Review article – *Pregledni rad*

Forest Fire Risk Mapping by Kernel Density Estimation

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Abstract – Nacrtak

When evaluating wildland fires, well prepared forest fire risk maps are regarded as one of the most valuable tools for forest managers, and during the production stage of these maps, association between historical fire data and other factors, such as topographic, anthropogenic and climatic, are often required. One of the most encountered problems in forest fire risk analyses is the fact that historical fire data, the dependent variable, are generally in point format, whereas other factors, the independent variables, are often expressed in areal units and available in raster format. Kernel density estimation is a widely preferred method for converting historical fire data into a continuous surface. In this study, kernel density estimate of forest fire events in the Middle East Technical University (METU) campus, in Ankara, Turkey, between 1993 and 2009, were obtained by using different bandwidth choices. Kernel density maps with regard to seasons and years were also produced and the final result was expressed as mean density value in each polygon of the study area. Actions that should be taken in high-risk areas were given on the basis of the results obtained.

Keywords: wildfire, Kernel density estimation, Kernel bandwidth, METU campus, mean random distance

1. Introduction – *Uvod*

Forests have various crucial functions such as maintaining the balance of climate, conserving soil, water, and biodiversity; however, they have been threatened by a number of destructive factors, like droughts, insect infestations, diseases, encroachment for agricultural applications, and unplanned settlements. However, among these factors, fire events are the most important disturbance factor in forests.

Forest fires in Boreal and Mediterranean landscapes of Europe have always coexisted with human activities and been considered as one of the main disturbance agents, due to the abundance of coniferous trees and highly flammable ground vegetation, especially during hot and dry summer seasons, which favor the occurrence of fire ignition and propagation. Every year, millions of hectares of forested land are burned, which causes a wide variety of effects such as atmospheric emissions, soil erosion, biodiversity loss and drainage alterations. The use of fire for a number of activities such as grazing, agriculture and hunting has significantly modified fire regimes, primarily in the Mediterranean region. As a result of the recent increase in population density and extensive use of natural and forest regions for recreation, the number of human-caused fires has increased (Barbosa et al. 2009, Larjavaara et al. 2005, Morgan et al. 2001, Chuvieco et al. 2005).

Being located in Mediterranean climate zone, forest fires are also one of the most important factors that threaten forests in Turkey. The period from June to October is observed as high-season for forest fire events, and especially from July to August with very high temperatures, very low humidity and effective wind. In Turkey, 2 135 forest fires occurred in 2008, devastating a total area of 29 749 ha, 23 577 ha of which were forest land (JRC 2009).

An increase in the trend of occurrence of extreme natural hazards and disasters directly or indirectly related to wildland fires has been observed and fatal accidents resulted in human casualties have occurred in these events for the past several years as in the United States (2003), Canada (2002 – 2003), Greece (2000), Australia (2002 – 2003), and more recently the large fires took place in Iberian Peninsula and France (2003 – 2006). When viewed within this frame, to design and implement operational projects in order to successfully face forest fires for prevention, forecast and suppression are important priorities of fire fighting organizations (Balatsos et al. 2007).

Due to the fact that objective tools are required in pre-fire planning in order to monitor when and where a fire is more likely to occur, or when it will have more negative effects, the most important and critical part of fire prevention is the evaluation of fire risk (Chuvieco et al. 2010). Two crucial aspects of fire management determine the factors influencing the occurrence of fire and understanding the dynamic behavior of fire, and therefore a well-prepared fire risk map is needed in order to evaluate forest fire problems and make decisions on solution methods. Wildfire risk maps would help the managers in planning the main roads, subsidiary roads, inspection paths, etc. and may lead to a reliable communication and transport system to efficiently fight small and large forest fires. Moreover, fire risk mapping definitely constitutes strategic operational advantage to develop a proper decision support system, in which the necessary actions can be taken according to their spatial and temporal priorities inside the high risk zones. Based on the risk zoning in forest fire maps, more efficient allocation of available resources can also be achieved for more effective fire prevention and suppression (Jaiswal et al. 2002, Balatsos et al. 2007).

In order to have a realistic fire risk estimate, the history of fire events in terms of occurrence, frequency and spatial distribution must be available to fire managers. World and/or national fire atlases are very useful sources of information, where the fire event is recorded by means of geographical position and other details. Especially for small fires, data related to perimeters, size and severity are mostly not included in the fire atlases, and even countries significantly affected by forest fires do not have proper data on fire incidence. Besides, a fire event is generally registered by x and y coordinates, totally loosing its surface nature and its spreading behavior. The assumption of considering each fire event as a single point process with a spot nature is currently valid in the Mediterranean fire regimes, where small dimension of fire events and broad pixel resolution of sensors do not allow a surface recording but only an event point process recognition, leading to serious positional inaccuracies since the exact location of ignition points are usually not known (Amatulli et al. 2005, Koutsias et al. 2004). Therefore, a reliable method is necessary to convert ignition point dataset into a continuous surface representation of the fire ignition density as a source of data to create fire occurrence maps and fire risk maps. Another advantage of the use of a continuous density is the possibility to integrate this information with other types of area data, especially in the framework of fire risk assessment (Amatulli et al. 2005, Amatulli et al. 2007, De la Riva et al. 2004).

There are several interpolation techniques to convert data from point observations to continuous fields. Although most techniques necessitate a variable to be estimated as a function of location, when dealing with positional uncertainties of historical fire data and converting them into a continuous surface, Kernel Density Estimation (KDE), a nonparametric method, has been widely used in many studies recently.

