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Mapping Wildland-urban interfaces to support wildfire management over fire-prone forest outskirts of the Zhytomyr region

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Abstract. Recent wildfire events in Ukraine caused considerable economic and human losses, drawing the attention of public opinion in Ukraine to further research the issue related to the management of the risks of forest fires, specially, in the current context of climate change and due to the growing frequency of critical fire weather conditions. Current approaches to fighting wildfires in Ukraine are focused on fire extinction, currently omitting the management of vegetation fuels and their effect on wildfire behaviour to facilitate its mitigation. Due to current wildfire risks to the population and forests, and insufficient research on this issue in Ukraine, it is needed to further develop and test new approaches to reduce wildfire risk. For that purpose, it is required a deep understanding of the fire resilience of vegetation as well as the factors that make the communities vulnerable. In this manuscript, a method for assessing and mapping the Wildland-urban interface with a focus on fire risks for part of the Ukrainian Polissya is suggested. Wildland-urban interface zones were delineated for settlements in the study area and used to identify areas for wildfire risk remediation and silvicultural practices to increase forest resilience to fire. A biodiversity analysis of the main tree species, undergrowth, and understory of the study region, produced a list of local deciduous species that could be used to reduce fire intensity by increasing their proportion in pure pine forests. The volume of silvicultural efforts to increase forest resilience to fire and reduce wildfire risks to human settlements was assessed for one of the most forested regions of Ukraine. Moreover, the first comprehensive assessment of wildlands, which can potentially contribute to wildfire impacts on communities, was provided, making recommendations to reduce wildfire risks for the settlements. In this study, feasible and effective methods to assess Wildland-Urban-Interfaces, and reduce fire risks are suggested, suggesting a methodology concerning wildfire risks for a heavily forested region of Ukraine. Moreover, the suggested approaches that could be used in Ukrainian Forest Management to mitigate wildfire risks in the context of climate change, urbanization, and low resistance of pure pine stands to fires as well as pests and diseases

Keywords: climate change; Forest Fire Resilience Edges; Pine stands; Ukrainian Polissya

Introduction

Growing the frequency and intensity of forest fires, especially in the context of climate change, poses a threat to ecosystems and settlements. Studying and mapping these interfaces allows for the development of effective strategies and measures to manage risks and prevent the spread of fires in regions where the interaction between nature and populated areas becomes particularly vulnerable. The development and implementation of new wildfire management strategies aimed at preserving ecosystems and protecting the population in the face of growing natural disaster risks are crucial.

An increasing tendency of the frequency of large fires with catastrophic consequences is observable in Ukraine (Soshenskyi *et al.*, 2021). The problem of forest fires in the WUI (Wildland Urban Interface) is a growing issue in the entire world (Ager *et al.*, 2019b; Bar-Massada *et al.*, 2023). Current dynamics of fires in the world show a growing trend in the number and frequency of large wildfires with catastrophic consequences (Dowdy *et al.*, 2019; Goldammer, 2021).

There are several differently developed approaches to identify and map WUI (Radeloff *et* *al.*, 2005). Considering all developed methods, two WUI mapping methods must be highlighted: 1) the point-based approach and 2) the zonal approach, which are detailed in the study conducted by A. Bar-Massada (2021).

The main factors that determine the risk of wildfires and their exposure are the characteristics of vegetation fuels, weather conditions, and the source of ignition (Ager *et al.*, 2019a). The majority of wildfires in Europe (95% of all wildfires) are directly or indirectly caused by human behaviour and activities (San-Miguel-Ayanz *et al.*, 2021; European Union, 2023). Such a situation is also typical in Ukraine where the main reason for wildfires is human activity, including negligence and arson as noted by O. Soshenskyi *et al.* (2021).

Vegetation has one of the main impacts on fire behaviour during wildfires. E.L. Loudermilk *et al.* (2022) indicated that long-term ecosystem management by altering vegetation structure as a fuel management practice can change fire distribution and intensity. Vegetation types can behave quite differently as fuel. Tree species affect flammability and are characterized by different resistance to fires (Stevens *et al.*, 2020; Chuvieco *et al.*, 2023). The overall ability of trees to resist fire is one of the indicators of forest resistance to increased fire activity under climate change conditions (Day *et al.*, 2023). Hence, forest structure, the species composition of forests and the adaptation of forest landscapes to fire are key elements in the formation of fire resistance in forests.

While conducting this research study, no publications for Ukraine could be found that had been focused on fuel management, in particular, increasing the proportion of deciduous species in the pure pine stands of Ukraine. Moreover, the research issue of the wildfire occurrence in the WUI zones in Ukraine has not yet been studied. The wildfire occurrence in 2020, when seven settlements were affected in the Zhytomyr region, in which 82 households were destroyed and damaged (Emergency Service of Ukraine, 2021) demanded researching of this issue.

