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How to Approach the Definition of WUI in Northern Europe

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ABSTRACT

This article aims to delineate the wildland–urban interface in the sparsely populated, limited-resourced Scandinavian peninsula (excluding Finland). Common WUI mapping assumptions and how different thresholds capture the reality of building ignition from wildfire in this region are evaluated. We show that dedicated fuel maps capture areas at risk slightly better than vegetation maps, although the choice of map per se is less important than the selected limit for possible ember transport. The commonly used 6.17 buildings/km^2 threshold for building density fails to capture most wildfire incidents that have led to building ignition.

1 | Introduction

When humans settle in natural or seminatural landscapes, their interactions with the environment inevitably affect both the settled area and its surrounding landscape. Examples include an increased rate of anthropogenic footprints such as wildfire ignitions [1], fragmentation effects on urban and peri-urban wildlife [2], spread of diseases between humans, domestic and wild animals [3] and local establishment and spread of invasive plants [4]. The zone in which resident–environment interactions occur is sometimes referred to as the wildland–urban interface (WUI) [5].

Conceptually, the WUI is defined as the place where human-built structures are located adjacent to or within forested or grass/shrub vegetation. However, there is no consensus on how to numerically define these areas. One of the most used definitions is from Radeloff et al. [5], defining WUI as the area where houses exist at more than 6.17 housing units per km^2 and where (1) wildland vegetation covers more than 50% of the land (intermix WUI), or where (2) wildland vegetation covers less than 50% of the land, but a large area (over 5 km^2) covered with more than 75% wildland vegetation is within 2.4 km (interface WUI).

Within this definition, there is an existing difference between the interface and intermix. The interface community *exists where structures directly abut wildland fuels*, while the intermix community *exists where structures are scattered throughout a wildland area* [6], this is exemplified in Figure 1.

Most wildfire ignitions are caused by humans, and there is a strong correlation between fire occurrence and population density [7]. The coexistence of flammable fuel, buildings and anthropogenic ignition sources in the WUI motivates efforts to identify developed areas that could be at risk in the advent of a wildfire [8]; thus, this is a focal area for fire management and wildfire prevention policies [9]. Cohen [8] defined the WUI as *an area or location where a wildland fire can potentially ignite homes*; Radeloff et al. [5] defined it as the area *where wildfire problems are most pronounced*.

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FIGURE 1 | Examples of the Swedish wildland-urban interface: (a) interface and (b) intermix. Photographs: Lantmäteriet, 2018.

Researchers and practitioners have focused their efforts during recent years on delimiting this area, developing maps where the interaction between urban and rural is established. These WUI maps, when completed, often become the basis for national preparedness and prevention programmes and wildland fire management policies. Examples are, for the USA: National Fire Plan, Federal Wildland Fire Management Policy, 10-Year Comprehensive Strategy and the Healthy Forests Restoration Act; for Europe: Alcasena et al. [10], Lampin-Maillet et al. [11] and Modugno et al. [10–12]. Moreover, WUI maps can contribute to planning decisions regarding the location of new developments [13] and vulnerability assessments (e.g., Papathoma-Köhle et al. [14] and Vacca et al. [14, 15]).

Several attempts have been made to map the WUI at different scales, from regional to worldwide maps. Examples of European attempts can be compared in Table 1. Although the USA, Canada and Australia have been working on mapping and understanding WUI since the 1980s, research on the spread of wildfires to infrastructures in southern Europe started just in the last decades. This leaves most European countries with a lack of detailed understanding of the fire hazard at the WUI and a lack of effective tools to improve the situation. Some of these countries are in northern Europe, where wildfires are comparably less frequent and less severe, but the occurrence is consistently increasing [18].

Focusing on Scandinavia, there is no existing national WUI map representing this area; however, several attempts at mapping the WUI have been made in which the Scandinavian countries are included. Modugno et al. [12] estimated the WUI in Norway and Sweden to be less than 2% of the total national areas. Bar-Massada et al. [17] estimated that the WUI in Norway and Sweden comprises 2.09% and 3.16% of the total areas, respectively, which agrees with the results obtained by Schug et al. [19]. However, these maps are not helpful at the scale they are developed for fire management purposes. The maps are produced at low resolution (county level), and values are averaged across large areas, which can be the cause of a misinterpretation of the obtained values. In the case of Bar-Massada et al. [17], the vegetation map only includes woody fuels, assuming that they are representative of all wildfire events but does not include shrublands, which are the main burning vegetation in large parts of Scandinavia, hence underestimating the risk. Therefore, a regional map focused only on Scandinavia, with relatively smaller studied areas and more detailed vegetation is necessary to understand the current WUI situation. This type of mapping will be necessary in the future for planning prevention and protection measures against wildfires in the WUI.

