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ORIGINAL PAPER

Historical and recent land use/land cover changes as a driving force of biological invasion: a Hungarian case study

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Abstract The spread of invasive plant species is influenced by various geographic factors such as the topography, climate, soil and hydrology, but the importance of each factor varies according to the species. Another major influencing factor that must be considered is historical and recent changes in Land Use/Land Cover (LULC). LULC changes may support the appearance of some invasive species, but there is uncertainty over the persistence of their effects on biological invasion. This study investigated the potential connections between historical LULC patterns over the past 200 years and the recent emergence of four common invasive plant species in Hungary: *Ailanthus altissima* (tree of heaven), *Asclepias syriaca* (common milkweed), *Elaeagnus angustifolia* (Russian olive) and *Solidago* spp. (goldenrod). Geographic Information System (GIS) data and statistical methods were used to compare historical (1848–1990) and recent (1990–2018) LULC changes with the occurrence patterns of these invasive plants in 2018. The results indicated that *Asclepias syriaca* is more influenced by recent LULC changes while *Ailanthus altissima, Elaeagnus angustifolia* and *Solidago* spp. are more affected by historical LULC changes. *Ailanthus altissima* and *Eelaeagnus angustifolia* tend to thrive in areas experiencing more intense LULC changes. *Asclepias syriaca* was more often found in areas with mixed and decreasing LULC change intensities while *Solidago* spp. prefers areas with continuously increasing and decreasing LULC change intensities.

Keywords Invasive plants · CORINE · Land Use/Cover Area Frame Statistical Survey (LUCAS) · Land-use intensity · Historical maps

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Introduction

Human interventions play a crucial role in shaping the distribution of invasive plant species, with one key anthropogenic factor being changes in Land Use Land Cover (hereafter referred to as LULC) as well as proximity to human settlements. In areas of high anthropogenic activity (e.g. intensive housing during urban and suburban sprawl), frequent changes in LULC facilitate the introduction of new plant species and their subsequent dispersal to proximate regions (Aronson et al. 2014; Gaertner et al. 2017; González-Moreno et al. 2013). Examples of this phenomenon

can be found around the world, as evidenced by the naturalisation of invasive plant species in New Zealand which typically occurs over decades or even centuries (Sullivan et al. 2004), and in the USA, where housing development, a major LULC disturbance, contributes to the introduction of invasive species and facilitates the spread of propagules (Gavier-Pizarro et al. 2010).

The success of invasive plant species is not only shaped by recent LULC, but the interplay between historical and recent patterns of LULC (Mattingly and Orrock 2013). Historical changes in LULC such as past agricultural practices or land abandonment modify the soil characteristics and plant communities, which can increase the probability of biological invasion (Bičík et al. 2001; Chytrý et al. 2012; Mattingly and Orrock 2013; Mosher et al. 2009). Human-induced LULC changes, such as deforestation and agricultural expansion, have led to the displacement of native vegetation and the spread of invasive species, with negative impacts on biodiversity and primary productivity (Franklin and Molina-Freaner 2010; Kuhman et al. 2011; Maráková et al. 2016; Silveira et al. 2022). It can be stated that changes in LULC frequency have a significant impact on various ecological factors, including plant growth, survival, resource availability, competition, species diversity, and ecological processes (Huston 2004).

The successful propagation of invasive plant species can be attributed to various factors, including their capacity to tolerate diverse environmental conditions (Gala-Czekaj et al. 2021). Although the introduction of invasive species such as *Ailanthus altissima* is recognised to lead to ecological harm, it has been used in restoration projects for its drought tolerance (Erdélyi et al. 2023). The objective of this approach is to maintain vegetation cover in the short term under increasingly dry conditions, although this method involves significant ecological trade-offs. Inadequate management strategies have been demonstrated to exert substantial adverse effects on native ecosystems, and the ecological consequences of such interventions remain contentious within the scientific community (Nyssen et al. 2024; Rigling et al. 2016; Woodward et al. 2016). Climate change, as evidenced by rising global temperatures, prolonged droughts, and increasingly frequent extreme weather events, has been demonstrated to facilitate the spread of heat-tolerant, non-native species. This, in turn, has the effect of complicating predictive models of invasion dynamics and amplifying ecological impacts that extend beyond those associated with anthropogenic mismanagement alone (Finch et al. 2021; Sanders et al. 2024).

As Funk (2013) argues, effective restoration efforts and invasive plant control strategies require a comprehensive understanding of the mechanisms by which native and non-native invasive species respond to both current and anticipated changes in resource availability and climate conditions. It is evident that LULC is subject to continuous transformation, both through anthropogenic activities and natural disturbances, including wildfires and climate change. Consequently, the distribution of invasive species is influenced by temporal variations in land management practices and the dynamic suitability of specific LULC classes for invasion (Ficetola et al. 2010).

The need for effective land management strategies is therefore emphasised (Gordienko and Kulik 2024; Kis et al. 2023; Saunders et al. 1991). To the best of our knowledge, no other study has investigated the impact and importance of historical and recent LULC changes, more precisely the effects of both the frequency of LULC changes and LULC change intensity over an extended period (1849–2018) on the current (2018) abundance of important invasive species within a single country (Hungary).

However, distinguishing between historical and recent changes in Land Use and Land Cover (LULC) is crucial for understanding the long-term impacts of land disturbance, particularly the mechanisms and key factors that enable specific species to spread in response to these changes. To state it more precisely, many invasive plant species undergo a multiphase spread, starting with a slow initial part, followed by rapid expansion and eventual stabilisation. In order to capture these dynamic phenomena, there is a necessity for the utilisation of long-term spatial data. However, it should be noted that this pattern is not universally applicable and may vary depending on species traits and environmental conditions. The time lags in the process of invasion could be observed at various stages, including the initial arrival and subsequent establishment of invasive plant species. These lags have the potential to obscure the genuine threat posed by invasive species until the conditions shift in their favour (Crooks 2005). It is evident that these circumstances may encompass a range of biological

traits and events, including but not limited to extreme weather conditions and nutrient enrichment. More importantly land disturbances have been demonstrated to exert a significant influence on the success of invasions (Pyšek and Hulme 2005). Furthermore, the phenomenon of plant invasions often happens to originate in disturbed, human-modified environments, subsequently evolving as long-term, dynamic processes influenced by evolving ecological and anthropogenic conditions (Dietz and Edwards 2006). Lag phases, defined as periods of delayed spread preceding exponential growth, underscore the notion that contemporary invasion patterns may serve as a reflection of introduction and ecological processes that occurred decades, or even centuries, prior. As previously indicated, an extended presence of alien species is capable of increasing propagule pressure and thus the likelihood of invasion (Richardson and Pyšek 2006). This understanding underscores the importance of the present study, which investigates long-term LULC changes and their potential influence on the present-day distribution of invasive plant species. Although lag phases provide valuable insight and a useful framework for many invasions, they are not universally applicable and should be applied with caution. Analysing anthropogenic events that may precede the introduction of invasive propagules by several decades is essential for understanding the spread of invasive plants (Mattingly and Orrock 2013) and setting vital management practices is also very important.