This research study aimed to highlight regional-scale aspects of the wildfire problems within the WUI in Ukraine. The study provides the first comprehensive assessment of where wildlands can potentially contribute to wildfire impacts on communities as well as recommendations to reduce wildfire risks for the settlements through forest management to increase the resilience of pine stands in the context of climate change for the Polissya region.

Materials and Methods

Study area

The study was conducted in the region of Zhytomyr (29,827 km^2) which is located in northern Ukraine (Fig. 1). The forests cover a surface of 1,123,000 ha, being primarily (59.1%) composed of Scots pine (*Pinus sylvestris* L.). The total forest cover of the Zhytomyr region is 34.1% and ranges in different administrative regions from 6.2% (in the south) to 69.8% (in the north) (Zhytomyr Regional State Administration, 2021). The population density of this region is 40 inhabitants per square km. The study area is characterized by a large fragmentation of settlements on the territory of the region. The northern part of the region is the most forested with the dominance of pure pine stands and the location of small settlements directly in the forests (Humanitarian Data Exchange, n.d.; Buchhorn *et al.*, 2020). According to the official sources, as of January 1, 2021, there are 12 cities and 1600 rural-type settlements with 1,195,500 people (59.5% are urban, and 40.5% – rural population) in this territory (Zhytomyr Regional State Administration, 2021). Study regions with spatial patterns of forest and density of settlements are shown in Figure 1.

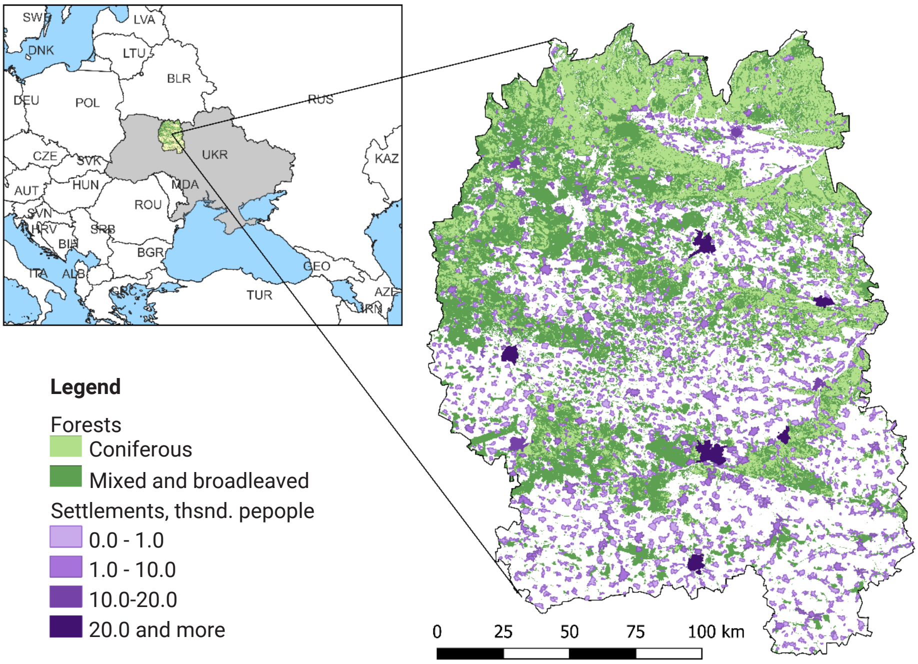

Figure 1. Study area and settlement distribution by people density
Source: Humanitarian Data Exchange (n.d); M. Buchhorn *et al*. (2020)

The climate within the Zhytomyr region is moderately continental, characterized by mild winters and wet summers. The average annual temperature is 10°C, ranging from 4°C in January to 20°C in July. The average annual precipitation is 570-600 mm. According to climatic and soil conditions, the territory is dominated by pine stands, being the representation of stands of other tree species: oak forests (19.1%), birch (14.7%), alder (4.7%), aspen (0.9%) and others (1.5%) (Zhytomyr Regional State Administration, 2021).

Data
Land cover
The "Land Cover 100 m data" (Buchhorn *et al.*, 2020) was used to characterize the land cover. The original land cover was reclassified as displayed in Table 1.

