule-sets and provide additional information for monitoring and areal planning. This can contribute to preventive locust management by prioritizing areas for locust control measurements based on historical and ongoing favorable conditions as well as by predicting hatching and outbreak times.

The application of geoscientific data provides additional opportunities which can be used independently from funding, political programs, or security situation. Especially, because locusts can inhabit vast areas during favorable conditions, it is vital to monitor and map areas of potential risk for all locust pests around the world in collaboration with regional locust experts. Therefore, the application and development of remote sensing and geospatial datasets regarding different locust species do not only support locust management but also provide a back-up database for periods with less funding or socio-political conflicts. Nevertheless, operating field officers will remain the most crucial factor.

Author **Contributions:** Conceptualization, I.K.; methodology, I.K.; formal analysis, I.K., S.U.; investigation, I.K., S.U.; writing—original draft preparation, I.K.; writing—review and editing, I.K., S.U., C.E., N. O., and C.K.; visualization, I.K., S.U.; field data acquisition, V.P.; supervision, N.O. and C.K.; project administration, I.K.; funding acquisition, I.K. All authors have read and agreed to the published version of the manuscript. Please turn to the CRediT taxonomy for the term explanation.

Funding

This research has been performed within the Locust-Tec project (https://www.locust-tec.eoc.dlr.de) funded by BMBF in the framework of CLIENT-II program (https://www.bmbf-client.de/en).

CRediT authorship contribution statement

Igor Klein: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Soner Uereyen:** Formal analysis, Investigation, Writing – review & editing, Visualization, Funding acquisition. **Christina Eisfelder:** Writing – review & editing, Funding acquisition. **Vladimir Pankov:** . **Natascha Oppelt:** Writing – review & editing, Supervision, Funding acquisition. **Claudia Kuenzer:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

First of all, we would like to thank the entire staff of "Pavlodar regional branch of SD Republican Methodological Center of phytosanitary diagnostics and forecasts" for supporting this study with field data, discussions, and expert knowledge. We would also like to thank Nadiya Muratova, international consultant of FAO for the recommendation of Locust-Tec project and Zhyembayev's Institute of Plant Protection and Quarantine for supporting this project and research with their resources, knowledge, and help. We thank the anonymous reviewers for their time and constructive feedback, which helped substantially to improve this manuscript.

References

Abatzoglou, J.T., Dobrowski, S.Z., Parks, S.A., Hegewisch, K.C., 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Sci. Data 5, 170191. https://doi.org/10.1038/sdata.2017.191.

Antão, L.H., Weigel, B., Strona, G., Hällfors, M., Kaarlejärvi, E., Dallas, T., Opedal, Ø.H., Heliölä, J., Henttonen, H., Huitu, O., Korpimäki, E., Kuussaari, M., Lehikoinen, A., Leinonen, R., Lindén, A., Merilä, P., Pietiäinen, H., Pöyry, J., Salemaa, M., Tonteri, T., Vuorio, K., Ovaskainen, O., Saastamoinen, M., Vanhatalo, J., Roslin, T., Laine, A.-L., 2022. Climate change reshuffles northern species within their niches. Nat. Clim. Change 12, 587–592. https://doi.org/10.1038/s41558-022-01381-x.

Aragón, P., Coca-Abia, M.M., Llorente, V., Lobo, J.M., 2013. Estimation of climatic favourable areas for locust outbreaks in Spain: integrating species' presence records and spatial information on outbreaks. J. Appl. Entomol. 137, 610–623. https://doi.org/10.1111/jen.12022.

Bevacqua, E., Zappa, G., Lehner, F., Zscheischler, J., 2022. Precipitation trends determine future occurrences of compound hot–dry events. Nat. Clim. Change 12, 350–355. https://doi.org/10.1038/s41558-022-01309-5.

Boedeker, W., Watts, M., Clausing, P., Marquez, E., 2020. The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review. BMC Public Health 20, 1875. https://doi.org/10.1186/s12889-020-09939-0.

Bousquin, J., 2021. Discrete Global Grid Systems as scalable geospatial frameworks for characterizing coastal environments. Environ. Model. Softw. 146, 105210 https://doi.org/10.1016/j.envsoft.2021.105210.

Breiman, L., 2001. Random Forests. Mach. Learn. 45, 5–32. https://doi.org/10.1023/A:1010933404324.