The dynamic nature of LULC change highlights the significance of historical LULC legacies, though the impact can vary across species (Mosher et al. 2009). Therefore, considering the difference between historical and recent LULC changes is crucial when assessing the factors driving plant invasions and shaping management strategies. A comprehensive understanding of LULC changes throughout different periods is imperative for the early detection and management of LULC change, with a view to controlling the spread of invasive species (Wang et al. 2016). Incorporating the temporal dimension of LULC changes into studies of biological invasions has the potential to enhance the effectiveness of management strategies (Ficetola et al. 2010).

In this study, we investigated the relationships between LULC patterns over the past 200 years and the current (2018) distributions of four invasive plant species in Hungary. Statistical methods were employed to analyse the connections between three distinct datasets: historical LULC changes (1848–1990), recent LULC changes (1990–2018) and the current (2018) distributions of the four invasive plant species. Our objective was to answer the following questions:

1. To what extent has the frequency of historical and recent LULC changes influenced the current (2018) spatial distribution of the four invasive plant species?
2. How have historical and recent dynamics in LULC change intensity influenced the current distributions (2018) of the four invasive plant species? How do patterns of LULC change intensity vary between the four invasive plant species?

We hypothesised that both the frequency and intensity of LULC changes over time may be connected to the risk of invasive plant spread. However, this connection is likely to be strongly species-dependent.

Materials and methods

Study area and invasive plant species

Hungary (45°45′–48°35′ N, 16°5′–22°58′ E) is a country in Europe with an area of 93 033 km^2 and diverse climate zones owing to the interactions between both a humid oceanic climate and drier continental climate (Mezősi 2017a). The basin-like geography presents both hydrological advantages and challenges such as flash floods and droughts (Mezősi 2017b). The climate, relief, soil and hydrological conditions have shaped the vegetation, which comprises deciduous forests in hilly areas and forest steppes in lowland areas. The orographic and climatic features have greatly influenced the distribution of soil types (Mezősi 2017c, d).

The selection of the four species (*Ailanthus altissima, Asclepias syriaca, Elaeagnus angustifolia, and Solidago* spp.) was based on two key criteria: the availability of verified spatial data and their ecological relevance. The selection of species was based on the availability of spatial distribution data, which were exclusively accessible for these specific taxa through the LUCAS-based National GIS Database

of Invasive Plant Species in Hungary (2018), thus providing a reliable foundation for analysis. While data were also available for *Robinia pseudoacacia* and *Amorpha fruticosa*, these species were excluded from the analysis for the following reasons: *Robinia pseudoacacia* is extensively cultivated in plantations, which complicates the distinction between planted stands and naturally occurring invasive populations. In the case of *Amorpha fruticosa*, the number of recorded invaded points was negligible, rendering the dataset insufficient for robust spatial analysis. From an ecological perspective, these four selected species are characterised by their wide distribution, high levels of competitiveness, and substantial negative impacts on native ecosystems. This poses a significant challenge for biodiversity conservation and land management. It is noteworthy that all four species are included in the exhaustive assessment by Botta-Dukát and Balogh (2008), which identifies the most ecologically harmful invasive plants in Hungary. Their inclusion in this reference underscores the imperative for the implementation of effective management strategies to curtail further propagation and mitigate ecological degradation.

Ailanthus altissima (tree of heaven) requires high levels of sunlight and is intolerant of low light conditions. It is drought-resistant, shade-intolerant and early successional species that grows best in open sites and soils with low productivity, a high calcium carbonate content and deficiency of nutrients (Korda 2018; Kowarik and Säumel 2007; Visztra et al. 2023). *Ailanthus altissima* originates from Eastern Asia (parts of China and Korea) and was first observed in Hungary in the nineteenth century (Botta-Dukát and Balogh 2008; Demeter and Czóbel 2016). *Asclepias syriaca* (common milkweed) is particularly adapted to sandy soils that have been disturbed by anthropogenic activities (Szilassi et al. 2019), and it spreads rapidly to impede the regeneration of native plant communities (Bagi 2008; Stef et al. 2022). *Asclepias syriaca* is indigenous to North America and was introduced to Hungary in the nineteenth century (Bagi 2008). *Elaeagnus angustifolia* (Russian olive) thrives in deep, sandy or loamy soils, and its expansion is closely associated with urbanisation and the development of water networks. It is drought-resistant and salt-resistant, and it requires high levels of sunlight. It has demonstrated adaptability to diverse environmental conditions making it an effective option for erosion control in arid regions, but it is challenging to manage (Bartha and Csiszár 2008; Szilassi et al. 2022). *Elaeagnus angustifolia* originates from the warm continental parts of Western and Central Asia (Bartha and Csiszár 2008) and it was brought to Hungary by the Ottomans in the sixteenth and seventeenth centuries (Csiszár and Korda 2015). The distribution of *Solidago* spp. (which includes *Solidago gigantea* and *Solidago canadensis*, are difficult to distinguish from each other and are therefore grouped as *Solidago* spp. in this study) in Hungary is predominantly shaped by precipitation and water deficits. The mismanagement of LULC has been identified as a major factor contributing to biodiversity loss and the spread of *Solidago* spp. (Botta-Dukát and Dancza 2008). *Solidago* spp. is indigenous to North America and was introduced to Hungary in the nineteenth century. The success of invasive plants is attributable to factors such as environmental tolerance, soil nutrient transformation, and high reproductive potential. Urgent management is required to mitigate soil degradation and preserve biodiversity (Botta-Dukát and Dancza 2008; Gala-Czekaj et al. 2021). The selected invasive plant species are widely distributed throughout Hungary (Fig. 1), and they represent a major threat to local biodiversity, even in protected areas (Csiszár et al. 2020; Szigeti et al. 2023). Their presence can also result in considerable economic losses (Kovács and Bela 2015).