1.1 | Aim

Knowing and understanding the distribution of WUI can help in wildfire prevention and mitigation planning, as well as wildfire risk governance. This study therefore aims to evaluate the methodologies applied for the definition of WUI around the globe, by adapting them to the specific case of the Scandinavian peninsula (i.e., Norway and Sweden). We propose a methodology that reflects the reality of northern Europe. Special consideration is given to how accurately different WUI thresholds capture previous building ignitions.

2 | Theoretical Framework

2.1 | The WUI Components

The WUI definition by Radeloff et al. [5] suggests that the WUI includes three main components; the biophysical, the social and the fire components, respectively, which are further described later.

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TABLE 1 | Existing WUI maps in Europe (vs. Radeloff et al. 2005).

	(Radeloff et al., 2005) [5]	(Lampin-Maillet et al., 2009) [11]	(Conedera et al., 2015) [16]	(Modugno et al., 2016) [12]	(Sirca et al., 2017) [16] (regional scale)	(Alcasena et al., 2018) [10]	(Bar-Massada et al., 2023) [17]	(Schug et al., 2023) [17]
Interface	6.17 dwellings/km^2 < 50% wildland	4–50 dwellings < 100 m apart (scattered dwellings)	Dwellings < 100 m from drivable roads	Buffer zones, 200 m from the urban fabric, with > 30% urban coverage. Industrial areas are included, 400 m from wildland	30%–79% soil sealing (scattered housing)	6.18–49.42 dwellings/km^2, < 50% wildland	> 0 dwellings/km^2 < 50% wildland	0.5%–15% aggregated building density, over a 500 m radius. < 50% wildland
Intermix	6.17 dwellings/km^2 > 50% wildland	< 4 dwellings > 100 m apart (isolated dwellings)	—	—	0%–29% soil sealing (isolated housing)	6.18–49.42 dwellings/km^2 ≥ 50% wildland	> 0 dwellings/km^2 > 50% wildland	0.5%–15% aggregated building density, over a 500 m radius. > 50% wildland
Distance to and size of wildland	2.4 km 5 km^2 > 75% wildland	—	—	< 600 m	< 200 m (200 m veg buffer overlapping a 400 m housing buffer)	2 km, 5 km^2	600 m, 5 km^2 > 75% wildland	2.4 km 5 km^2 > 75% wildland
Excluded vegetation (nonwildland)	Arable land	—	All non-woody, non-shrub, nonopen forest	All non-woody	—	Arable land, built-up area, and sparse vegetation	All non-woody, nonshrubland	Cropland, built-up area, bare soil and sparse vegetation
Fuel/Vegetation data source	1992 NLCD, 30 m resolution	—	2015 TLM3D	European Corine Land Cover (CLC), 100 m resolution	2006 CLC, 100 m resolution	2016 Land parcel identification system (LPIS)	2020 European Space Agency global land cover	2020 European Space Agency global land cover, 11 classes, 10 m resolution
Settlement data source	U.S. 2000 decennial census	1992 BD TOPO and 2003 BD ORTHO	2015 TLM3D	European Corine Land Cover (CLC), 100 m resolution	2006 Soil Sealing (SS), 100 m resolution	2016 Base Topográfica Nacional 1:25.000 (BTN25)	2019 World Settlement Footprint dataset, 10 m resolution	GHS-BUILT-S—R2022A, 10 m resolution

(Continues)

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TABLE 1 | (Continued)

	(Radeloff et al., 2005) [5]	(Lampin-Maillet et al., 2009) [11]	(Conedera et al., 2015) [16]	(Modugno et al., 2016) [12]	(Sirca et al., 2017) [16] (regional scale)	(Alcasena et al., 2018) [10]	(Bar-Massada et al., 2023) [17]	(Schug et al., 2023) [17]
Geometric entity	Census blocks	Buffered area, 50 m radius	Buffered areas, 100 m radius	Area, overlapping buffers	Area, overlapping buffers	150 m grid	500 m radius, circular area	500 m radius, circular area
Area	U.S.	Provinces in France	Parts of Switzerland	Europe	Sardinia (Italy)	Catalonia (Spain)	Europe	Global

2.1.1 | The Biophysical Component: Flammable Vegetation

The biophysical condition is represented by two vegetation criteria, to describe:

1. What vegetation types are flammable
2. The minimum coverage of flammable vegetation

"Wildland" has been defined as "flammable" natural and semi-natural land cover types, regardless of their relative fire hazard, an example is given here by Radeloff et al. [5]:

> We defined as wildland vegetation the following land cover classes: coniferous, deciduous, and mixed forest; shrubland; grasslands/herbaceous; transitional; and woody and emergent herbaceous wetlands. Excluded from wildland vegetation were low- and high-intensity residential, commercial/industrial, orchards/vineyards, pasture/hay, row crops, small grains, fallow, urban/recreational grasses, bare rock/sand/clay, quarries, open water, and perennial ice/snow.

Both vegetation and fuel maps are currently available at a wide range of scales, providing different information. The choice of map used as the basis of the WUI classification is key to determining the most representative WUI areas.