The study by Chuvieco et al. (2005) presented the results of the fire danger component of the Spread project, which was a European funded project for assessing fire risk conditions at several spatial scales. A GIS database covering all the EUMed countries (Portugal, Spain, Italy, Greece and Southern France) was developed within the frame of this project. In the study, KDE approach was used in order to produce continuous fire occurrence density surfaces from the location of ignition points for the representation of fire danger associated to human factors. According to the results of the study, the final product shows promising potential for helping fire managers in simulating different danger scenarios, as well as for obtaining a single evaluation of fire danger conditions for the whole EUMed area.

The spatial distribution patterns of the historical forest fires in DaXingAn mountainous area in the northeast of China were studied by Liu et al. (2010). In the study, Ripley's *K* function and KDE method were combined to reveal the spatial distribution patterns of human-caused and lightning-caused forest fires. The analysis showed that this kind of spatial distribution information is very useful for forest managers to predict and manage forest fires.

In the study of Kuter and Kuter (2010), a wildfire risk map was generated for Bodrum Forest Sub-district in Muğla city, located on the south-west coast in the Mediterranean region of Turkey. Different layers with associated risk ratings and weights regarding anthropogenic, topographic and vegetation factors were combined through GIS overlay analysis, and then using the historical fire data between 1999 and 2009, a continuous density map of fire events in the study area was obtained by KDE method.

KDE approach was also used in the study of Kalabokidis et al. (2007) for analyzing the wildfire dynamics of Greece, which is in the Mediterranean ecosystem. In their paper, they focused on spatial distribution of long-term fire patterns versus physical and anthropogenic elements of the environment that determine wildfire dynamics in Greece. Within a GIS environment, a spatial database, in which logistic regression and correspondence analysis were carried out, was developed and managed. Cartographic fire data were statistically correlated with the basic physical and human geography factors in order to estimate the degree of their influence at landscape scale. Since the original data of wildland fire ignition points, control points and livestock activities were provided as point observations, KDE method was applied in the study to transform these point observations into continuous density surfaces.

The main framework of this study is to reveal the spatiotemporal patterns of forest fire events in METU campus, which has suffered from high fire incident rate, by using KDE method. As a first step, the necessary spatial database was built by combining the historical fire data (between 1993 and 2009) and digital stand map of the study area in ArcInfo environment. Two different bandwidth selection methods were applied; mean random distance and subjective choice. After determining the final bandwidth value, KDE maps with respect to seasons and years were produced. The final density map was converted into one that shows the mean density value in each compartment of the study area.

2. Materials and Methods – *Materijal i metode*

2.1 Study Area – *Područje istraživanja*

METU campus is located at the south-west of Ankara, the capital of Turkey, and it covers an area of 40.52 km^2, 30.4 km^2 of which is forested, and in 1995 it was declared as the natural conservation area by the Republic of Turkey, Ministry of Culture (Fig. 1). The campus serves about 25000 people including students, academic and administrative staff. The campus area is also important since it hosts Lake Eymir, one of the rarest natural recreational areas in the vicinity of Ankara. The dominant tree species in the campus are *Pinus nigra, Pinus syilvestris, Cedrus libani, Quercus* sp. and *Populus* sp. (METU APFF 2009). Due to high anthropogenic pressure and fire-prone tree species, forested land in the campus is a high fire risk area and as a result it was chosen as the study area.

2.2 Data – *Podaci*

Stand map of the study area in digital format (in ED50 datum, UTM zone 36N projection) and forest fire data of METU campus between 1993 and 2009 were obtained from the General Secretariat of METU. According to the historical fire data, there were 80 fire ignition points in the study area in the mentioned period.

The stand map consists of 211 polygons, also called »*compartments*«, and even though the exact positions of fire ignition points were not available, the number of ignition points in each compartment was acquired from the historical fire data. Then, the historical fire data were combined with the digital stand map in ArcInfo environment, and the number of fire ignition points in each compartment was assigned to that compartment as the attribute value. As a next step, a random distribution of 80 ignition points was obtained in the study area by considering the mean distance to the nearest neighbor by ArcInfo. The mean distance to the nearest neighbor is also known as »*inhibition distance*« and defines the distance between a point and its nearest neighbor that would be expected if the individual point observations were randomly distributed, and given by (Clark and Evans 1954):

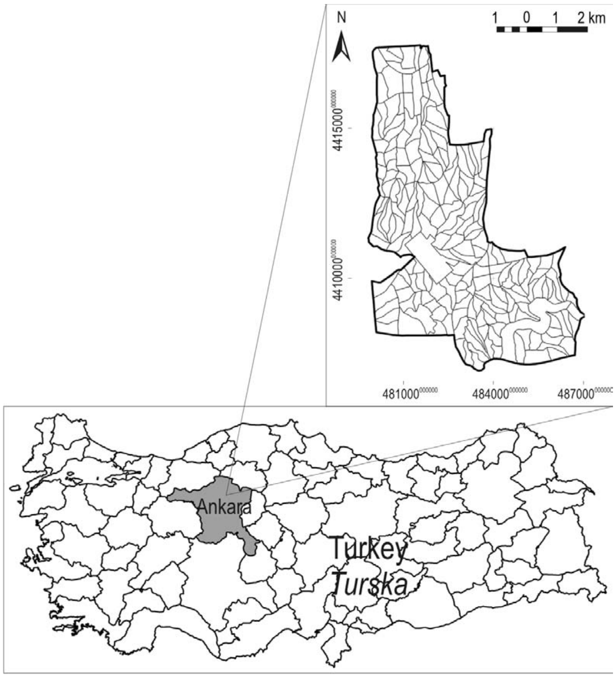

Fig. 1 Location of study area
Slika 1. *Položaj područja istraživanja*

$$\hat{r}_E = \frac{\sqrt{k}}{2\sqrt{\rho}} \tag{1}$$

Where:

- ρ density of the observed distribution expressed as the number of events per unit of area,
- k number of sectors in a circle of an infinite radius surrounding the point from which measurements of distance are taken, and generally a single sector is sufficient for the description and comparison of spatial relations in most natural populations.