Datasets

Datasets were collected for two distinct timescales (Fig. 2): historical (1848–1990) and recent (1990–2018). The historical and recent LULC changes were compared with the current (2018) distributions of invasive plant species to examine the temporal scale at which the LULC change frequency and LULC change intensity trend affect the spread of invasive plant species.

LUCAS-based national GIS database of invasive plant species of Hungary (NDIPS)

The Land Use/Cover Area Frame Statistical Survey (LUCAS) is a field survey programme financed and implemented by Eurostat that provides consistent and harmonised statistical data on LULC in the European Union (EU) (d'Andrimont et al. 2020, 2022). The

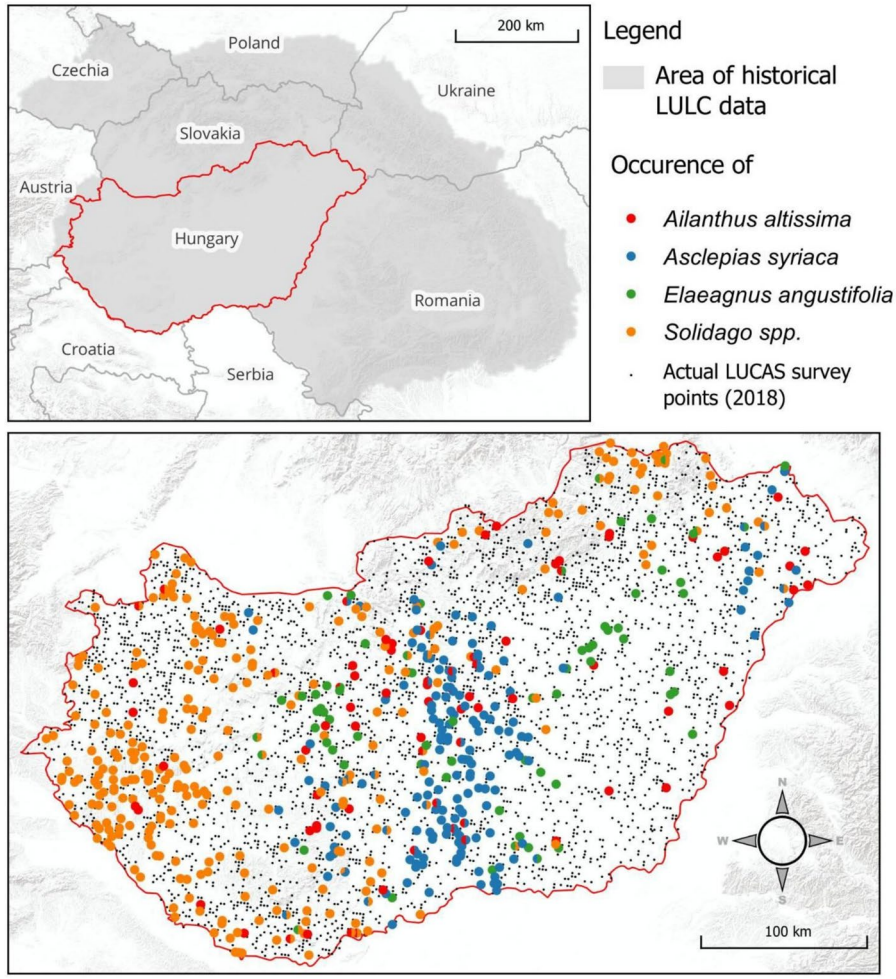


Fig. 1 The study area, historical LULC data, and the occurrence of four invasive plants investigated in Hungary in 2018

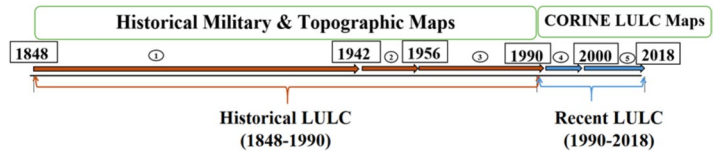


Fig. 2 Timescale of the datasets

European Environmental Angency (EEA) LUCAS point database has been used in various studies to validate LULC maps and analyse topsoil characteristics (Gebauer et al. 2022; Karydas et al. 2015; Makó et al. 2017; Schürz et al. 2020) and it has been instrumental in standardising LULC data across the EU to enhance the classification accuracy of LULC categories (d'Andrimont et al. 2020, 2022; Landa et al. 2022). It is a valuable resource for analysing the distribution patterns of crops, cultivation intensity and soil characteristics (Hagyó and Tóth 2018; Szigeti et al. 2023) and it includes Natura 2000 areas, road networks, and ecological networks to provide a comprehensive understanding of how invasive plant species spread (Szilassi et al. 2021). Automated classification techniques can be used to determine the LULC category at a given point on a LUCAS survey map (Martinez-Sanchez et al. 2024).

The Hungary National GIS Database of Invasive Plant Species (NDIPS) (Internet 1 2024) provides comprehensive data on the prevalence and distribution of invasive plant species in Hungary based on

the LUCAS point database. Members of the Department of Ecology at the University of Szeged visually identified 4156 points (Table 1) that were or were not invaded with our studied invasive plant species (Balogh et al. 2023; Kitka and Szilassi 2016; Szilassi et al. 2019; Visztra et al. 2023). The plant occurrences were captured by field surveyors in 2018. Specifically, 4156 points were recorded between May 7, 2018, and September 24, 2018.

We used the this points dataset to obtain information on the distributions of the four invasive plant species. As the NDIPS points are based on the LUCAS dataset, in our publication we have consequently used the term 'LUCAS' to refer to the LUCAS-based NDIPS dataset.