Table 1. Land cover classification

Original land cover classes (Buchhorn *et al.*, 2020)		Recoded classes
Class code	**Class description**	
111	"Closed Forest, evergreen needle leaf"	Coniferous forests
112	"Closed Forest, evergreen, broad leaf"	Broadleaved and mixed forests
113	"Closed Forest, deciduous needle leaf"	Broadleaved and mixed forests
114	"Closed Forest, deciduous broad leaf"	Broadleaved and mixed forests
115	"Closed Forest, mixed"	Broadleaved and mixed forests
116	"Closed Forest, unknown"	Broadleaved and mixed forests
20	"Shrubs"	Other natural landscapes

Table 1, Continued

Original land cover classes (Buchhorn *et al.*, 2020)		Recoded classes
Class code	Class description	
30	"Herbaceous vegetation"	Other natural landscapes
60	"Bare / sparse vegetation"	Other natural landscapes
90	"Herbaceous wetland"	Other natural landscapes
40	"Cultivated and managed vegetation/ agriculture (cropland)"	Croplands
50	"Urban / built up"	Settlements

Source: M. Buchhorn *et al*. (2020)

To analyse the species diversity of trees and shrubs that can be used to transform pure pine stands into more fire-resilient mixed stands, information about the forest stands from the Ukrainian State Forest Management Planning Association (n.d.) was used. A list of species that form various structural elements of the forest; main tree species, understory, and undergrowth was prepared (Table 2-Table 4).

Table 2. Distribution of the forest area by main tree species in the Zhytomyr region

Main tree species	Area, thousand ha	Share of area, %
Pinus sylvestris L.	3549.4	56.1
Betula pendula Roth.	1050.7	16.6
Quercus robur L.	957.3	15.1
Alnus glutinosa (L.) Gaerth.	427.9	6.8
Picea abies L.	88.0	1.4
Pinus sylvestris L.	83.2	1.3
Populus tremula L.	69.9	1.1
Other (44 species)	95.4	1.5
Total	6321.8	100

Source: developed by the authors using the data of the Ukrainian State Forest Management Planning Association (n.d.)

The species composition of the forests of the Zhytomyr region is very limited. The presence of deciduous species such as birch (*Betula pendula* Roth.) and oak (*Quercus robur* L.) is observed. These tree species can grow in those conditions where Scots pine also does. Although oak presents a lower commercial quality where this tree species is located in the conditions where pine grows, a mixed stand composed of these two species can have a positive effect on the resistance of pine trees to climate changes and fires, improving in this way their resilience.

Information about the species that can be found in the undergrowth and understory makes it possible to choose local species to compose pine forest stands with a greater proportion of deciduous tree species (Table 3 and Table 4). The presence of *Quercus robur* L. and *Betula pendula* Roth. in the undergrowth of nature indicates the possibility of the formation of the under-canopy crops from these species. The diversity of shrubs is very high, being the most common in the regional stands: 1) *Frangula alnus* Mill., 2) *Corylus avellana* L., 3) *Rhododendron luteum*.

Table 3. Distribution of the forest area with understory of Zhytomyr region

Species	Area (ha)	Share of area, (%)
Quercus robur L.	395,300	42.4
Carpinus betulus L.	225,100	24.2
Pinus sylvestris L.	131,000	14.1
Betula verrucosa Ehrh.	108,000	11.6
Acer platanoides L.	16,300	1.7
Picea abies L.	10,300	1.1
Other (33 species)	45,500	4.9

Source: developed by the authors using the data of the Ukrainian State Forest Management Planning Association (n.d.)

Table 4. Distribution of the forest area with undergrowth of Zhytomyr region

Species	Area (ha)	Share of area (%)
Frangula alnus Mill.	1554,500	58.8
Corylus avellana L.	467,300	17.7
Rhododendron luteum, Sweet	241,500	9.1
Sorbus aucuparia L.	118,100	4.5
Salix caprea L.	53,500	2.0
Salix pentandra L.	50,800	1.9
Salix aurita L.	30,500	1.2
Sambucus nigra L.	27,500	1.0
Other (59 species)	100,200	3.8
Total	2,643,900	100

Source: developed by the authors using the data of the Ukrainian State Forest Management Planning Association (n.d.)

According to the type of forest vegetation conditions, which determine the potential species diversity of forests, an important part of the territory is occupied by poor soils that are fresh (soil moisture index – 2) in terms of moisture. 33% of the forests of the studied region grow on poor soils corresponding to the type of forest vegetation conditions A_2, 34% on B_2 soils and 10% in poor, dry conditions A_1 where site conditions A, B, C, D stand for soil fertility (from poor to fertile) and 0, 1, 2, 3, 4, 5 – soil moisture (from very dry to very wet) (Pogrebnyak, 1955).

Classification of wooded areas according to wildfire hazard

To assess fire hazard, broadleaved and mixed forests were combined in two groups: 1) mixed forests that included land cover classes with class codes 112, 113, 115, 116 and 2) deciduous forests – land cover class with class code 114. Accordingly, three levels of fire risk were assigned: 1) high (pine forest), 2) medium (mixed forest), and 3) low (deciduous forest). Such classification facilitates the selection of effective fuel treatment scenarios aimed at creating more fire-resistant forests in transition zones between natural forested landscapes and settlements (WUI).