2.3 KDE Calculations – *Izračun KDE (procjene Kernelove gustoće)*

KDE for multivariate case is mathematically defined by (Amatulli et al. 2007, De la Riva et al. 2004, Koutsias et al. 2004, Silverman 1998):

$$\hat{f}(x) = \frac{1}{nh^d} \sum_{i=1}^{n} K \frac{1}{h}(x - X_i) \qquad (2)$$

Where:

n number of point observations,

h bandwidth,

K kernel function,

x a vector of coordinates that represent the location where the function is estimated,

X_i vectors of coordinates that represent each point observation,

d number of dimensions in space.

A kernel can be selected from a variety of functions, for example normal distribution, triangular function, quartic function, Epanechnikov, etc (De la Riva et al. 2004). In this study, Epanechnikov kernel, which is default in ArcInfo, is used and it is defined by (Silverman 1998):

$$K_e(x) = \begin{cases} \frac{1}{2} C_d^{-1}(d+2)(1 - x^T x) & if\ x^T x < 1 \\ 0 & otherwise \end{cases} \qquad (3)$$

The bandwidth directly influences the smoothness of the density function. If the bandwidth is narrow, a finer mesh density is obtained; otherwise, a smoother distribution density is produced with larger bandwidths, resulting in less variability between areas (Amatulli et al. 2007).

There are several methods to find the appropriate size of the bandwidth. One of them is the selection of the bandwidth subjectively by eye. This method is based on looking at several density estimates over a range of bandwidths and selecting the density that is the most suitable in some sense. This method begins with the choice of a large bandwidth and then the amount of smoothing is decreased until fluctuations that are more »*random*« than »*structural*« start to appear (Wand and Jones 1995). Subjective bandwidth choices of 250 m, 500 m, 750 m, 1000 m, 1250 m, 1500 m, and 2000 m were applied in KDE of 80 ignition points.

Another method to select the kernel bandwidth is the mean random distance (*RDmean*) calculations, and it can be based on either local or global approach. In the former, mean polygon size and mean number of ignition points per polygon is taken into account, whereas total size of the study area and total number of ignition points is considered in the latter. *RDmean* is defined as (De la Riva et al. 2004):

$$RDmean = \frac{1}{2}\sqrt{\frac{A}{N}} \qquad (4)$$

Where:

A mean polygon size,

N mean number of ignition points falling inside the polygons (for local approach).

The double of *RDmean* was recommended as the bandwidth value in previous studies (De la Riva et al. 2004, Koutsias et al. 2004). The parameters used in bandwidth calculations and bandwidth values are given in Table 1. KDE maps of 80 fire ignition points were generated using both subjective and *RDmean* approaches. Firstly, different bandwidths (250 m, 500 m, 750 m, 1000 m, 1250 m, 1500 m, 2000 m) were applied (Fig. 2) in order to select the bandwidth subjectively by eye. While there were too much smoothing in higher bandwidths, lower bandwidths produced spikier kernel density maps. Therefore, 750 m was selected as the most suitable bandwidth in the study area for the subjective method. Secondly, for the mean random distance approach, the bandwidth was calculated by using local and global mean random distance calculations and both approaches yield-

Table 1 Parameters related to bandwidth calculations
Tablica 1. *Parametri povezani s izračunavanjem širine Kernelova pojasa*

Total size of the study area, A – Ukupna površina istraživanoga područja, A	40.52 km^2
Total number of polygons – *Ukupan broj poligona*	211
Total number of ignition points, N – *Ukupan broj inicijalnih točaka zapaljenja požara,* N	80
Mean polygon size – *Srednja (prosječna) veličina poligona*	192 045 m^2
Mean number of ignition points per polygon – *Srednji (prosječni) broj inicijalnih točaka zapaljenja požara po poligonu*	0.379
Local *RDmean*, x2 – *Lokalna srednja slučajna udaljenost,* x2	712 m
Global *RDmean*, x2 – *Globalna srednja slučajna udaljenost,* x2	712 m
Subjective bandwidth choices – *širina Kernelova pojasa određena subjektivnom metodom*	250 m, 500 m, 750 m, 1000 m, 1250 m, 1500 m and 2000 m