Historical LULC patterns

The historical LULC dataset of the Carpathian region (1819–1980) covers over 360,000 km^2 of the former Austro-Hungarian Empire where nine LULC categories were defined based on a set of detailed topographic maps prepared by the military or the government from three historical periods: the nineteenth century (1829–1866), interwar period (1940–1944) and post-war period (1953–1959) (Lieskovský et al. 2018). The information from the historical LULC dataset is assigned to LUCAS points on a 2 km × 2 km grid. Because of potential geometric inaccuracies, the backdating approach was used to define the LULC category during each historical period for the current position of a given LUCAS point (Kaim et al. 2014, 2016). The historical LULC dataset is fully open to the scientific community, and it has already been used to assess the impact of historical LULC patterns on contemporary forests (Munteanu et al. 2015) and agricultural land abandonment (Munteanu et al. 2017) as well as combined with other independent datasets (Feurdean et al. 2017). The historical LULC dataset covers 91 319 LUCAS points of which 23 263 LUCAS points are in Hungary. Thus, the historical LULC dataset and NDIPS dataset on invasive plant species could be compared at LUCAS points. In this study, we took the mean year of each historical period to represent the LULC pattern at that time: 1848, 1942 and 1956.

Recent LULC patterns

The CORINE Land Cover (CLC) database is a comprehensive LULC map for EU countries with a scale of 1:100 000, minimum mapping unit of 25 ha, thematic accuracy of > 85% and geometric accuracy of < 25 m. The CLC database is free to access for all users and it employs a hierarchical classification of LULC categories with three levels of thematic detail across five main groups: artificial surfaces, agricultural areas, forests and seminatural areas, wetlands and water bodies (Büttner 2014; Heymann 1994; Szilassi et al. 2017). The CLC vector polygon maps for 1990, 2000 and 2018 were overlaid with the LUCAS points to get point maps of the recent LULC patterns of Hungary (1990–2000 and 2000–2018). We aggregated the detailed LULC categories of the CLC dataset to facilitate comparison with the historical LULC dataset (Table 2).

Statistical analysis

The historical and recent LULC datasets were overlaid with the LUCAS 2018 dataset using the software QGIS 3.34. The LULC changes in the historical and recent datasets were then assigned to the closest LUCAS point in the NDIPS dataset to facilitate comparison among the three datasets.

LULC change frequency

The LULC change frequency at a given LUCAS point was calculated from the number of LULC

Table 1 The number of invaded and non-invaded points (LUCAS 2018) of the studied plant species in Hungary

Species	Ailanthus altissima		Ascelpias syriaca		Elaeagnus angustifolia		Solidago spp.	
Invaded and non-invaded LUCAS 2018 points with a given species	Invaded	Non-invaded	Invaded	Non-invaded	Invaded	Non-invaded	Invaded	Non-invadedd
	80	4076	175	3981	71	4085	297	3859
Number of total LUCAS 2018 points in Hungary	4156							

Table 2 Aggregated LULC categories from the CLC and historical LULC datasets

LULC categories of historical military maps			Aggregated CORINE LULC categories
1	Urban / Built-up		1.1 Urban fabric 1.2 Industrial, commercial and transport units 1.3 Mine, dump and construction sites 1.4 Artificial, non -agricultural vegetated areas
2	Agriculture		2.1 Arable land 2.2 Permanent crops 2.4 Heterogeneous agricultural areas
3	Grassland and shrubs		2.3 Pastures 3.2 Associations of shrubs and / or herbaceous vegetation associations
4	Forest		3.1 Forest
5	Wetlands		4.1 Inland wetlands
6	Water		5.1 Inland waters
7	Bare land		3.3 Open spaces with little or no vegetation

changes that occurred during the historical (1848–1990) and recent (1990–2018) periods. Then, the difference in LULC change frequencies between invaded and non-invaded LUCAS points could be calculated for each invasive plant species:

$$DF = \frac{\left\{\left(\frac{\{hc_i\}}{\{hc_i+nc_i\}}\right)-\left(\frac{\{hc_{ni}\}}{\{hc_{ni}+nc_{ni}\}}\right)\right\}}{pmc}\times 100 \quad (1)$$

where DF is the difference in LULC change frequencies of invaded and non-invaded LUCAS points for a given invasive plant species (%), hc_i is the number of invaded LUCAS 2018 points with a LULC change for a given period (historical, recent or all), nc_i is the number of LUCAS 2018 points with no LULC change for the given period, hc_{ni} is the number of non-invaded LUCAS 2018 points with a LULC change for the given period, nc_{ni} is the number of non-invaded LUCAS 2018 points with no LULC change for the given period and *pmc* is the maximum possible LULC changes for a given period (historical: 3, recent: 2, all: 5).

Equation (1) was used to establish the average LULC change frequencies in historical and recent periods and to analyse how they influenced the current (2018) distributions of the four invasive plant species in Hungary.

If DF value (%) is positive, then the LUCAS points invaded with a given plant have a higher frequency of LULC type change over the study period than those not invaded with that species. If DF is negative, then the number of LULC changes at LUCAS points invaded by that species is less than the number of LULC changes at non-invaded LUCAS points over a given time-period.

LULC change intensity

To compare the probabilities of LULC changes in areas invaded and not invaded by an invasive plant species, we used odds ratio analysis, a statistical method widely used in other studies on biological invasions (Huebner and Tobin 2006; Milbau and Stout 2008; Miller et al. 2021). To analyse changes in Land Use/Land Cover (LULC), the employment of odds ratio analysis was chosen, a method based on contingency tables that provides a clear summary of how two categorical variables interact. The objective of this study was to quantify the association between two binary variables (Bland and Altman 2000): the presence or absence of invasive plants, and LULC change or no LULC change. The odds ratio was selected as it is specifically designed to compare the relationship between categorical variables and focuses solely on their association (Rudas 1998). This methodological approach effectively quantifies the strength of preference within each category, with the odds ratio providing a comparative metric of these strengths (Rudas 1998). The interpretation of odds

ratios for categorical variables is relatively straightforward, with greater deviations from 1 indicating stronger relationships relative to a reference category (Dawson et al. 2009; Milbau and Stout 2008; Ritters et al. 2018). It is evident that the odds ratio is a suitable metric for the purposes of this research, as demonstrated by the available theoretical information and the aims of our analysis.

We defined the odds ratio as follows:

$$OR = \frac{\left\{\left(\frac{hc_i}{nc_i}\right)\right\}}{\left\{\frac{hc_{ni}}{nc_{ni}}\right\}} \quad (2)$$

where OR is the odds ratio, hc_i is the number of LUCAS 2018 points invaded by a given invasive species with a LULC change during a given period (historical, recent or all), nc_i is the number of invaded LUCAS 2018 points with no LULC change during the given period, hc_{ni} is the number of non-invaded LUCAS points with a LULC change during the given period, nc_{ni} is the number of non-invaded LUCAS points with no LULC change during the given period.