2.1.2 | The Social Component: Building Density

The social component is represented by a population or housing density criterion. This component aims to answer one or several of the following questions:

1. Which objects are worthy of protection in the case of a wildfire?
2. What is the location of objects worthy of protection?
3. At which housing density can anthropogenic WUI fire ignitions be expected?
4. What is the minimum settlement size to prioritise during a wildfire?
5. Will the natural and/or ornamental vegetation spread the fire through the settlement at higher building densities? And if so, at what density?

Population or housing density is a variable parameter that highly depends on socioeconomic factors. Generally, highly populated regions account for dense communities with lower interaction between the rural and urban environments. The thresholds between them can be more clearly defined around large settlements, and the density is normally high (interface WUI-type is predominant). On the contrary, regions with more dispersed populations have less defined thresholds between rural and urban environments and tend to have dwellings embedded in the forest areas (intermix WUI-type is predominant).

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The variability of population distributions shows the need for a specific evaluation of these characteristics prior to deciding the values required for a WUI classification.

2.1.3 | The Fire Component: Spotting Distance

The last component represents the hazard of housing destruction by spotting which is understood by three processes: ember generation, ember transport and structure ignition. The threat of ember-induced ignition increases with fire intensity because a stronger plume allows larger embers to be lofted and transported a longer distance [20, 21]. It is therefore commonly assumed that spotting only occurs with crown fire activity [22] involving spotting distances up to several kilometres. However, short-distance spotting with embers landing close to the source fire (< 100 m, e.g. [23]) can also be significant in most fire events.

To represent ember transport in WUI mapping, one may consider if significant ember production is possible, and how far these embers will be lofted and if they will ignite buildings ahead of the fire front. To this end, the best threshold regarding embers travelling is determined, being necessary to study if this is the mean/median or the longest travel distance.

2.2 | Existing Methods to Delineate the WUI

WUI maps may be created with differing purposes in mind, which likely accounts for differences in modelling approaches. For instance, vegetation is included in the WUI zone when the map will later include fire hazards or be used for land management, etc., whereas only buildings (treated as points or lines) are sometimes delineated if the sole purpose is to show the proximity of houses to wildland [24]. Similarly, small evaluation radii may be used to identify defensible space or garden management zones, while the mapping of wildfire threat may involve larger radii due to the threat of embers [25].

Radeloff et al. [5] bounded the WUI calculations by irregular polygons (census tracts) used for demographic statistics in the USA. The zonal approach by [5] has been widely used in the USA state and federal agencies [9]. However, it suffers from the modifiable areal unit problem [26] because the polygons vary in size, meaning that mapping precision varies. The mapping is least precise in larger polygons, and this often corresponds to areas with low housing density, that is, where it may be more important to create wildfire hazard prevention plans since the rescue service is allocated according to population density.

Another zonal mapping method, utilised, for example, in Australia, is to define the WUI by previously burned areas that include buildings [27]. Although this is a practical approach, without the need for mapping thresholds, it is mainly feasible for vegetation that undergoes rapid regrowth. For boreal regions, it takes at least 20 years before the surface fuel is sufficiently accumulated to carry a large wildfire through the same place [28].

In Europe, where wildfire policies vary between countries, different methods have been employed. Modugno et al. [12] defined the European WUI as buffer zones around city borders, which is feasible when the wildfire hazard is most prominent for the interface. Lampin-Maillet et al. [11] and Caballero [29] have used a point-based approach, meaning that WUI areas/lines/points are defined by housing locations. With this approach, a buffer around each building is the basis of housing density and vegetation evaluation. Bar-Massada et al. [17] included all buildings and decreased the distance of firebrand transport to represent a mean value. These differences are detailed in Table 1, where the specifications of existing WUI maps in Europe (in comparison with Radeloff et al. [5]) are shown.

2.3 | Characteristics of the Northern WUI

The low population density, large, vegetated areas and different cultural use of, and response to fires in the northern countries raises concern about the applicability of current WUI protocols, definitions and strategies used in southern Europe.

For instance, the demographics that are of interest when studying the WUI are different in northern Europe compared to the south, and wildfires and population densities are directly related. The total population and population density in Norway (5.5 mil., 15 inh./km^2, respectively) and Sweden (10.5 mil. inhabitants, 26 inh./km^2) are far lower than the numbers for other European countries; for example, 95 inh./km^2 in Spain or 277 inh./km^2 in the United Kingdom. The size of large cities also differs, with 0.6 and 1.5 mil. Inhabitants, respectively, in Oslo and Stockholm (compared to 3.3 mil. in Madrid, or 7.6 mil. in London) [30].

Living conditions in the north differs from the south. Northern Europe is characterised by urbanisation, with most areas consisting of single wood-based houses amid the forest [31], with a building density much lower than 6.17 units/km^2. Another difference involves the working conditions for the rescue service, including a sparce force, large patches of forest, scattered road networks and relatively long travel distances. Moreover, there are no wildfire risk awareness and prevention programmes addressed to the people living in the WUI. In Norway, wildfire ignitions are reduced by a strict fire ban prohibiting any type of open fire in unrestricted areas during wildfire season, but this is not the case in Sweden.