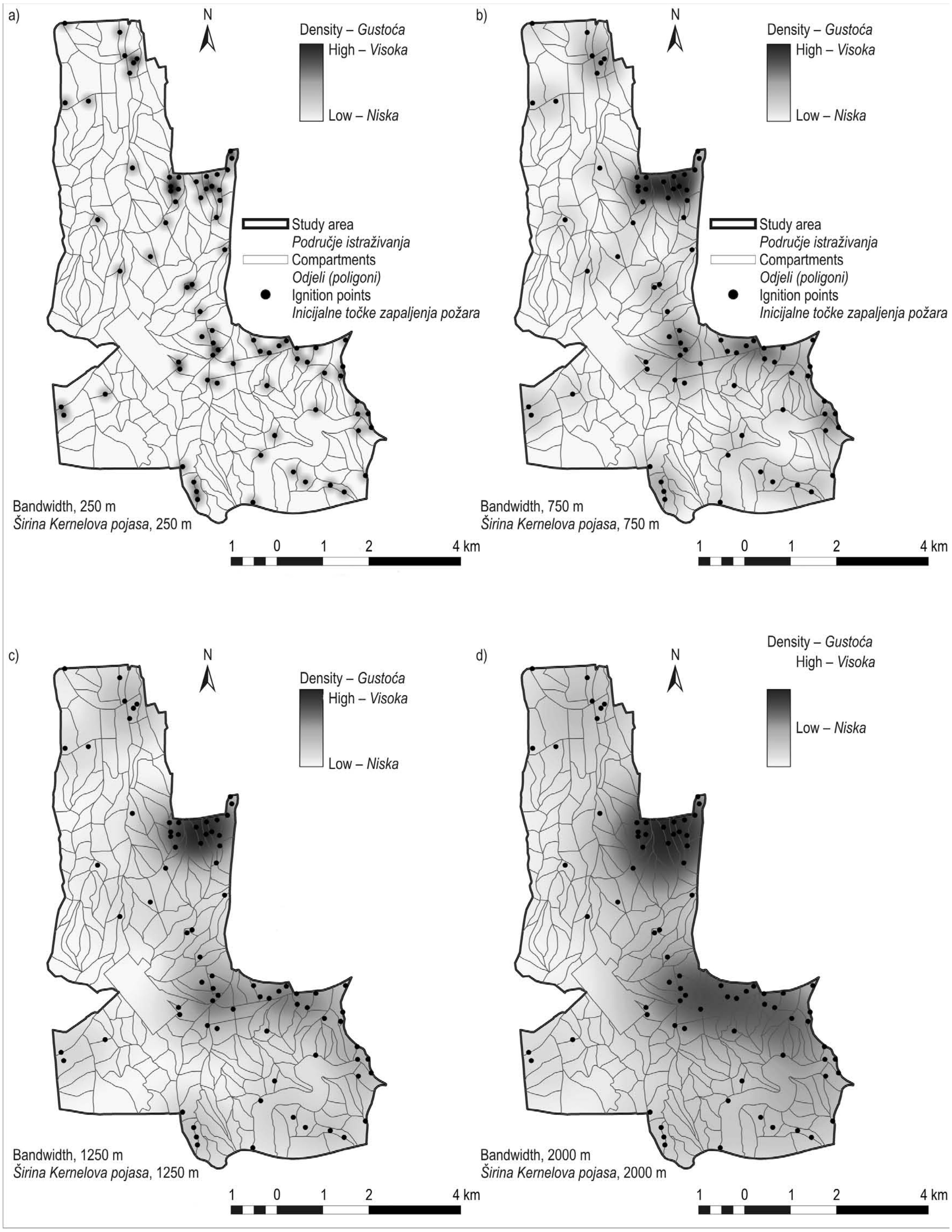

Fig. 2 KDE maps of campus fires for different bandwidths: a) 250 m, b) 750 m, c) 1250 m, d) 2000 m

Slika 2. *KDE zemljovid požara u kampusu za različite širine Kernelova pojasa: a) 250 m, b) 750 m, c) 1250 m i d) 2000 m*

ed the same bandwidth value: 712 m, which was also in compliance with the bandwidth calculated subjectively by eye. The final bandwidth value for the study area was decided to be 731 m by taking the arithmetic mean of the bandwidths found in both methods. Using the final bandwidth value, KDE maps with respect to seasons and years were obtained. As a final step, the map showing the mean density value in each compartment of the study area was generated.

3. Results – *Rezultati*

According to the seasonal KDE maps, fire events show different cluster patterns both spatially and temporally. As expected, the major portion of forest fires took place in summer season with a percentage of 61% out of 80 ignition points (Fig. 3). This can be attributed to the increase in recreational activities around Lake Eymir and at the north-east part of the campus adjacent to residential areas. It is also notice-