The odds ratio compares the probability of LULC changes occurring in areas invaded by an invasive species with the probability of LULC changes occurring in non-invaded areas. An odds ratio greater than 1 indicates a higher probability of LULC change in invaded areas. The LULC change intensity of the LULC categories has been defined in terms of hemeroby, because it reflects LULC changes due to human impact (Yorkina et al. 2022). The abundance of species could also be linked to forest management intensity (Winter 2012) because anthropogenic disturbances in forests often lead to habitat loss and reduced biodiversity (Cegielska et al. 2018; Yuan et al. 2016). The LULC categories are organised according to their anthropogenic intensity (Table 3), where category 1 (Urban/Built-up areas) represents the highest intensity of human use. Category 2 (Agriculture) and 3 (Grassland and shrubs) represent progressively lower levels of intensity. Overall, lower LULC category value (with 1 being the most intensive and 7 the least) indicates a higher degree of human influence on the landscape. We defined four trends for the LULC intensity of a given period (historical, recent or all): no change, decreasing steadily, increasing steadily and mixed intensity. For our LULC change intensity analysis, we used odds ratios along with trends in LULC change intensities at invaded and non-invaded points for the investigated invasive plant species. The aim was to determine which LULC change intensity types are more associated with the presence of invasive species. For example, when we calculated the odds ratio value for *Ailanthus altissima* in the historical period we compared the number of invaded versus non-invaded points located in areas with decreasing LULC change intensity to the number of points located in all other LULC change intensity types (i.e., increasing intensity, mixed intensity, and no change). This allowed us to determine how many times higher the odds were for an invasive species to occur in areas of decreasing LULC intensity compared to other types of LULC change.

As illustrated in Table 3, the term 'bare land' is classified with the lowest LULC intensity due to its

Table 3 Change intensities of LULC categories and defined trends

LULC category		LULC change intensity		
		Increasing intensity of LULC	Decreasing intensity of LULC	Mixed intensity of LULC
1	Urban / Built-up	↑	↓	↓↑
2	Agriculture			
3	Grassland and shrubs			
4	Forest			
5	Wetlands			
6	Water			
7	Bare land			

current state, which is characterised by minimal vegetation coverage and high level of human activity. Bare land may result from past high-intensity human use, such as deforestation, human-induced degradation or environmental events like forest fires. A total of 3864 LULC change trajectories were analysed, of which only 12 (0.31%) involved bare land (Appendix 1.). The transition from bare land to other LULC categories, predominantly to agriculture or grassland and shrubs, and on one occasion grassland to shrubs to bare land. Consequently, the present study focused mainly on cases where bare land changed to another LULC type, and only once where land changed to bare land. This suggests that the low-intensity classification of bare land does not significantly affect the results, and its transition to more intensive LULC categories supports this interpretation.

Results

LULC change frequency

The LULC change frequency results (Fig. 3) showed which period had the greatest impact on the current (2018) distributions of the invasive plant species. The LULC change frequency was species-dependent, and the mean LULC change frequencies differed between invaded and non-invaded points. With the help of our formula (Eq. 1) we calculated how often LULC changes have occurred during the analysed time periods (historical, recent, all), and the goal was to compare how frequently LULC changes happened at invaded (where invasive plants are present) and non-invaded (where invasive plants are absent) LUCAS points. *Ailanthus altissima*, *Elaeagnus angustifolia*

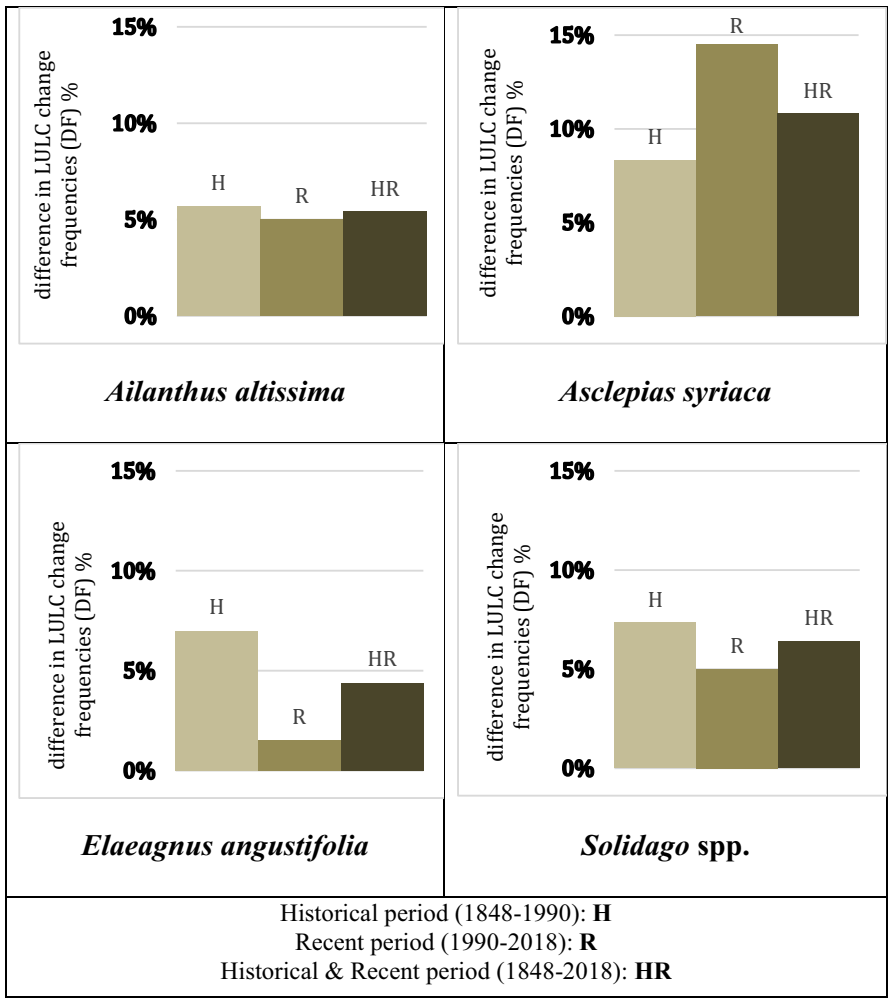


Fig. 3 Difference in LULC change frequencies of invaded and non-invaded LUCAS points for a given invasive plant species (%)

and *Solidago* spp. had higher LULC change frequency at invaded points in the historical period, while *Asclepias syriaca* was more affected by LULC changes in the recent period. Our results indicate that LULC changes had the most pronounced impact on the distribution of *Asclepias syriaca*, as it exhibited the highest LULC change frequency percentages among the investigated plant species (Fig. 3).