Settlements

Boundaries of the settlements within the Zhytomyr region and their total population data were extracted from the Humanitarian Data Exchange (HDE) service (Humanitarian Data

Exchange, n.d.). According to that reference, 1,539 (92.8%) settlements in the Zhytomyr region are small, limiting their population to 1,000 inhabitants. Most of these settlements are located near the forests and are therefore vulnerable to forest wildfires. The methodology for assessing the area of fuel treatment that should be done to transform pure pine forests into more fire-resistant ones requires spatial information about settlements and forests to determine the WUI. Official data from the State Statistics Service of Ukraine, the Main Department of Statistics in the Zhytomyr region for the period from 1990 to 2021 were then used to estimate the dynamics of the population (State Statistics Service of Ukraine, 2022).

Within the Zhytomyr region, a decreasing trend in both urban and rural populations was observed. Over the last three decades, the population has decreased by 22.2%. The number of the rural population has decreased more intensively than the urban population (compared to 1990, the number of the urban population has decreased by 13.9%, and the rural population by 31.9%) (State Statistics Service of Ukraine, 2022). Generally, the population has decreased in small villages located far from large urban agglomerations, predominantly in the north of the region. This situation reduced wildfire risks due to the reduction of ignition sources but must be weighed against the increased wildfire hazard for settlements and individual houses located next to the forests due to the accumulation of fuels (growth of biomass) (Maillé & Espinasse, 2006; Maillé & Espinasse, 2012).

Mapping WUI

The term Wildland Urban Interface (WUI) is used to define those areas where buildings meet or encounter wild vegetation (Butler, 1974; Radeloff *et al.*, 2005). V.C. Radeloff *et al.* (2005) classified WUI into two types: 1) an intermix WUI (the area where houses and wildland vegetation directly intermingle), and 2) an interface WUI (where settled areas abut wildland vegetation).

There are several ranges to determine the buffer distance from the forest area to settlements (houses). According to studies by W.G. Page *et al.* (2018), the maximum distance over which fires can spread is 2.7 km, and the distance within which they spread is 94% of all fire points within 500 m. California Fire Alliance (2001) recommended a distance of 2.4 km as an average distance in which a firebrand can fly ahead of a firefront. Although fuel types affect the potential spotting distance in the absence of data for Ukrainian conditions, we used a distance of 2.4 km to identify and map WUI in the method of V.C. Radeloff *et al.* (2005).

Due to the availability of data, the WUI point-based approach for mapping the WUI with some modifications was used. Instead of using houses, outlines of settlements were used. Implementing WUI approaches, the settlements located in the WUI zone were determined. A density threshold of 6.17 buildings per km^2 (i.e., 1 building per 16 hectares) was considered, where within 2.4 km of an area that is heavily vegetated (0.75% wildland vegetation) and larger than 5 km^2 (Radeloff *et al.*, 2005). Settlements located within a radius of 2.4 km from a forest with an area of more than 5 km^2 were identified. In addition, based on the research of W.G. Page *et al.* (2018), according to which 94% of all fire ignitions occur within 500 m, forest parts that are located in the buffer of 500 m from settlements were also identified. Thus, two arrays of data were defined: 1) zones of forest fire danger for settlements within the WUI (within a radius of 2.4 km) and 2) zones of extreme forest fire danger for settlements within the WUI (within a radius of 500 m). A distance of 2.4 km, which is recommended by the California Fire Alliance (2001) as an average distance that a firebrand can fly ahead of a firefront, was considered.

Results and Discussion

One of the ways to reduce fire risks is to manage combustible materials, especially in the WUI zone. Two buffer zones in radiuses of 2, 4 and 0.5 km around settlements were determined based on land cover information (Buchhorn *et al.*, 2020). Buffer zones within the WUI were mapped and classified into three wildfire risk classes defined above, and the forest zones around settlements (Fig. 2).