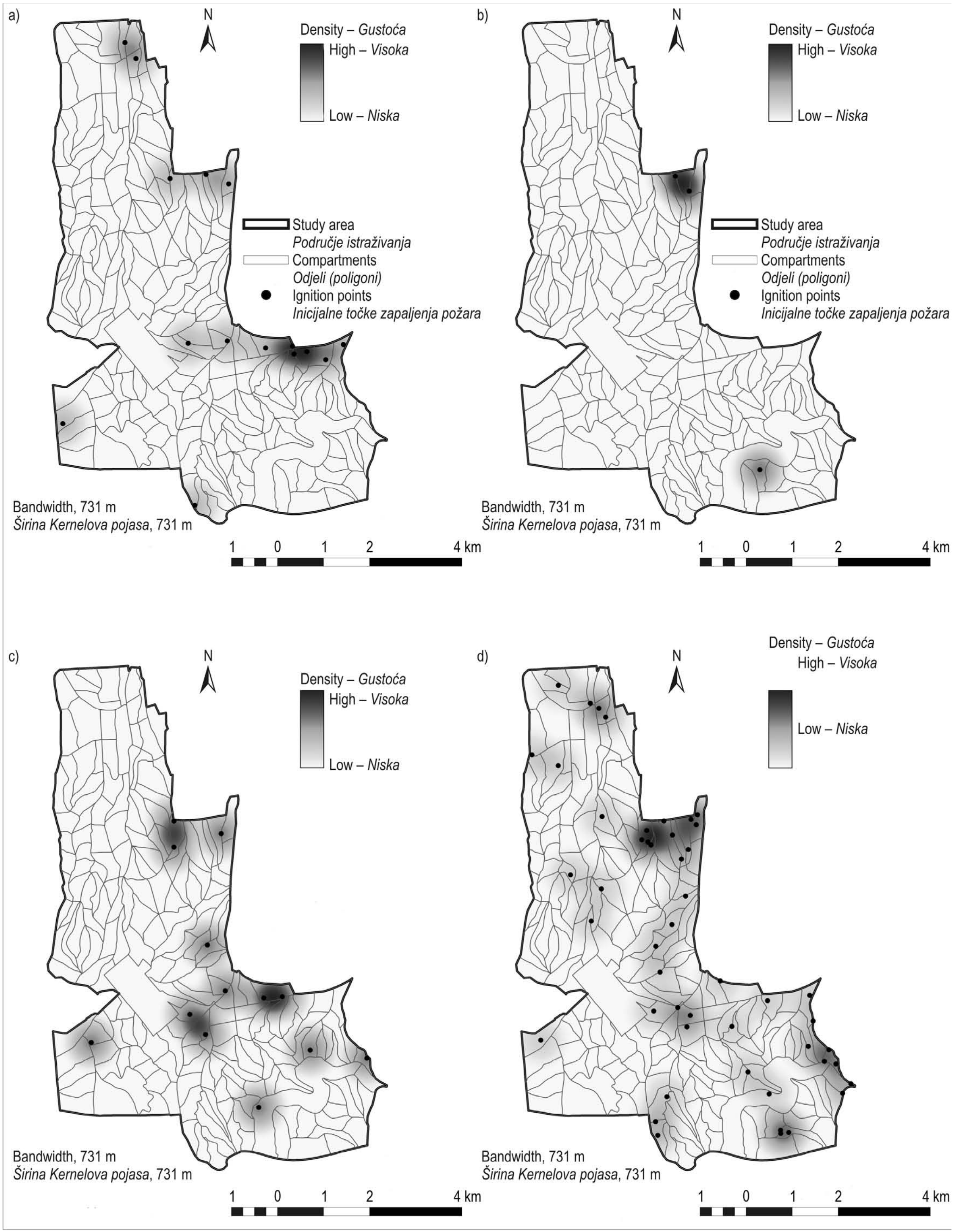

Fig. 3 KDE maps according to seasons: a) fall, b) winter, c) spring, d) summer

Slika 3. *KDE zemljovid požara u različito doba godine a) jesen, b) zima, c) proljeće i d) ljeto*

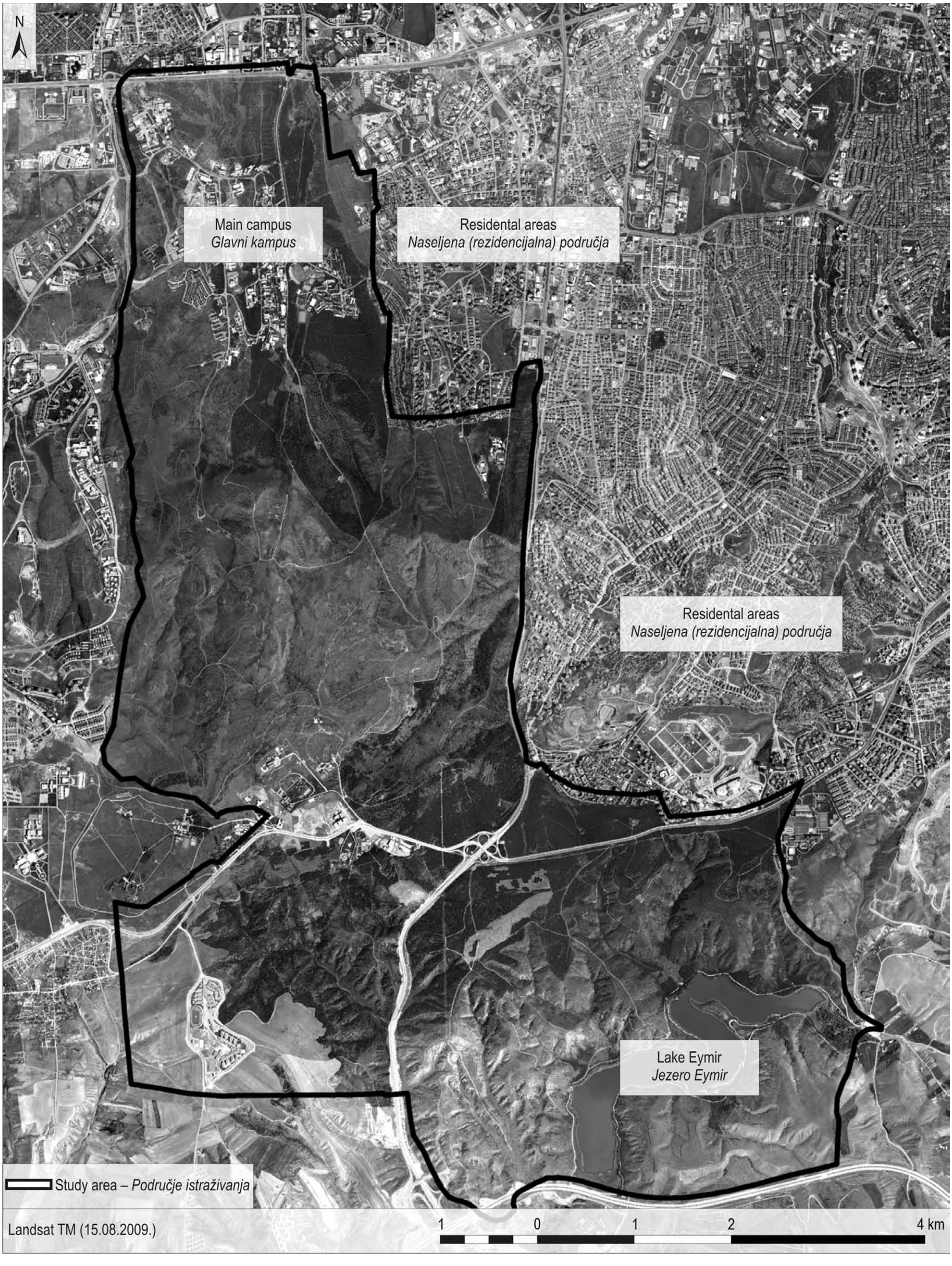

Fig. 4 Satellite image of the study area
Slika 4. *Satelitski prikaz istraživanoga područja*