Since a positive DF value (%) was obtained for all invasive plant species studied in all of three time periods (historical, recent, all), therefore invaded LUCAS points had a higher frequency of LULC change than non-invaded points, it can be concluded that, although to different weights, change in LULC played a significant role in the current (2018) occurrence of *Ailanthus altissima, Asclepias syriaca, Elaeagnus angustifolia* and *Solidago* spp.. Invaded and non-invaded LUCAS points are separated in the first part of the equation (Eq. 1), where we first calculated the proportion of invaded LUCAS points that experienced LULC changes out of the total invaded LUCAS points and also the proportion of non-invaded LUCAS points that experienced LULC changes out of the total non-invaded LUCAS points. The subsequent stage of the research was to calculate the difference between these two proportions to determine whether LULC changes were more or less frequent at the location of invaded LUCAS points compared to non-invaded LUCAS points with a given species.

If a specific period, whether it pertains to the historical or the recent, exerts a more significant influence on the distribution of invasive plants, it can be deduced that changes in LULC during that period may have contributed to a greater extent to the current occurrence of these species.

LULC change intensity

The odds ratio analysis indicated that invasive species were more likely to invade areas surrounding LUCAS points with LULC changes in the recent period compared to the historical time period (Fig. 4). The odds ratio values consistently exceeded 1 across all invasive plant species and time periods. This finding suggests that LULC changes are more frequently associated with invaded LUCAS points than with non-invaded ones, indicating a higher likelihood of LULC changes in areas where invasive species are present.

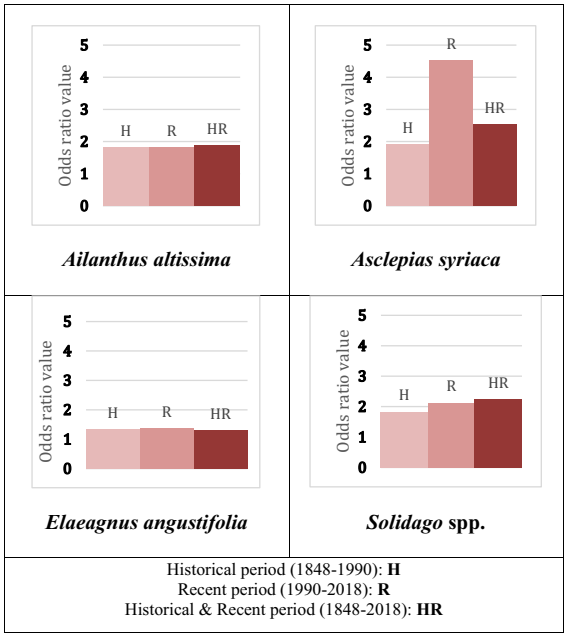


Fig. 4 Odds ratio analysis comparing LULC changes with the presence of each invasive plant species during three time periods. An odds ratio value greater than 1 indicates a stronger association between LULC change and the occurrence of the given invasive species

The odds ratio was substantially higher for *Asclepias syriaca* in areas with LULC changes in the recent period, which agrees with the LULC change frequency results (Fig. 3). In contrast, the odds ratios for *Ailanthus altissima* (Fig. 4) and *Elaeagnus angustifolia* (Fig. 4) remained relatively constant for all periods with only slight increases in the recent and all (historical + recent) time periods. The odds ratios were notably higher for *Asclepias syriaca* and *Solidago* spp. with LULC changes in the recent time (Fig. 4).

Ailanthus altissima

An odds ratio of above the value of 1 indicates that LULC changes have a more significant impact on invaded points than on non-invaded points for a given invasive plant species. For *Ailanthus altissima* (Table 4), the highest odds ratio was observed with decreasing LULC change intensity in the historical and all (historical + recent) periods. However, the highest odds ratio was observed with the increasing and mixed LULC change intensity trends in the recent period. The odds ratio

Table 4 Odds ratios and trends of LULC change intensities at invaded and non-invaded points for the investigated invasive plant species

Time periods	LULC change intensity types	*Ailanthus altissima*	*Asclepias syriaca*	*Elaeagnus angustifolia*	*Soldago spp.*
		Odds ratio values			
Historical LULC change (1848–1990)	No change in LULC intensity	*0.55*	*0.52*	*0.74*	*0.55*
	Steadily decreasing LULC intensity	**1.69**	**1.59**	*0.69*	**2.74**
	Steadily increasing LULC intensity	**1.32**	**1.13**	*0.79*	*0.92*
	Mixed LULC intensity	**1.26**	**1.69**	**2.24**	**1.42**
Recent LULC change (1990–2018)	No change in LULC intensity	*0.55*	*0.22*	*0.73*	*0.47*
	Steadily decreasing LULC intensity	**1.13**	**5.93**	*0.82*	**1.77**
	Steadily increasing LULC intensity	**2.36**	**1.82**	**1.78**	**2.60**
	Mixed LULC intensity	**2.46**	**2.87**	*0*	*0.62*
Historical & Recent LULC change (1848–2018)	No change in LULC intensity	*0.53*	*0.39*	*0.77*	*0.44*
	Steadily decreasing LULC intensity	**1.67**	**1.82**	*0.68*	**2.52**
	Steadily increasing LULC intensity	**1.30**	*0.57*	*0.63*	*0.93*
	Mixed LULC intensity	**1.26**	**3.06**	**2.20**	**1.69**

Values are presented in a single table for comparative purposes

Values below 1 have italic display; values above 1 have bold display

results indicated that the no change in LULC had a negligible effect. In the recent period (1990–2018), the decreasing LULC change intensity trend was common in Hungary owing to the possible abandonment of agricultural lands. This contrasts with the results for *Ailanthus altissima*, which was most likely to invade points with increasing and mixed LULC change intensity trends in the recent period.