Finally, fire behaviour and cause differ, both from southern Europe and from other parts of the world with a similar biome, for example, North America. A large part of northern European forests is designated for production purposes (which means that the WUI is a misnomer), and therefore generally lacks an understory layer that can act as ladder fuel to the crowns—therefore, most fires are surface fires. Another difference is the contrasting vegetation on the forest floor that is the result of a combined effect of a warmer winter climate in Europe, and differences in both forest stand structure and herbivore cycles [32]. However, shrub and tall grass are the most common WUI fuels despite the large areas of forested land. These fuels, having

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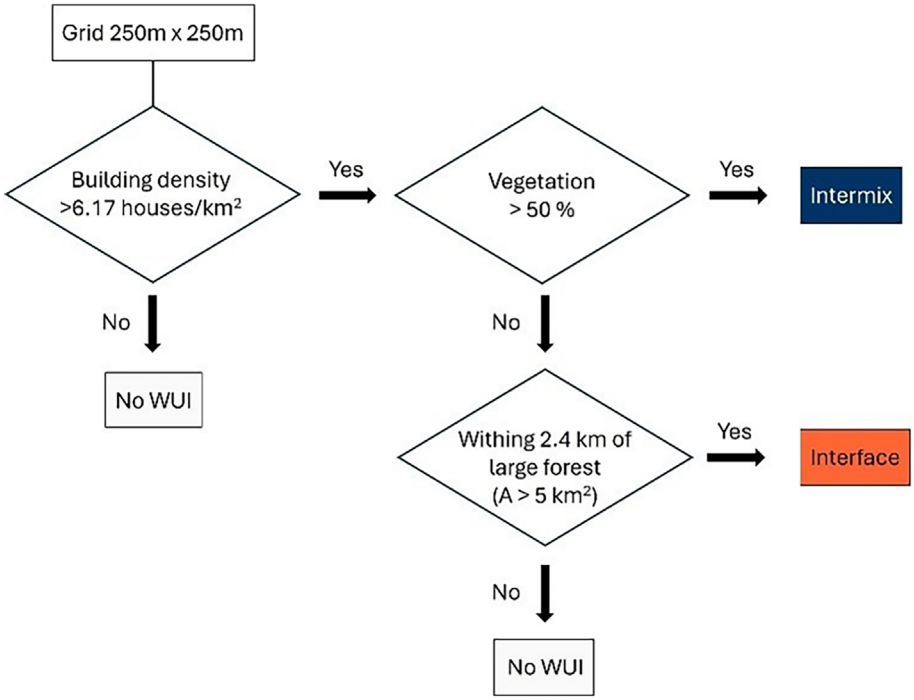

FIGURE 2 | Basic scheme on the methodology followed to determine the WUI.

their flammability peaks in spring (after snow-melt and before green-up), are involved in the largest portion of building loss in Fennoscandia [33].

3 | Method

We have carried out the analysis with R software [34], using as main packages terra [35], sf [36, 37] and tidyverse [38]. Other packages used are: tidyterra [39], patchwork [40], gt [41], gtExtras [42], purr [43] and quarto [44]. In this section, we briefly discuss the data collection and processing; however, we refer readers to the following GitHub pages (https://javiereliomedina.github.io/wui_definition_neur/) for a reproducible data analysis.

3.1 | WUI Classification

The scheme for delineating WUI areas, both intermix and interface, was developed following the methodology described in Radeloff et al. [5] and synthetised in Figure 2. We applied a point-based approach at the national level in Norway and Sweden, with a raster resolution of 250 x 250 m. As a basemap, we used the values in Radeloff et al. [5] of 6.17 #/km^2 for building density and 2400 m for the distance to large vegetation zones (i.e., area larger than 5 km^2), hereafter referred to as the *standard* threshold values. These values will be used as baseline or standard for this work and will be referred from here as standard values. Then, we varied the model parameters (i.e., building density, fuel map/vegetation and distance to vegetation) to study the influence of these parameters in the classification of WUI and to produce alternative WUI maps (Table 2).

Finally, we collected the available information on wildfires affecting infrastructures in both countries, and determined the number of these fires that would have been located in a WUI-defined area according to the different criteria to show the precision of these maps.

TABLE 2 | Parameters for WUI classification.