Brovelli, M., Molinari, M., Hussein, E., Chen, J., Li, R., 2015. The first comprehensive accuracy assessment of GlobeLand30 at a national level: methodology and results. Remote Sens. 7, 4191–4212. https://doi.org/10.3390/rs70404191.

Cease, A.J., Elser, J.J., Ford, C.F., Hao, S., Kang, L., Harrison, J.F., 2012. Heavy livestock grazing promotes locust outbreaks by lowering plant nitrogen content. Science 335, 467–469. https://doi.org/10.1126/science.1214433.

Chaminé, H.I., Pereira, A.J.S.C., Teodoro, A.C., Teixeira, J., 2021. Remote sensing and GIS applications in earth and environmental systems sciences. SN Appl. Sci. 3, 870, s42452-021-04855–3. https://doi.org/10.1007/s42452-021-04855-3.

Cheke, R.A., Young, S., Wang, X., Tratalos, J.A., Tang, S., Cressman, K., 2020. Evidence for a causal relationship between the solar cycle and locust abundance. Agronomy 11, 69. https://doi.org/10.3390/agronomy11010069.

Çiplak, B., 2021. Locust and grasshopper outbreaks in the near east: review under global warming context. Agronomy 11, 111. https://doi.org/10.3390/agronomy11010111.

Cressman, K., 2016. Desert Locust, in: Biological and Environmental Hazards, Risks, and Disasters. Elsevier, pp. 87–105. doi: 10.1016/B978-0-12-394847-2.00006-1.

Cressman, K., 2013. Role of remote sensing in desert locust early warning. J. Appl. Remote Sens. 7, 075098 https://doi.org/10.1117/1.JRS.7.075098.

Cullen, D.A., Cease, A.J., Latchininsky, A.V., Ayali, A., Berry, K., Buhl, J., De Keyser, R., Foquet, B., Hadrich, J.C., Matheson, T., Ott, S.R., Poot-Pech, M.A., Robinson, B.E., Smith, J.M., Song, H., Sword, G.A., Vanden Broeck, J., Verdonck, R., Verlinden, H., Rogers, S.M., 2017. From molecules to management: mechanisms and consequences of locust phase polyphenism, in: Advances in Insect Physiology. Elsevier, pp. 167–285. doi: 10.1016/bs.aiip.2017.06.002.

Dabrowska-Zielinska, K., Malinska, A., Bochenek, Z., Bartold, M., Gurdak, R., Paradowski, K., Lagiewska, M., 2020. Drought model DISS based on the fusion of satellite and meteorological data under variable climatic conditions. Remote Sens. 12, 2944. https://doi.org/10.3390/rs12182944.

Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., Battisti, D.S., Merrill, S.C., Huey, R.B., Naylor, R.L., 2018. Increase in crop losses to insect pests in a warming climate. Science 361, 916–919. https://doi.org/10.1126/science.aat3466.

Deveson, E.D., 2013. Satellite normalized difference vegetation index data used in managing Australian plague locusts. J. Appl. Remote Sens. 7, 075096 https://doi.org/10.1117/1.JRS.7.075096.

Duszak, P., Siemiątkowska, B., Więckowski, R., 2021. Hexagonal grid-based framework for mobile robot navigation. Remote Sens. 13, 4216. https://doi.org/10.3390/rs13214216.

Evarte-Bundere, G., Evarts-Bunders, P., 2012. Using of the Hydrothermal coeffcient (HTC) for interpretation of distribution of non-native tree species in Latvia on example of cultivated species of genus Tilia. Acta Biol Univ Daugavp 12, 135–148.

FAO, 2022. Locust Hub. Food and Agriculture Organization of the United Nations (FAO). Available from: <https://locust-hub-hqfao.hub.arcgis.com/>.

FAO, 2021. Locust Watch - Locusts in Caucasus and Central Asia. Food and Agriculture Organization of the United Nations (FAO). Available from: <http://www.fao.org/locusts-cca/en/>.

Foody, G.M., 2002. Status of land cover classification accuracy assessment. Remote Sens. Environ. 80, 185–201. https://doi.org/10.1016/S0034-4257(01)00295-4.

Gay, P., Trumper, E., Lecoq, M., Piou, C., 2021. Importance of human capital, field knowledge and experience to improve pest locust management. Pest Manag. Sci. 77, 5463–5474. https://doi.org/10.1002/ps.6587.