Asclepias syriaca

For *Asclepias syriaca*, the odds ratios were high in areas with decreasing and mixed LULC change intensity trends in the historical and recent periods (Table 4). The highest odds ratio was 5.93 in areas with a decreasing trend in the recent period. Thus, the decreasing LULC change intensity trend was the primary influencing factor for the distribution of *Asclepias syriaca.*

Elaeagnus angustifolia

For *Elaeagnus angustifolia*, the odds ratio was more than 2 in areas with the mixed LULC change intensity trend in the historical period (Table 4) period. In contrast, the odds ratio was below 1 for all other LULC change intensity trends. The mixed trend describes a situation with no clear continuous decreasing or increasing intensity in LULC changes. In the historical period, an odds ratio exceeding the value 2 for mixed LULC change intensity indicates that the likelihood of mixed, rapidly varying LULC was more than twice as high for invaded points, compared to non-invaded points. This suggests that the invasion of *Elaeagnus angustifolia* (Table 4) was mostly influenced by complex mosaic LULC changes rather than stable (decreasing or increasing) intensity changes. However, during the recent period, increasing LULC change intensity trend had the highest odds ratio value.

Solidago spp.

For *Solidago* spp., the highest odds ratio of 2.74 was observed in areas with a decreasing LULC change intensity trend in the historical period (Table 4). This result indicates a reduction in the severity of anthropogenic LULC changes. These findings suggest that declining human influence on LULC change intensity may have shaped the species' distribution patterns in the historical time period. In the recent period (1990–2018), the highest odds ratio of 2.6 was

observed in areas with an increasing LULC change intensity trend. However, it was observed that areas demonstrating an increasing trend during the historical period exhibited an odds ratio of 0.92. This finding suggests a substantial shift in the behaviour of anthropogenically impacted sites, characterised by an increase in LULC change intensity. The mixed LULC change intensity trend did not have a significant effect on *Solidago* spp. in the recent period.

Discussion

In order to evaluate the relative influence of historical versus recent LULC change frequency, a comparison was made of the responses of four invasive plant species with differing ecological strategies. The analysis revealed that historical changes in LULC had a more pronounced impact on three of the four species, with *Asclepias syriaca* being the exception, responding more strongly to recent changes. The observed pattern, in which odds ratios consistently exceeded in areas subjected to LULC changes across nearly all investigated species (Fig. 4), underscores the statistically significant and widespread influence of LULC transformations on invasive species occurrence. This fit into the literature that identifies anthropogenic land disturbances and LULC dynamics as key drivers in the facilitation, establishment, and proliferation of invasive plant species (Huston 2004; Sousa 1984; With 2002). As regarding LULC change intensities, the decreasing trend, which can be explained by land abandonment (Lenda et al. 2023; Pyšek and Prach 2003; Valkó et al. 2016) was the most significant. Nevertheless, an escalating degree of LULC change intensity has the potential to disrupt the integrity of the land, thereby facilitating the propagation of many invasive plant species (Grez et al. 2013). This phenomenon can be exemplified by the process of clear-cutting, which creates isolated, fragmented habitats that are conducive to the successful establishment of invasive species (Saunders et al. 1991). Anthropogenic disturbances such as historical or recent LULC changes frequently disrupt ecological communities, which facilitate the spread of invasive species by reducing biodiversity and soil health (Calinger et al. 2015; Mcdonald et al. 2013; Purswani et al. 2020; Thomas and Moloney 2015).

Each plant has distinctive characteristics that influence its ability to adapt to environmental changes, both natural and induced by humans (Lundgren et al. 2004).

Ailanthus altissima exhibits a marked capacity to thrive in urban and suburban landscapes, where its rapid proliferation reflects its broad ecological tolerance and aligns with earlier findings documenting its success in highly anthropogenically modified environments (Balogh et al. 2023; Szilassi et al. 2021). The spatial distribution patterns of the species suggest that the timing and intensity of LULC changes significantly shape its invasion dynamics. The species was most prevalent in areas experiencing a decreasing trend in LULC change intensity during the historical period and mixed or increasing intensity more recently (Table 4). This is consistent with its known adaptability to fluctuating and contaminated habitats such as transportation corridors, post-industrial zones, and agricultural margins. This resilience, coupled with its tolerance to pollutants and its ability to exploit disturbances—including logging and land-use intensification—further underscores its role as a disturbance-adapted invader whose spread is tightly linked to both historical legacies and ongoing land transformation processes (Erdélyi et al. 2021; Szigeti et al. 2023).

Asclepias syriaca was predominantly associated with areas characterised by decreasing or mixed trends in LULC change intensity (Table 4), a pattern that reflects its linkage to socio-economic transformations such as land abandonment and privatisation, particularly in post-socialist landscapes (Meinhardt et al. 2024; Szilassi et al. 2019). Its capacity to respond rapidly to disturbances is attributable to its high reproductive potential, which includes wind-dispersed seeds and vigorous vegetative propagation. This enables it to colonize a wide range of disturbed habitats, such as roadsides, fallow lands, and sandy soils (Bagi 2008; Csontos et al. 2009). The species' capacity for invasiveness is further enhanced by its resilience to control measures, its ability to tolerate diverse edaphic conditions, and its potential for climate-induced range expansion. These factors have contributed to its persistent spread across the Kiskunság region since the 1960s, continuing well into recent decades (Berki et al. 2023; Mojzes and Kalapos 2015; Szilassi et al. 2019; Tokarska-Guzik and Pisarczyk 2015).

The proliferation of *Elaeagnus angustifolia* was most pronounced in areas experiencing increasing LULC change intensity, particularly within riparian and wetland environments (Table 4). This finding corroborates previous research highlighting the role of intensified anthropogenic activities, especially in agriculture and water management, in facilitating its expansion (Borsukevych et al. 2023; Madurapperuma et al. 2013). While recent changes in LULC appeared to exert limited influence, the species' spread during the historical period was strongly associated with heterogeneous, mixed-intensity LULC dynamics. This suggests that the cumulative effects of fluctuating disturbance regimes rather than uniform LULC trends (Szilassi et al. 2022) may drive its invasion. Such regimes, shaped by recurring anthropogenic interventions, not only create suitable ecological niches for establishment but also may themselves be increasingly restructured by invasive species like *Elaeagnus angustifolia*. Therefore, invasive species can act as both products and drivers of landscape transformation, altering successional trajectories and reinforcing feedback loops in LULC change (Keane 2013; Mack and D'Antonio 1998).