Building density [#/km^2]	Vegetation/fuel maps	Distance to vegetation [m]
6.17	1. National vegetation maps:	200
3.08	a. Norwegian Forest	500
1.00	resource map (SR16)	1000
	b. Swedish National Land	2000
	Cover Database (NMD)	2400
	2. Corine Land Cover 2018 (Version 2020_20u1)	
	3. EFFIS Fuel Map	
	4. European fuel map (FirEUrisk)	

3.2 | Data Collection of the WUI Components

3.2.1 | Building Density

We downloaded the building data from OpenStreetMaps (OpenStreetMap contributors 2017), and then calculated the building density by grid cells of 250 m x 250 m. In this regard, we calculated building centroids and assigned them to the grid they belonged in (Figure 3a), then we smoothed the data with a circular moving window of 500 m (buffer area) for avoiding noise in the data (Figure 3b). Finally, the building density was calculated as the smoothed number of buildings in the grid cell divided by the buffer area.

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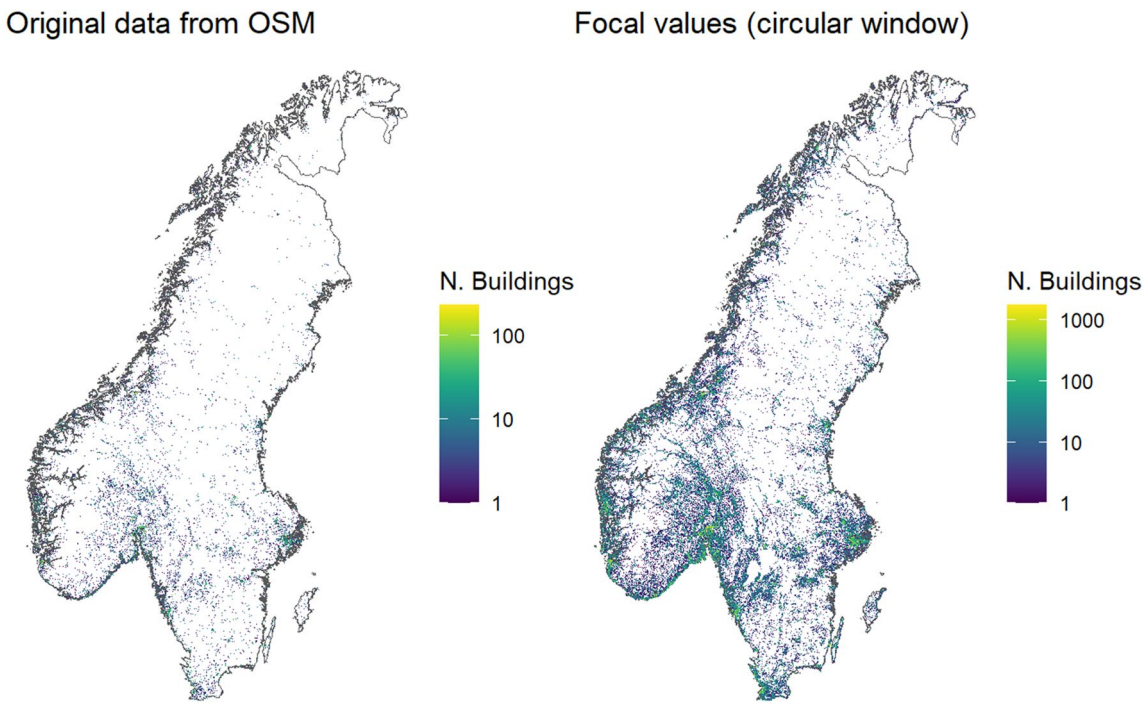

FIGURE 3 | a) Number of buildings per grid cell of 250 x 250 m (Original data—left). b) Smoothed number of buildings per grid cell of 250 m x 250 m (focal values – right).

TABLE 3 | Characteristics of the fuel/vegetation maps.

Map	Type	Raster resolution	Veg classification
SR16	Vegetation	16 m	Spruce (gran) Pine (furu) Deciduous (lauv)
NMD	Vegetation	10 m	Forest (Skog - level 1) Wetland (Våtmark – level 2)
Corine	Vegetation	100 m	Broad-leaved forest Coniferous forest Mixed forest Natural grassland Moors and heathland Sclerophyllous vegetation Transitional woodland-shrub
EFFIS	Fuel	250 m	Short grass Tall grass Brush Dormant brush Southern rough Closed timber litter Hardwood litter Timber
FirEUrisk	Fuel	1000 m	Medium shrubland High shrubland Low grassland Medium grassland High grassland Open broadleaf deciduous Closed broadleaf deciduous Open needleleaf evergreen Closed needleleaf evergreen Open mixed forest Closed mixed forest

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3.2.2 | Vegetation and Fuel Maps

Five datasets were selected to study the biophysical influence on the WUI: i) Corine Land Cover 2018 – CORINE [45], ii) Norwegian Forest Resource map – SR16 [46]; iii) Swedish National Land Cover Database – NMD [47], iv) European Forest Fire Information System (EFFIS) Fuel map [18] and v) a recent published European fuel map at 1 km – FirEUrisk [48]. The details of the maps are shown in Table 3. SR16 and NMD were developed at a national scale, so we merged them for our analysis (i.e., national datasets).