Gómez, D., Salvador, P., Sanz, J., Rodrigo, J.F., Gil, J., Casanova, J.L., 2021. Prediction of desert locust breeding areas using machine learning methods and SMOS (MIR_SMNRT2) Near Real Time product. J. Arid Environ. 194, 104599 https://doi.org/10.1016/j.jaridenv.2021.104599.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens. Environ. Big Remotely Sensed Data: tools, applications and experiences 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031.

Hao, H., Chen, Y., Xu, J., Li, Z., Li, Y., Kayumba, P.M., 2022. Water deficit may cause vegetation browning in Central Asia. Remote Sens. 14, 2574. https://doi.org/10.3390/rs14112574.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. https://doi.org/10.1002/qj.3803.

Hou, G., Yuan, X., Wu, S., Ma, X., Zhang, Z., Cao, X., Xie, C., Ling, Q., Long, W., Luo, G., 2022. Phenological changes and driving forces of lake Ice in Central Asia from 2002 to 2020. Remote Sens. 14, 4992. https://doi.org/10.3390/rs14194992.

Hu, Q., Han, Z., 2022. Northward expansion of desert climate in central asia in recent decades. Geophys. Res. Lett. 49, e2022GL098895. doi: 10.1029/2022GL098895.

Hunter, D.M., McCulloch, L., Spurgin, P.A., 2008. Aerial detection of nymphal bands of the Australian plague locust (Chortoicetes terminifera (Walker)) (Orthoptera: Acrididae). Crop Prot. 27, 118–123. https://doi.org/10.1016/j.cropro.2007.04.016.

IPCC, 2019. Summary for Policymakers, in: Shukla, P.R., Skea, J., Calvo Buendi, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., Diemen, R. van, Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. pp. 1–36.

Kambulin, V.E., 2018. Locust - methods of assessing harm, forecasting the number and technologies for identifying populated areas. Almaty.

Kang, Y., Ozdogan, M., Gao, F., Anderson, M.C., White, W.A., Yang, Y., Yang, Y., Erickson, T.A., 2021. A data-driven approach to estimate leaf area index for Landsat images over the contiguous US. Remote Sens. Environ. 258, 112383 https://doi.org/10.1016/j.rse.2021.112383.

Kietzka, G.J., Lecoq, M., Samways, M.J., 2021. Ecological and human diet value of locusts in a changing world. Agronomy 11, 1856. https://doi.org/10.3390/agronomy11091856.

Kimathi, E., Tonnang, H.E.Z., Subramanian, S., Cressman, K., Abdel-Rahman, E.M., Tesfayohannes, M., Niassy, S., Torto, B., Dubois, T., Tanga, C.M., Kassie, M., Ekesi, S., Mwangi, D., Kelemu, S., 2020. Prediction of breeding regions for the desert locust Schistocerca gregaria in East Africa. Sci. Rep. 10, 11937. https://doi.org/10.1038/s41598-020-68895-2.

Klein, I., Oppelt, N., Kuenzer, C., 2021. Application of remote sensing data for locust research and management—a review. Insects 12, 233. https://doi.org/10.3390/insects12030233.

Klein, I., van der Woude, S., Schwarzenbacher, F., Muratova, N., Slagter, B., Malakhov, D., Oppelt, N., Kuenzer, C., 2022. Predicting suitable breeding areas for different locust species – a multi-scale approach accounting for environmental conditions and current land cover situation. Int. J. Appl. Earth Obs. Geoinformation 107, 102672. https://doi.org/10.1016/j.jag.2021.102672.

Latchininsky, A., Sword, G., Sergeev, M., Cigliano, M.M., Lecoq, M., 2011. Locusts and grasshoppers: behavior, ecology, and biogeography. Psyche J. Entomol. 2011, 1–4. https://doi.org/10.1155/2011/578327.

Latchininsky, A.V., 2013. Locusts and remote sensing: a review. J. Appl. Remote Sens. 7, 075099 https://doi.org/10.1117/1.JRS.7.075099.

Latchininsky, A.V., 1998. Moroccan locust Dociostaurus maroccanus (Thunberg, 1815): a faunistic rarity or an important economic pest? J. Insect Conserv. 167–178.