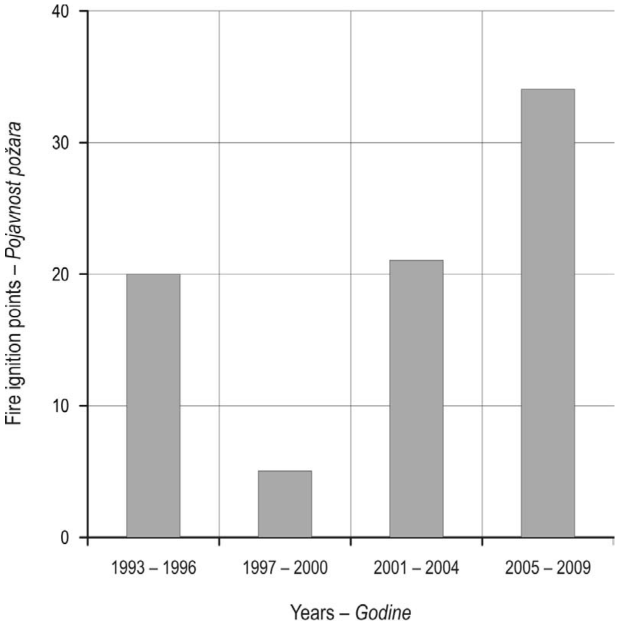

Fig. 5 Fire ignition points with respect to years
Slika 5. *Pojave požara prema godinama*

able that fire events are highly concentrated around residential areas. Whereas the main campus area is located at the north, the majority of residential areas are along the eastern border of the study area, and Lake Eymir is at the south-east part (Fig. 4).

When KDE maps generated for periods between 1993 – 1996, 1997 – 2000, 2001 – 2004 and 2005 – 2009 were inspected, a gradual increase in ignition points was observed after 2000, reaching its peak between 2005 – 2009 (42.5% of 80 ignition points) (Fig. 5).

In the first period, fire events were dense in east and south-east part of the study area, and during the second period (1997 – 2000) a decrease in the intensity and a shift toward central zone were observed. Between 2001 and 2004, the rate of fire events started to increase and had a similar spatial pattern as in the first period. Finally, in the last period (2005 to 2009), a significant spread in fire events throughout the whole study area, including the main campus area at the north, was observed (Fig. 6).

4. Concluding Remarks – *Zaključna razmatranja*

In order to analyze forest fire risk and to take effective counteractions, well prepared maps indicating the association between fire and topographic, anthropogenic and climatic factors are highly demanded by fire management planners. One major drawback of using historical fire data in this kind of analysis is the fact that it is in point format and also contains positional inaccuracies, whereas anthropogenic, topographic and climatic conditions are mostly expressed as continuous areal maps. KDE is a nonparametric method to obtain continuous surfaces from point observations and has been widely and effectively used for converting historical fire data into forest fire density maps. In this study KDE method was used to map the historical fire data in METU campus in order to analyze the forest fire events.

When preparing KDE maps for forest fires, mean random distance method for the calculation of bandwidth was preferred and applied by several authors such as by De la Riva et al. (2004) in Central Spanish Pre-Pyrenees and the East central Iberian range of Spain, by Koutsias et al. (2004) when estimating kernel densities of wildland fires in Halkidiki peninsula, Greece, and by Kuter and Kuter (2010) for predicting forest fire densities in Bodrum Forest Sub-district located at south-west Mediterranean coast of Turkey.

Alternative approach is the selection of bandwidth subjectively by eye, and as stated by Wand and Jones (1995) it is based on looking at several density estimates over a range of bandwidths and selecting the density that fits the study area best. This approach was also applied in the study of De la Riva et al. (2004).

The calculation of bandwidth by mean random distance method is solely based on mean polygon size and mean number of fire ignition points per polygon; however, subjective approach requires detailed a priori knowledge and expertise about the study area, which is not always possible for the analyst. These two methods were successfully utilized in this study and yielded nearly the same bandwidth values.

Based on interviews with authorities from General Secretariat of METU, it can be concluded that neither a geospatial database of fire events in the campus nor a fire risk map has been prepared, therefore as a first step, such database should be immediately built up and maintained thoroughly, and the geospatial database compiled in this study can be used as such a base. Integration of the fire density map (Fig. 7) generated via KDE with topographic and anthropogenic factors in order to obtain the forest fire risk map of the campus area should certainly be considered as a further stage of this study, and according to the results obtained from the map, fire towers and/or autonomous early warning system at critical zones in the campus area should be installed. Especially for summer seasons, security measures should be increased around these zones and necessary actions should be taken in order to enhance public awareness, since a great percentage of observed fire events are human caused.

As indicated in this study, it should prove to be helpful to managers, as this type of forest fire density mapping by effective use of KDE together with GIS geospatial analysis tools would enable fire departments to take appropriate precautions and build up a necessary fire-fighting infrastructure for the areas more prone to fire damage.