The maps can be divided in two categories: a) vegetation maps (i.e., CORINE, SR16 and NMD) and b) fuel maps (i.e., EFFIS and FirEUrisk). Vegetation maps classify the vegetation only by the species family, while fuel maps group vegetation types with similar fire behaviour into fuel types and models [49]. From these maps, we classify wildland vegetation as only the vegetation/fuel type that is susceptible to burn (Table 3 – Veg. classification; Figure 4a) (Note: from EFFIS dataset, we only selected the 8 categories of potential burnable vegetation presented in the study area, although there are more in the dataset). Wildland vegetation is then used to calculate the percentage of vegetation within a buffer distance from the centre of the grid.

Finally, we calculated the distance from the centre of each grid cell to the closest large wildland vegetation area (i.e., wildland vegetation areas larger than 5 km^2). We took the standard of 2400 m as the baseline to compare results (Figure 4b), and then modified the threshold from 200 to 2400 m (Table 2 – maps not shown).

3.3 | Characterising WUI Fires in the Scandinavian Peninsula

Fire locations (point data) were collected from the *Norwegian Directorate for Civil Protection* (DSB) and the *Swedish Civil Contingencies Agency* (MSB). For Norway, the information collected from the fires is provided by the firefighters attending the incidents. The fire locations are registered by the GPS devices installed in the trucks, which do not capture beginning or the spread of the fires. For Sweden, the fire location is the presumed start of ignition. Fires that have threatened or destroyed houses between 1 January 2016 and 31 December 2023 were selected.

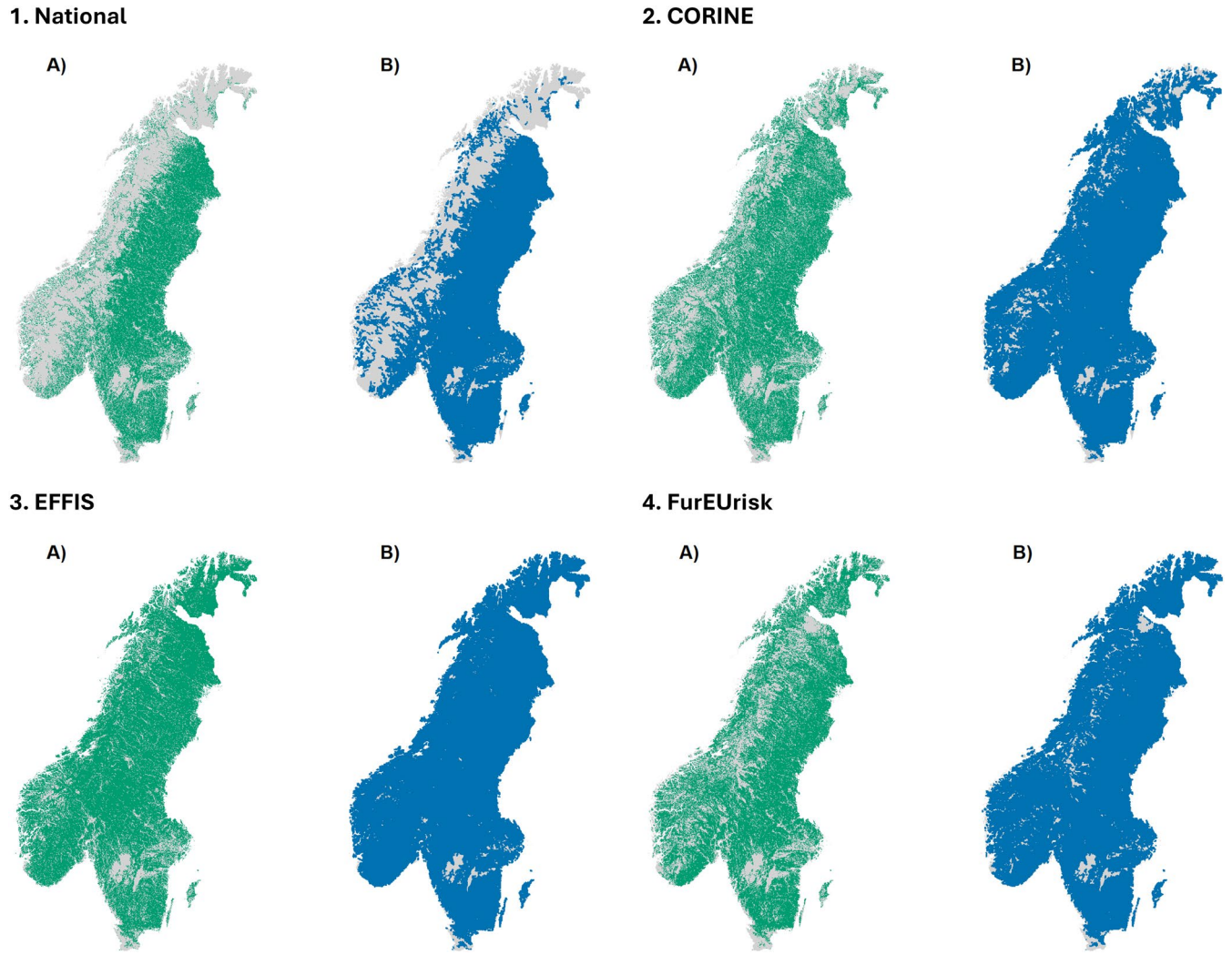

FIGURE 4 | A) Wildland vegetation in the study area based on the different vegetation datasets and B) grids cells within a distance to large vegetation areas (> 5 km^2) of 2.4 km.