Lazar, M., Aliou, D., Jeng-Tze, Y., Doumandji-Mitiche, B., Lecoq, M., 2015. Location and characterization of breeding sites of solitary desert locust using satellite images landsat 7 ETM+ and terra MODIS. Adv. Entomol. 03, 6–15. https://doi.org/10.4236/ae.2015.31002.

Le Gall, M., Overson, R., Cease, A., 2019. A global review on locusts (Orthoptera: Acrididae) and their interactions with livestock grazing practices. Front. Ecol. Evol. 7, 263. https://doi.org/10.3389/fevo.2019.00263.

Lecoq, M., 1995. Forecasting systems for migrant pests. III. Locusts and grasshoppers in West Africa and Madagascar. In: Drake, V.A., Gatehouse, A.G. (Eds), Insect Migration: Physical Factors and Physiological Mechanisms. Cambridge University Press, Cambridge, UK. pp. 377–395.

Lecoq, M., Cease, A., 2022. What have we learned after millennia of locust invasions? Agronomy 12, 472. https://doi.org/10.3390/agronomy12020472.

Li, M., McGrath, H., Stefanakis, E., 2022. Multi-resolution topographic analysis in hexagonal Discrete Global Grid Systems. Int. J. Appl. Earth Obs. Geoinformation 113.

Li, Y., Chen, Y., Sun, F., Li, Z., 2021. Recent vegetation browning and its drivers on Tianshan Mountain. Central Asia. Ecol. Indic. 129, 107912 https://doi.org/10.1016/j.ecolind.2021.107912.

Liu, Z., Shi, X., Warner, E., Ge, Y., Yu, D., Ni, S., Wang, H., 2008. Relationship between oriental migratory locust plague and soil moisture extracted from MODIS data. Int. J. Appl. Earth Obs. Geoinformation 10, 84–91. https://doi.org/10.1016/j.jag.2007.09.001.

Lyons, M.B., Keith, D.A., Phinn, S.R., Mason, T.J., Elith, J., 2018. A comparison of resampling methods for remote sensing classification and accuracy assessment. Remote Sens. Environ. 208, 145–153. https://doi.org/10.1016/j.rse.2018.02.026.

Ma, Y., Li, G., Yao, X., Cao, Q., Zhao, L., Wang, S., Zhang, L., 2021. A precision evaluation index system for remote sensing data sampling based on hexagonal discrete grids. ISPRS Int. J. Geo-Inf. 10, 194. https://doi.org/10.3390/ijgi10030194.

Malakhov, D.V., Zlatanov, B.V., 2020. An Ecological Niche Model for Dociostaurus maroccanus, Thunberg, 1815 (Orthoptera, Acrididae): the Nesting Environment and Survival of Egg-Pods. BiosisBiological Syst. 1, 08–24. https://doi.org/10.37819/biosis.001.01.0048.

Mangeon, S., Spessa, A., Deveson, E., Darnell, R., Kriticos, D.J., 2020. Daily mapping of australian plague locust abundance. Sci. Rep. 10, 16915. https://doi.org/10.1038/s41598-020-73897-1.

Matthews, G.A., 2021. New technology for desert locust control. Agronomy 11, 1052. https://doi.org/10.3390/agronomy11061052.

Meynard, C.N., Gay, P.-E., Lecoq, M., Foucart, A., Piou, C., Chapuis, M.-P., 2017. Climate-driven geographic distribution of the desert locust during recession periods: subspecies' niche differentiation and relative risks under scenarios of climate change. Glob. Change Biol. 23, 4739–4749. https://doi.org/10.1111/gcb.13739.

Meynard, C.N., Lecoq, M., Chapuis, M., Piou, C., 2020. On the relative role of climate change and management in the current desert locust outbreak in East Africa. Glob. Change Biol. 26, 3753–3755. https://doi.org/10.1111/gcb.15137.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D.G., Piles, M., Rodríguez-Fernández, N.J., Zsoter, E., Buontempo, C., Thépaut, J.-N., 2021. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. Earth Syst Sci Data 13, 4349–4383. https://doi.org/10.5194/essd-13-4349-2021.

Piou, C., Gay, P., Benahi, A.S., Babah Ebbe, M.A.O., Chihrane, J., Ghaout, S., Cisse, S., Diakite, F., Lazar, M., Cressman, K., Merlin, O., Escorihuela, M., 2019. Soil moisture from remote sensing to forecast desert locust presence. J. Appl. Ecol. 56, 966–975. https://doi.org/10.1111/1365-2664.13323.