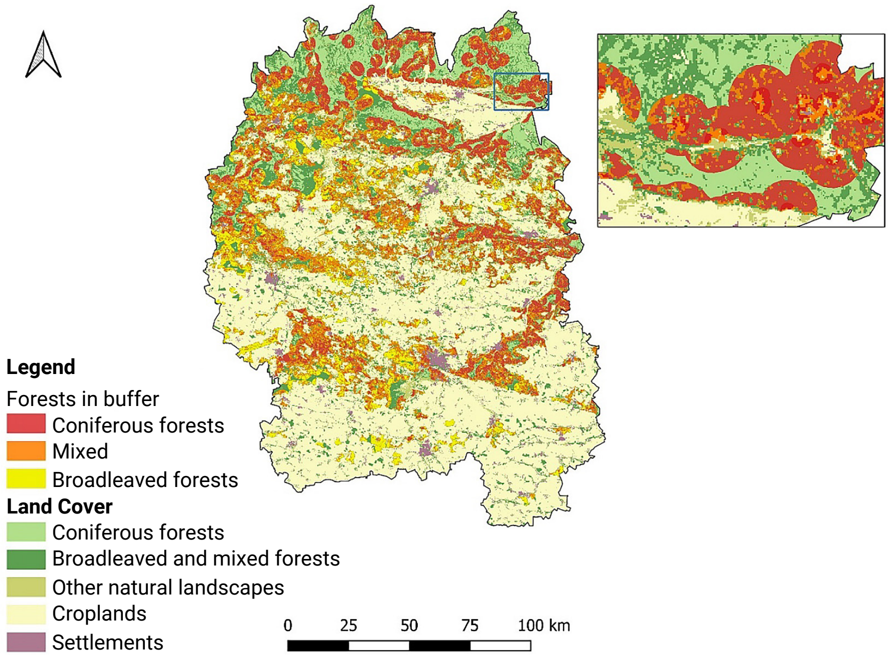

Figure 2. WUI over the Zhytomyr region:
fire-prone forested areas are shown within buffers of 2.4 km apart from settlements
Source: developed by the authors based on M. Buchhorn *et al*. (2020)

Figure 2 highlighted numerous zones that were classified as a high fire-risk area (pure pine forests – coniferous forests). Settlements in high fire-risk areas of the WUI zone, mainly located in the northern part of the region have a risk of negative consequences of forest fire. Furthermore, the forest cover over both buffer zones (2.4 km and 0.5 km) was calculated. In doing so, the share of forests in the buffer zone with gradation by 25 per cent and the number of settlements in each gradation was calculated for each buffer (Table 5).

Table 5. Forest cover in the fire risk buffer zone of settlements in the Zhytomyr region

	Percentage of forests cover in the buffer zone (%)					Total
	<0.1	0.1-25.0	25.1-50.0	50.1-75.0	75.1-100	
Buffer zone 2,400 m						
Forest cover						
Forest area (ha) Percentage	43,125 6.7	406,893 63.2	136,043 21.2	51,131 7.9	6,327 1.2	643,519 100

Table 1, Continued

	Percentage of forests cover in the buffer zone (%)					Total
	<0.1	0.1-25.0	25.1-50.0	50.1-75.0	75.1-100	
Buffer zone 2,400 m						
Number of settlements Percentage	357 21.5	583 35.2	347 20.9	252 15.2	119 7.2	1,658 100.0
Pine forest cover						
Pine forest area, ha Percentage	41,584 0.0	94,230 42.3	82,915 37.2	39,676 17.8	6,002 2.7	264,408 100.0
Number of settlements Percentage	612 36.9	838 50.5	152 9.2	50 3.0	6 0.4	1,658 100.0
Buffer zone 500 m						
Forest cover						
Forest area, ha Percentage	4,751 14.6	20,713 63.8	5,575 17.2	1,357 4.2	53,496 0.2	85,893 100.0
Number of settlements Percentage	640 38.6	494 29.8	242 14.6	157 9.5	125 7.5	1658 100.0
Pine forest cover						
Pine forest area, ha Percentage	1,420 0.0	3,053 54.6	1,895 33.9	616 11.0	28,410 0.5	35,394 100.0
Number of settlements Percentage	987 59.5	559 33.7	89 5.4	22 1.3	1 0.1	1,658 100.0

Note: numerator – absolute value, denominator – percentage
Source: developed by the authors

The categories of forest highlighted in the map (Fig. 2) that characterize WUI made it possible to assess the scale of the possible impact of forest fires on the population. The total area of forests located in buffer zones with distribution by fire danger classes around settlements is presented in Table 6. This spatial information identified the forest fire hazard for settlements in different zones of the Zhytomyr region and enabled effective fire management planning in these areas. Structural analysis of forests in these high fire-risk forests in WUI zones enables planning to develop a diverse fire-resistant forest structure based on species of diversity (Tables 2-4).