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A total of 246 wildfires (88 in Norway and 158 in Sweden) were found that indicated structure damage. The allocation of these fires in WUI classified areas according to the parameters in Table 2 have been analysed to study the accuracy of the maps.

4 | Results

Based on the definition by Radeloff et al. [5], and using the EFFIS fuel map, the total WUI area in the Scandinavian peninsula (excluding the patch belonging to Finland) is 98 054 km^2 (36 302 km^2 interface and 61 752 km^2 intermix), including 4 968 520 building units (3 213 257 WUI interface and 1 755 263 WUI intermix), that is, 12.5% of the land area and 69% of the building stock.

Although WUI areas exist across the entire region, most are in the south, specifically outside the largest cities. In general, the WUI (and settlements overall) is located along natural landscape features, especially coastal and lake shorelines and watercourses. Northern areas, with scarce settlements and low housing densities, have relatively little WUI. Intermix areas are more common than interface areas due to the continuous vegetation cover that extends all the way up to (and into) the perimeters of cities. Only the most southern Swedish county (Skåne) and the area south of the largest lake (Vänern) have large percentages of agricultural land cover.

4.1 | Influence of the Biophysical Component

The data obtained using the different vegetation/fuel information are shown in Table 4 and Figure 5. The proportion of wildland cover varies both spatially (between counties) and between map types, where the highest area proportion of wildland is given by EFFIS, with around 80% compared to 50%–70% given by the other vegetation datasets, although the difference is less evident for Sweden than for Norway. The Norwegian national map (SR16) only considers tree species, not shrubs or grass, making the area covered by vegetation much smaller than the other datasets.

Using the WUI definition of Radeloff et al. [5], Table 4 shows the percentage of WUI for the various vegetation and fuel maps. The total area classified as WUI, as well as both interface and intermix, is higher in Norway than in Sweden, around 12%–17% versus 7%–10%, respectively. There is also an observed difference of classified WUI areas between vegetation/fuel maps; around 5% between the minimum and maximum values in Norway (Table 4) and around 2% in Sweden. These variations may not seem to have a high impact on the consequences of the map selection. However, they represent a considerable increase in the area classified, given the relatively small area that is classified in these countries.

Additionally, depending on the used maps used, there are areas that change their classification between interface and intermix, which could represent a significant change when applying policies and regulations.

4.2 | Influence of the Building Density

Population density in Norway and Sweden is among the lowest in Europe [30]. That is reflected in the low building densities, with average national values of 12.8 and 6.8 #/km^2, respectively, in Norway and Sweden. Furthermore, it varies drastically at the county level and, for example, 1 out of 11 counties in Norway has a building density of 6.2 #/km^2 (i.e., standard threshold for defining an area as potential WUI) or less, while in Sweden it is 5 out of 21.

At grids cells of 250 x 250 m, the population density variation is even larger, as seen in the histogram of building density values (Figure 6). In this regard, there are a lot of disperse dwellings in remote areas in Scandinavia, observed by the high number of cells with a building density of 1.27 #/km^2 (i.e., one building in the studied area). This tendency is more acute for Norway than for Sweden. Nevertheless, both in Norway and Sweden, this means that there is an elevated number of buildings (> 25%) that are isolated, close to vegetated areas, where longer arrival times for the emergency services can be expected and that would not be classified as WUI based on standard thresholds.

It seems therefore that the standard value of 6.17 #/km^2 is relatively high for the Scandinavian countries since it is much higher

TABLE 4 | Percentage of area classified as WUI by country and vegetation-fuel map.

			WUI		
		No WUI (%)	Interface (%)	Intermix (%)	Total (%)
Norway	National	88.7	7.5	3.8	11.3
	Corine	83.1	6.6	10.3	16.9
	EFFIS	82.5	5.9	11.6	17.5
	FirEUrisk	86.5	3.8	9.7	13.5
Sweden	National	90.6	4.5	4.9	9.4
	Corine	91.2	4.1	4.7	8.8
	EFFIS	91.1	3.7	5.2	8.9
	FirEUrisk	92.7	2.2	5.1	7.3