Piou, C., Jaavar Bacar, M.E.H., Babah Ebbe, M.A.O., Chihrane, J., Ghaout, S., Cisse, S., Lecoq, M., Ben Halima, T., 2017. Mapping the spatiotemporal distributions of the Desert Locust in Mauritania and Morocco to improve preventive management. Basic Appl. Ecol. 25, 37–47. https://doi.org/10.1016/j.baae.2017.10.002.

Piou, C., Lebourgeois, V., Benahi, A.S., Bonnal, V., Jaavar, M.el.H., Lecoq, M., Vassal, J.-M., 2013. Coupling historical prospection data and a remotely-sensed vegetation index for the preventative control of Desert locusts. Basic Appl. Ecol. 14, 593–604. https://doi.org/10.1016/j.baae.2013.08.007.

Popova, E.N., Semenov, S.M., Popov, I.O., 2016. Assessment of possible expansion of the climatic range of Italian locust (Calliptamus italicus L.) in Russia in the 21st century at simulated climate changes. Russ. Meteorol. Hydrol. 41, 213–217. https://doi.org/10.3103/S1068373916030079.

Ryazanova, A.A., Voropay, N.N., 2019. Comparative analysis of hydrothermal conditions of Tomsk region by using different drought coefficients. IOP Conf. Ser. Earth Environ. Sci. 386, 012008 https://doi.org/10.1088/1755-1315/386/1/012008.

Sahr, K., White, D., Kimerling, A.J., 2003. Geodesic discrete global grid systems. Cartogr. Geogr. Inf. Sci. 30, 121–134. https://doi.org/10.1559/152304003100011090.

Selyaninov, G.T., 1928. About climate agricultural estimation. Proc Agric Meteorol 20, 165–177.

Sergeev, M.G., 2021. Ups and downs of the italian locust (Calliptamus italicus L.) populations in the siberian steppes: on the horns of dilemmas. Agronomy 11, 746. https://doi.org/10.3390/agronomy11040746.

Sergeev, M.G., Childebaev, M.K., Vankova, I.A., Gapparov, F.A., Kambulin, V.E., Kokanova, E.O., Latchininsky, A.V., Pshenitsyna, L.B., Temreshev, I.I., Chernyakhovsky, M.E., Sobolev, N.N., Molodcov, V.V., 2022. Italian Locust Calliptamus italicus (Linnaeus, 1758). morphology, distribution, ecology, population management. FAO, Rome.

Sergeev, M.G., Van'kova, I.A., 2008. The dynamics of a local population of the Italian locust (Calliptamus italicus L.) in an anthropo-genic landscape. Contemp Probl Ecol 1, 88–95. https://doi.org/10.1134/S1995425508010098.

Shi, L., Zhang, J., Yao, F., Zhang, D., Guo, H., 2020. Temporal variation of dust emissions in dust sources over Central Asia in recent decades and the climate linkages. Atmos. Environ. 222, 117176 https://doi.org/10.1016/j.atmosenv.2019.117176.

Showler, A.T., Lecoq, M., 2021. Incidence and ramifications of armed conflict in countries with major desert locust breeding areas. Agronomy 11, 114. https://doi.org/10.3390/agronomy11010114.

Sivanpillai, R., Latchininsky, A.V., Peveling, R., Pankov, V.I., Diagnosis, P., 2009. Utility of the IRS-AWiFS Data to Map the Potential Italian Locust (Calliptamus italicus) Habitats in Northern Kazakhstan. Presented at the American Society for Photogrammetry and Remote Sensing Annual Conference (ASPRS), Baltimore, USA.

Stehman, S.V., Foody, G.M., 2019. Key issues in rigorous accuracy assessment of land cover products. Remote Sens. Environ. 231, 111199 https://doi.org/10.1016/j.rse.2019.05.018.

Thackeray, C.W., Hall, A., Norris, J., Chen, D., 2022. Constraining the increased frequency of global precipitation extremes under warming. Nat. Clim. Change 12, 441–448. https://doi.org/10.1038/s41558-022-01329-1.