Table 6. Distribution of the total forest cover area within settlements buffer zones by the fire risk classes in the Zhytomyr region

Forest fire risk (land cover type)	Forest area within 2.4 km buffer		Forest area within 0.5 km buffer	
	ha	%	ha	%
High (pine forests)	264,408	41.1	35,394	41.2
Medium (mixed forests)	275,976	42.9	43,526	50.7
Low (broadleaved forests)	103,135	16.0	6,973	8.1
Total	643,519	100.0	85,893	100.0

Source: developed by the authors

The positive effect of introducing deciduous species into pine forests (Van Wilgen *et al.*, 1990; Parkins *et al.*, 2018) to increase forest fire safety justifies the planning to introduce deciduous tree species into pine stands of Zhytomyr oblast. Considering the species composition of main tree species, undergrowth and understory species, given in Tables 2-4, local deciduous species should be introduced in the pine forests of the study region: main shelter of a canopy – *Betula pendula* Roth., *Quercus robur* L.; undergrowth – *Frangula alnus* Mill., *Corylus avellana* L., *Rhododendron luteum, Sorbus aucuparia* L., *Salix caprea* L., *Salix pentandra* L., *Salix aurita* L., *Sambucus nigra* L.; understory – *Quercus robur* L., *Carpinus betulus* L., *Betula verrucosa* Ehrh. *Acer platanoides* L.

Considering the increased occurrence of severe wildfires over natural landscapes in Ukraine, as well as in Europe (FAO, 2015; San-Miguel-Ayanz *et al.*, 2020; European Environment Agency, 2021), it is necessary to comprehensively investigate the issue of landscape fire management in order to make further recommendations to reduce the risks of such fires. Climate change increases the potential for catastrophic wildfires that introduce a significant threat to settlements. Settlements and intense human activity next to forests in Ukraine increase the risk of human-caused ignition. Thus, there is an urgent need to promote the development of effective solutions to reduce the risks of forest fires in the WUI zone.

A survey conducted by a multidisciplinary team (composed of technicians of the fire management system as well as scientists) in 2020 at the national level regarding the forest fire and fire management system in Ukraine showed that the main cause of forest fires was the human activity (98%) (Soshenskyi *et al.*, 2021). O. Soshenskyi *et al.* (2021) found out that there was a relationship between the number of wildfires within pine forests and the population, which confirmed the fact that forest fires in Ukraine are mainly caused by activities related to forest visitors. Population growth leads to increased ignition probability, i.e., the fire occurrence, but simultaneously reduces wildfire burn probability due to reduced biomass (e.g., thinning forests for construction) (Maillé & Espinasse, 2006; 2012).

Thus, settlements with a few people located within fire-prone pine forests characterized, create low risks of fire ignition, but are high burning risks. Such situations' develop hazardous wildfires that can threaten settlements.

The problem of fire risks over WUI is influenced by the expansion of communities and the construction of new houses which does not account for the risk of forest fires, and forest policies that do not promote the reduction of the risk of forest fires for settlements. Currently, forest policy is limited to fire prevention measures rather than fuel treatments. A decrease in the number of rural populations leads to a reduction in the number of firefighting units in those regions, which reduces the effectiveness of reacting to fires.

In the Zhytomyr region, settlements are characterized by great fragmentation and are often located either close to or within the forests. The present study is the first research quantification effort devoted to the vulnerability of natural and anthropogenic landscapes to forest fire risk in the WUI zone in Ukraine.

Pure pine stands, which are inherent in the study region, correspond to the paradigm of forest policies in Ukraine of the last century, which promoted to plant of monospecific pine stands for production purposes. Under current circumstances of climate change and increases in the number of communities near the forests, such forests have risks of forest fires traversing settlements. Such a situation requires the development of guidelines to increase the resistance of pine forests to wildfires as well as to pests and diseases by transforming pure pine forests into mixed, complex coniferous-deciduous stands.

The composition of a mixed structure of stands instead of pure pine stands occasionally does not meet the central aim of forest management, e.g., it can lead to a decrease in the total volume of high-quality commercial wood.

However, the gained effect in terms of wildfire risk reduction transcends commercial revenue from timber. Increasing tree species diversity in forests through the creation of more mixed stands is a common aim of forest policies in different parts of the world, both as a means of increasing the delivery of ecosystem services from forests and as a way of increasing resilience to climate change as noted by W.L. Mason *et al.* (2018). One of the responsibilities of forest fire management is the execution of an analysis of how boundary and density of settlements as well as structural characteristics of forest change.

Two main approaches to reducing forest fire risks for settlements in the study region through forest management in the WUI zone are suggested in this study: 1) increasing the proportion of deciduous species in pine forests and forming complex multi-component forest edges; and 2) reducing the supply of combustible materials' trough thinning of pine stands to the point where the forest fire cannot spread through the crowns of trees. The first approach requires measures to create forests artificially or naturally, providing a proportion of deciduous species in the upper tier, understory, and undergrowth. The second approach requires regulation through controlled burning of the amount of combustible materials from grasses, which are formed with increased access of light to the soil surface. Considering the features of buffer zones, climatic anomalies in recent years and the economic features of the region, the most optimal way to increase the fire resistance of forests and the safety of settlements from fires is the regulation of combustible materials through the formation of more fire-resistant stands in forest edges and buffer zones of buildings during forest management. The use of the method of controlled burning is also an option to reduce the risks of wildfires. However, this method has not yet been tested, described, and regulated by legislation in Ukraine.