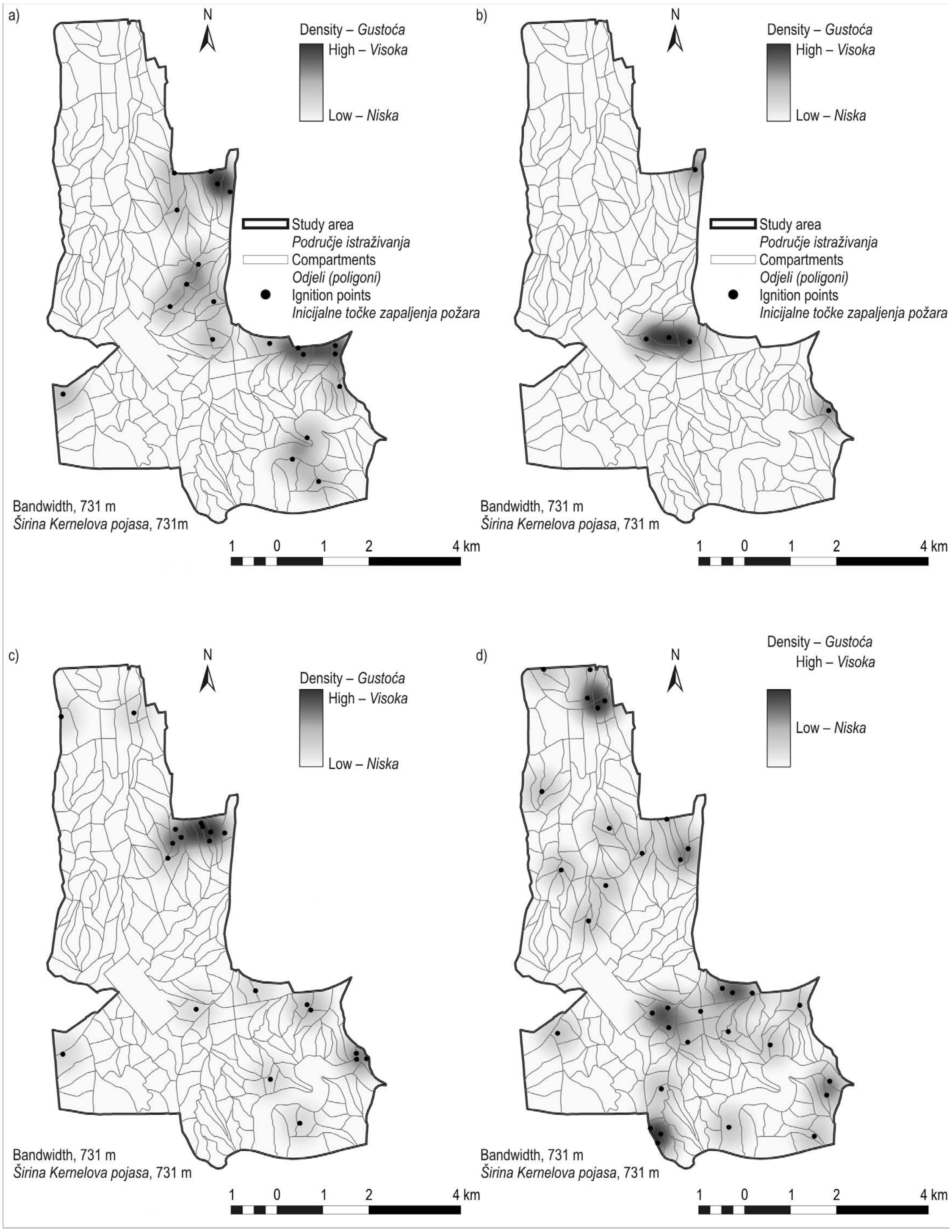

Fig. 6 KDE maps according to years: a) 1993 – 1996, b) 1997 – 2000, c) 2001 – 2004, d) 2005 – 2009

Slika 6. *KDE zemljovid po godinama: a) 1993 – 1996, b) 1997 – 2000, c) 2001 – 2004, d) 2005 – 2009*

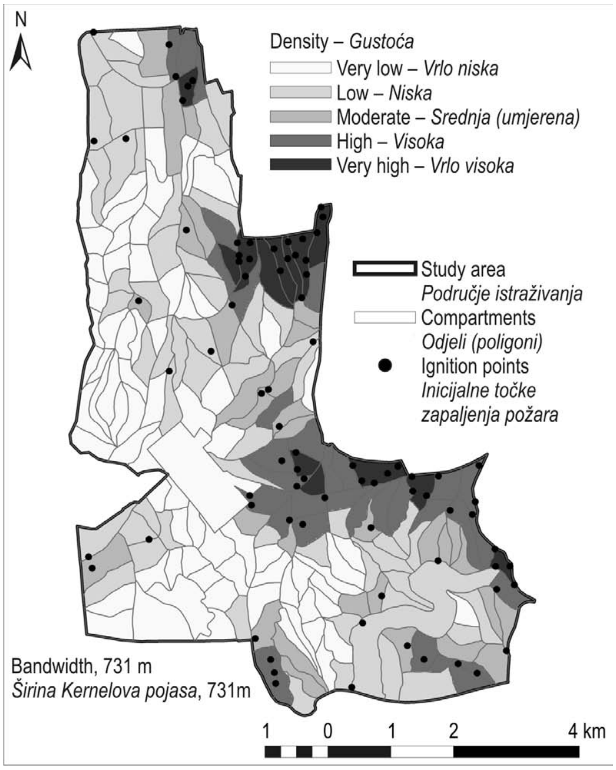

Fig. 5 Fire ignition points with res**Fig. 7** Mean fire densities for compartments (KDE bandwidth = 731 m)