Tratalos, J., Cheke, R., Healey, R., Stenseth, N., 2010. Desert locust populations, rainfall and climate change: insights from phenomenological models using gridded monthly data. Clim. Res. 43, 229–239. https://doi.org/10.3354/cr00930.

Tronin, A.A., Gornyy, V.I., Kiselev, A.V., Kritsuk, S.G., Latypov, I.S., 2014. Forecasting of locust mass breeding by using satellite data. Curr Probl Remote Sens Earth Space 11, 37–50.

Trumper, E.V., Cease, A.J., Cigliano, M.M., Copa Bazán, F., Lange, C.E., Medina, H.E., Overson, R.P., Therville, C., Pocco, M.E., Piou, C., Zagaglia, G., Hunter, D., 2022. A review of the biology, ecology, and management of the South American locust, Schistocerca cancellata (Serville, 1838), and future prospects. Agronomy 12, 135. https://doi.org/10.3390/agronomy12010135.

Uber Technologies Inc., 2018. H3: Hexagonal hierarchical geospatial indexing system. Available from: <https://h3geo.org/>.

Utsumi, N., Kim, H., 2022. Observed influence of anthropogenic climate change on tropical cyclone heavy rainfall. Nat. Clim. Change 12, 436–440. https://doi.org/10.1038/s41558-022-01344-2.

Uvarov, B.P., 1957. The aridity factor in the ecology of locusts and grasshoppers of the Old World. In: Arid Zone Research. Paris.

van Huis, A., 2021. Harvesting desert locusts for food and feed may contribute to crop protection but will not suppress upsurges and plagues. J. Insects Food Feed 7, 245–248. https://doi.org/10.3920/JIFF2021.x003.

Vlăduţ, A., Nikolova, N., St. Kliment Ohridski University of Sofia, Faculty of Geology and Geography, Licurici, M., University of Craiova, Faculty of Sciences, Geography Department, 2017. Aridity assessment within southern Romania and northern Bulgaria. Hrvat. Geogr. Glas. Geogr. Bull. 79, 5–26. doi: 10.21861/HGG.2017.79.02.01.

Wang, B., Deveson, E.D., Waters, C., Spessa, A., Lawton, D., Feng, P., Liu, D.L., 2019. Future climate change likely to reduce the Australian plague locust (Chortoicetes terminifera) seasonal outbreaks. Sci. Total Environ. 668, 947–957. https://doi.org/10.1016/j.scitotenv.2019.02.439.

Youngblood, J.P., Cease, A.J., Talal, S., Copa, F., Medina, H.E., Rojas, J.E., Trumper, E. V., Angilletta, M.J., Harrison, J.F., 2022. Climate change expected to improve digestive rate and trigger range expansion in outbreaking locusts. Ecol. Monogr. https://doi.org/10.1002/ecm.1550.

Zanaga, D., Van De Kerchove, Ruben, De Keersmaecker, Wanda, Souverijns, Niels, Brockmann, Carsten, Quast, Ralf, Wevers, Jan, Grosu, Alex, Paccini, Audrey, Vergnaud, Sylvain, Cartus, Oliver, Santoro, Maurizio, Fritz, Steffen, Georgieva, Ivelina, Lesiv, Myroslava, Carter, Sarah, Herold, Martin, Li, Linlin, Tsendbazar, Nandin-Erdene, Ramoino, Fabrizio, Arino, Olivier, 2021. ESA WorldCover 10 m 2020 v100. Zenodo Geneve Switz. doi: 10.5281/ZENODO.5571936.

Zhang, L., Lecoq, M., Latchininsky, A., Hunter, D., 2019. Locust and grasshopper management. Annu. Rev. Entomol. 64, 15–34. https://doi.org/10.1146/annurev-ento-011118-112500.

Zhao, L., Huang, W., Chen, J., Dong, Y., Ren, B., Geng, Y., 2020. Land use/cover changes in the Oriental migratory locust area of China: Implications for ecological control and monitoring of locust area. Agric. Ecosyst. Environ. 303, 107110 https://doi.org/10.1016/j.agee.2020.107110.

Zheng, L., Xu, J., Li, D., Xia, Z., Chen, Y., Xu, G., Lu, D., 2021. Increasing control of climate warming on the greening of alpine pastures in central Asia. Int. J. Appl. Earth Obs. Geoinformation 105, 102606. https://doi.org/10.1016/j.jag.2021.102606.