Since forest edges commonly overlap with WUI zones, it is important to mention that D. Armenteras *et al.* (2013) demonstrated that a vast majority of wildfires (98%) occurred within 1000 m of the edge, while only two per cent of fires occurred at greater distances. Authors D. Armenteras *et al.* (2013) also revealed that the most intense wildfires (exceeding 500 MW) occurred close to the edge, i.e., the first 2 km inside or outside the edge.

The classification of forest edges plays an important role in forest management in the WUI zone. In Ukraine, A.D. Kuzyk (2011) was engaged in the classification of forest edges according to their fire value, which distinguishes three types of forest edges, according to the width of the forest strip from the edge, which differs from the forest in the middle in microclimate, tree taxonomic indicators, biodiversity. According to this classification, false (Fig. 4), elementary (Fig. 3b) and multi-component (Fig. 3a) forests are distinguished. Multicomponent forest edges are formed naturally over a long period in the absence of human activity. Furthermore, it is possible to speed up the process of formation of such edges by forestry measures. In areas with a high risk of wildfires occurring and spreading from populated areas to forest areas, or vice versa, it is advisable to ensure the formation of such forest edges with a width of 100-200 m (Fig. 3).

Most forest edges in pine forests on the border with populated areas are false forest edges (Fig. 4) or elementary forest edges (Fig. 3). Such woodlands are characterized either by the absence of undergrowth, understory, and shrubs, or by an insignificant diversity of trees, shrubs, and herbaceous plants, which is observed in a strip with a width smaller than the average height of the stand.

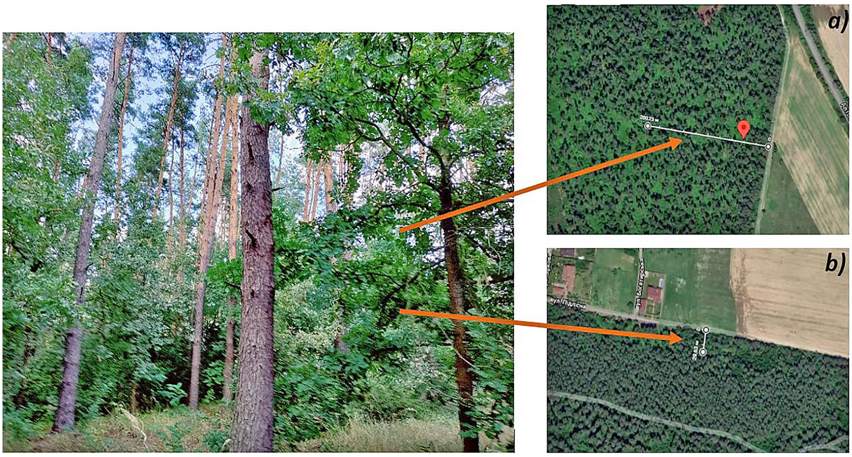

Figure 3. An example of multi-component (a) and elementary (b) forest edges
Source: authors' photos

Figure 4. An example of a false forest edge
Source: authors' photo

A separate example of fire-resistant edges in pine forests to reduce risks for settlements is the formation of sparse stands because continuity of surface fuels is important for the spread of fire, according to K. Parkins *et al.* (2018). Such forests play a recreational or protective function and thus, the loss of technical qualities of wood in such forests can be justified. The main advantage of such forest edges is the reduction of the amount of combustible materials in the path of a possible crown forest fire since such a structure does not support crown forest fire, and it is easier to stop ground fires in such places. The disadvantage of such forest edges is a large amount of sunlight, which contributes to the appearance of dense grass cover, which creates high fire risks in dry conditions (autumn and spring). Therefore, in such forest edges, it is necessary to implement the practice of using controlled burnings – safe and controlled burning of ground combustible materials. Examples of such edges are shown in Figure 5.

Figure 5. An example of a sparse forest edge in a pine stand on the border with settlements
Source: authors' photo

This study assessed two critical WUI zones in the Zhytomyr region that can be used to reduce wildfire risks through forest management. The first zone is pure pine forests in a buffer zone of 500 m around populated areas are the primary volume of forestry measures for the formation of fire-resistant forests, which is 38.4 thousand hectares (3.4% of all forests in the region). The second zone is pure pine forests in a buffer zone of 2,400 m around settlements, which requires a strategic plan for the transformation of pure pine forests over a long period – 275.3 thousand hectares (24.5% of the forests of the region). Forest management in this zone should take into account the economic functions of these forests but still follow the principles of formation of pine forests resilient to fires, pests, and diseases.