The expansion of *Solidago* spp. was most prominent in areas characterised by increasing LULC change intensity (see Table 4), aligning with previous research that highlights the species' affinity for highly anthropogenically altered environments, including along road networks and regions experiencing urbanisation or agricultural intensification (Gusev 2018). Concurrently, its substantial presence in regions exhibiting decreasing LULC change intensity underscores the role of land abandonment—particularly during the 1990s—in establishing conducive conditions for colonisation and propagation, as documented in earlier studies (Lenda et al. 2023; Valkó et al. 2016). This dual pattern suggests that *Solidago* spp. is not only highly responsive to ongoing disturbance but also capable of exploiting the ecological inertia following socio-economic transitions, thereby thriving across a broad disturbance spectrum and contributing to persistent vegetation change in transitional landscapes.

Beyond the species-specific findings, the present study provides broader insights into how dynamics of LULC influence plant invasions. By selecting four invasive species with differing ecological traits, it was demonstrated how variations in life form, dispersal strategy, and habitat preference affect responses to both historical and recent LULC changes. These two phenomena underscore the necessity of incorporating species-specific ecological data and long-term LULC legacy into invasion risk assessments.

Concurrently, the consistent correlation between the frequency of LULC change and invasion risk across most species indicates that our analytical framework—which integrates temporal LULC change detection with spatial modelling of invasion occurrence—can be applied more extensively. This approach has the potential to be transferable to other invasive species or regions, particularly those experiencing rapid land use transformation, where early detection and adaptive management are critical.

Furthermore, the method can be expanded through the utilisation of LUCAS imagery or similar data sources to detect invaded versus non-invaded sites, either manually or through automated approaches such as AI-based image classification. Once invasion status has been determined, intersecting with historical and recent LULC layers enables the construction of a similar, comprehensive dataset for modelling and prediction.

In conclusion, incorporating historical landscape dynamics into invasion studies enhances our understanding of how cumulative anthropogenic disturbances shape present and future patterns of biological invasions, supporting more proactive and spatially informed management strategies.

Conclusion

The results of the present study demonstrate that the frequency of Land Use/Land Cover (LULC) change exerts a significant and species-specific influence on the distribution of invasive plant species. Historical LULC changes exhibited a notably stronger effect on the majority of the studied species, with the exception of *Asclepias syriaca,* whose distribution was more closely linked to recent LULC changes. The findings underscore the efficacy of the odds ratio analysis as a valuable tool in invasion biology, offering a clear metric for quantifying the association between LULC dynamics and plant invasions. The results emphasise the long-term impact of anthropogenic landscape transformation and underscore the importance of

considering both historical and recent LULC patterns in invasive species management. The findings promotes the fact that past human activities and varying intensities of LULC changes can contribute to triggering and facilitating the spread of invasive species. The analysis indicates that most significantly herbaceous plants such as *Asclepias syriaca and Solidago* spp. may necessitate particularly targeted management in areas experiencing land abandonment or urban expansion. The methodological framework applied here offers a useful approach for identifying species-specific invasion risks, particularly when long-term spatial data are available. Future research will focus on incorporating the LUCAS 2022 dataset to enhance the spatial resolution and predictive capacity of invasion assessments.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Appendix 1: All LULC change types throughout the periods

		1_2 (1829-66 –1930-42)		2_3 (1930-42 –1955-56)		3_4 (1955-56 –1990)		4_5 (1990 –2000)		5_6 (2000 –2018)	
12	Urban / Built-up - Agriculture			2	0,25%	35	3,49%	1	0,50%	5	1,26%
13	Urban / Built-up - Grassland and shrubs					4	0,40%			2	0,51%
14	Urban / Built-up - Forest					2	0,20%			2	0,51%
21	Agriculture - Urban / Built-up	48	3,25%	25	3,18%	133	13,25%	11	5,47%	50	12,63%
23	Agriculture - Grassland and shrubs	193	13,08%	161	20,46%	194	19,32%	63	31,34%	105	26,52%
24	Agriculture - Forest	59	4,00%	57	7,24%	141	14,04%	10	4,98%	37	9,34%
25	Agriculture -Wetlands	10	0,68%	2	0,25%	5	0,50%				
26	Agriculture - Water	1	0,07%			6	0,60%			2	0,51%
31	Grassland and shrubs - Urban / Built-up	34	2,30%	12	1,52%	25	2,49%	1	0,50%	9	2,27%
32	Grassland and shrubs - Agriculture	631	42,75%	325	41,30%	217	21,61%	33	16,42%	34	8,59%
34	Grassland and shrubs - Forest	47	3,18%	70	8,89%	94	9,36%	36	17,91%	70	17,68%
35	Grassland and shrubs - Wetlands	26	1,76%	17	2,16%	20	1,99%	2	1,00%		
36	Grassland and shrubs - Water	3	0,20%	4	0,51%	4	0,40%				
37	Grassland and shrubs - Bare land					1	0,10%				
41	Forest - Urban / Built-up	1	0,07%	3	0,38%	6	0,60%			2	0,51%
42	Forest - Agriculture	200	13,55%	31	3,94%	42	4,18%	1	0,50%	1	0,25%
43	Forest - Grassland and shrubs	69	4,67%	32	4,07%	31	3,09%	30	14,93%	71	17,93%
45	Forest - Wetlands	1	0,07%			1	0,10%			1	0,25%
46	Forest - Water	1	0,07%			2	0,20%				
51	Wetlands - Urban / Built-up					1	0,10%				
52	Wetlands - Agriculture	58	3,93%	11	1,40%	9	0,90%	1	0,50%		
53	Wetlands - Grassland and shrubs	61	4,13%	27	3,43%	11	1,10%	11	5,47%	4	1,01%
54	Wetlands - Forest	2	0,14%	1	0,13%	3	0,30%			1	0,25%
56	Wetlands - Water	1	0,07%			1	0,10%				
61	Water - Urban / Built-up					3	0,30%				
62	Water - Agriculture	4	0,27%			7	0,70%				
63	Water - Grassland and shrubs	11	0,75%	4	0,51%	2	0,20%	1	0,50%		
64	Water - Forest	1	0,07%			4	0,40%				
65	Water - Wetlands	3	0,20%	3	0,38%						
72	Bare land - Agriculture	7	0,47%								
73	Bare land - Grassland and shrubs	4	0,27%								

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