Slika 7. *Srednja gustoća požara po odsjecima (KDE = 731 m)*pect to years

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Sažetak

Kartiranje opasnosti pojave šumskih požara primjenom metode KDE (Kernelova procjena gustoće)

Pri procjeni je opasnosti pojave šumskih požara na određenom šumskom području vrlo važno posjedovati kvalitetan zemljovid rizika nastanka šumskih požara. Takav se zemljovid, u pravilu, temelji na što potpunijoj bazi podataka o šumskim požarima na određenom području u prošlosti te najčešće topografskim, klimatskim, antropogenim i ostalim podacima. Pri tome nailazimo na problem da su povijesni podaci o šumskim požarima (ovisna varijabla) uglavnom u linijskom (točkastom) formatu, dok su svi ostali podaci (neovisne varijable) prikazani u rasterskom (površinskom) formatu. Stoga se za pretvorbu povijesnih podataka o šumskim požarima u prikaz na kontinuiranim površinama vrlo često primjenjuje metoda KDE.

*Istraživanje je provedeno na području kampusa Srednjoistočnoga tehničkoga sveučilišta u Ankari u Turskoj (METU) (slika 1 i slika 4). Kampus ima površinu od 40,52 km^2, od čega je 30,4 km^2 šumskoga područja 1995. godine proglašeno zaštićenim područjem prirode. U kampusu živi i radi oko 25 000 ljudi (studenti, profesori i administrativno osoblje), a u njegovu se sastavu nalazi i jezero Eymir, jedno od najvrednijih rekreacijskih područja u blizini Ankare. Među drvećem prevladavaju crni bor, bijeli bor, libanonski cedar, vrste hrasta (*Quercus *sp.) i topole (*Populus *sp.).*

Podaci o sastojini i staništu su, kao i podaci o šumskim požarima na istraživanom području u razdoblju 1993 – 2009 godine, preuzeti od Uprave METU-a. Navedeni su podaci za svaki od 211 poligona (odsjeka) bili u digitalnom obliku. Na istraživanom je području, u navedenom razdoblju, zabilježeno 80 šumskih požara. Inicijalne točke zapaljenja požara nisu bile definirane svojim točnim položajem, već su bile povezane uz konkretan odsjek.

Pri izračunu KDE je između različitih funkcija (distribucija) korištena Epanechnikova metoda (formula 3). Jedan od važnih parametara matematičke definicije KDE je Kernelova širina pojasa (formula 2). Postoje različite metode određivanja najpovoljnije širine Kernelova pojasa. U ovom su istraživanju korištene tzv. subjektivna metoda odabira i temeljem nje je određena širina pojasa od 250, 500, 750, 1000, 1250, 1500 i 2000 m te metoda srednje slučajne udaljenosti (formula 4) primijenjena na lokalnoj i na globalnoj razini.

Subjektivnom je metodom kao najpovoljnija širina Kernelova pojasa odabrana ona od 750 m, dok je metoda srednje slučajne udaljenosti (koja se temelji samo na srednjoj površini poligona odnosno odsjeka i na srednjoj vrijednosti broja požara po poligonu odnosno odsjeku), i na lokalnoj i na globalnoj razini, rezultirala širinom Kernelova pojasa od 712 m. U konačnici je izračunata aritmetička sredina širina pojasa određenih objema metodama i ona iznosi 731 m. Svi su parametri povezani s izračunavanjem širine Kernelova pojasa prikazani u tablici 1.

Na bazi konačne širine Kernelova pojasa izrađeni su zemljovidi KDE u ovisnosti o godini (razdoblju) i godišnjem dobu (sezoni) nastanka šumskih požara (slika 3 i slika 6). Završni je korak bio generiranje zemljovida koji prikazuje srednje vrijednosti gustoće šumskih požara u svakom odsjeku (slika 7).

Zemljovid šumskih požara KDE u različito doba godine prikazuje sezonsko pojavljivanje šumskih požara i prostorno i vremenski. Glavnina je šumskih požara (61 %), prema očekivanju, sezonska, vezana uz ljeto, a prostorno za okolicu jezera Eymir (rekreacijske aktivnosti) te uz sjeveroistočni dio kampusa koji graniči s gušće naseljenim područjima. Promatrano po višegodišnjim razdobljima najviše je šumskih požara bilo između 2005. i 2009. godine (42,5 %), a najmanje u razdoblju od 1993. do 1997. godine (slika 5).

Tijekom ovoga istraživanja pripremljene su baze prostornih podataka koje, u suradnji s upravom METU-a, treba doraditi, dopuniti i nastaviti održavati te koristiti kao osnovu u protupožarnoj zaštiti kampusa. Zemljovid gustoće šumskih požara po odsjecima, u daljnjim istraživanjima, treba dopuniti topografskim i antropogenim čimbenicima radi kreiranja zemljovida ugroženosti područja kampusa šumskim požarima. Takav bi zemljovid bio *dobra podloga za izlučivanje najugroženijih područja, planiranje šumske protupožarne infrastrukture (prometne i druge), odabir optimalnih mjesta za postavljanje protupožarnih osmatračnica i/ili različitih sustava brzoga otkrivanja šumskih požara i njihove dojave. U spomenutim bi područjima, poglavito tijekom ljeta, trebalo intenzivirati protupožarnu preventivu te poraditi na edukaciji ljudi jer obično ljudi uzrokuju velik broj šumskih požara.*

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