Within the framework of the "RESILPINE – Transformation of pine forests to a close-to-nature forest management in Ukraine and with special consideration of resilience to fire" (Global Fire Monitoring Center, 2021) project, eight permanent plots were established to test methods of transforming pure pines to increase their resistance to fires, pests, and diseases, and now have the first positive results of growth and adaptation. Experimental sites were laid out in different regions of the Polissya natural zone, which includes the Zhytomyr region. Various methods were tested in experimental plots – an increase of deciduous tree/shrub species in pure pine stands, planting of fire-resistant forest edges, fire-resistant forest edge, under canopy culture with common oak in pure pine stands. Proven options for creating understory crops or increasing the proportion of hardwoods in pure pine stands to reduce wildfire risk can be used to reduce wildfire risks in the WUI area described in this study.

Conclusions

Concluding this study, a method to assess and map WUI with a focus on fire risks for one of the regions of Ukraine is suggested. In the involved regions, pure pine forests are common and have forest fire risks for settlements. Assessment of the WUI zone in Zhytomyr region (oblast) showed 35.4 thousand ha of pine forests in the 0.5-km buffer zone (3.4% of the total forests of Zhytomyr oblast) and 264.4 thousand ha of pine forests in the 2.4-km buffer zone (25.3% of the total forest area of Zhytomyr oblast). Such pure pine forests with other species of single trees are characterized by a high risk of forest fires and require transformation into more resilient mixed stands to reduce the vulnerability of settlements near such forests. Based on the analysis of the species diversity of the main tree species, undergrowth and understory, a list of local species that can be used to increase the proportion of deciduous species in pure pine forests was suggested. The approaches, which are described in this study, can be used to estimate the areas of forests within the WUI zone in which it is necessary to reduce the risks of forest fires in other regions of Ukraine. Approaches to forest management in the WUI zone can be used to reduce the risks of forest fires both in the study region and in other regions of the Ukrainian Polissia. The WUI zone assessment method described in this study is a tool for defining forest management policies in these zones in order to reduce forest fire risks in the context of ongoing climate change, urbanization, and reduced resistance of pure pine stands to pests, diseases, and fires.

Future research could focus on refining and optimizing the methodology employed in mapping WUI zones. This could involve incorporating additional spatial and environmental variables, advanced remote sensing techniques, and data from emerging technologies such as satellite imagery, drones, or geographic information systems (GIS).

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Conflict of Interest

None

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Картування зон взаємодії між природними ландшафтами та населеними пунктами Житомирської області для зниження ризиків лісових пожеж

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Анотація. Лісові пожежі, які трапилися на території України в останнє десятиліття і мали масштабні негативні наслідки підтвердили актуальність досліджень управління ризиками лісових пожеж в умовах зміни клімату та зростання частоти критичних пожежонебезпечних погодних умов. Поточна система управління лісовими пожежами, яка передусім орієнтована на гасіння, потребує розробки нових стратегій для зниження ризиків лісових пожеж, що включає управління лісовими горючими матеріалами. Зважаючи на існуючі ризики лісових пожеж для населення та лісів, а також недостатню дослідженість цього питання в Україні, необхідно продовжувати розробляти та тестувати нові підходи до зниження ризиків лісових пожеж. Мета дослідження полягала в розробці та застосуванні методу для оцінки та картографування інтерфейсу «дика природа – населений пункт» з акцентом на пожежну небезпеку для частини Українського Полісся. Зони інтерфейсу «дика природа – населений пункт» були виділені для населених пунктів на досліджуваній території та використані для визначення територій, на яких необхідно відновити лісові насадження, а також лісогосподарських практик, спрямованих на підвищення стійкості лісів до пожеж. Аналіз біорізноманіття основних деревних порід, підліску та підросту досліджуваного регіону дозволив скласти список місцевих листяних порід, які можуть бути використані для зменшення інтенсивності пожеж шляхом збільшення їх частки в чистих соснових лісах. Для одного з найбільш лісистих регіонів України було оцінено обсяг лісогосподарських заходів, спрямованих на підвищення стійкості лісів до пожеж та зменшення ризиків пожеж для населених пунктів. Була проведена перша комплексна оцінка диких земель, які потенційно можуть сприяти впливу лісових пожеж на населені пункти, та надані рекомендації щодо зниження ризиків лісових пожеж для населених пунктів. Запропоновано методи оцінки взаємодії між природними ландшафтами та містом, а також зниження ризиків виникнення пожеж для частини Поліської природної зони України. Представлені підходи можуть бути використані в українському лісовому господарстві для зменшення ризиків лісових пожеж в умовах зміни клімату, урбанізації та низької стійкості чистих соснових деревостанів до пожеж, а також шкідників і хвороб

Ключові слова: зміна клімату; лісові протипожежні смуги; соснові насадження; Українське Полісся