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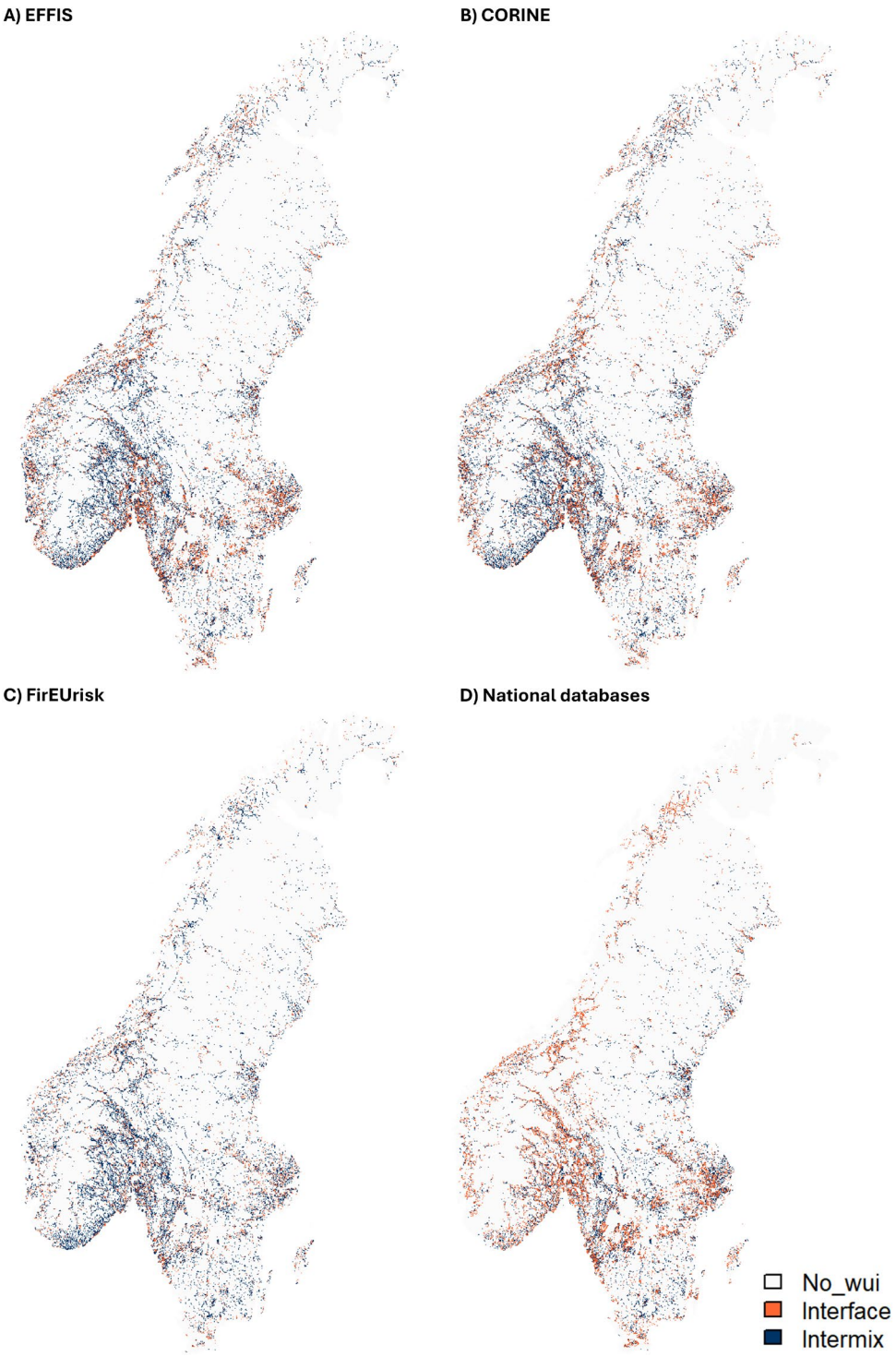

FIGURE 5 | WUI areas based on standard parameters (basemap).

that the 25th percentile (i.e., Q1%–25% of the data are lower than that value) both in Norway Q1 = 2.55 #/km^2 and in Sweden Q1 = 3.82 #/km^2. In fact, the standard value of 6.17 #/km^2 is closer to the median values (i.e., 50% of the data are lower than that value) of 10.19 and 11.46 #/km^2, respectively, for Norway and Sweden. Therefore, for analysing the possible effect on WUI classification, we vary the values of the building density to 1 #/km^2 (i.e., any area with a building is included in the definition of the WUI) and 3.08 #/km [2] (i.e., approximately 25% of grid cells have a building density lower than this value in each country). The resulting maps are shown in Figures 7 and 8, with the obtained results detailed in Tables 5 and 6.

Decreasing the threshold for building density produces an increase in the area classified as WUI. There is a considerable difference between the two studied countries; a more acute decrease is observed in Norway. When decreasing from 6.17 to 3.08 buildings/km^2, there is a slight increase of the average classified area of 3% in the case of Norway, and 1.8% in the case of Sweden. However, this increase is more obvious when decreasing to 1

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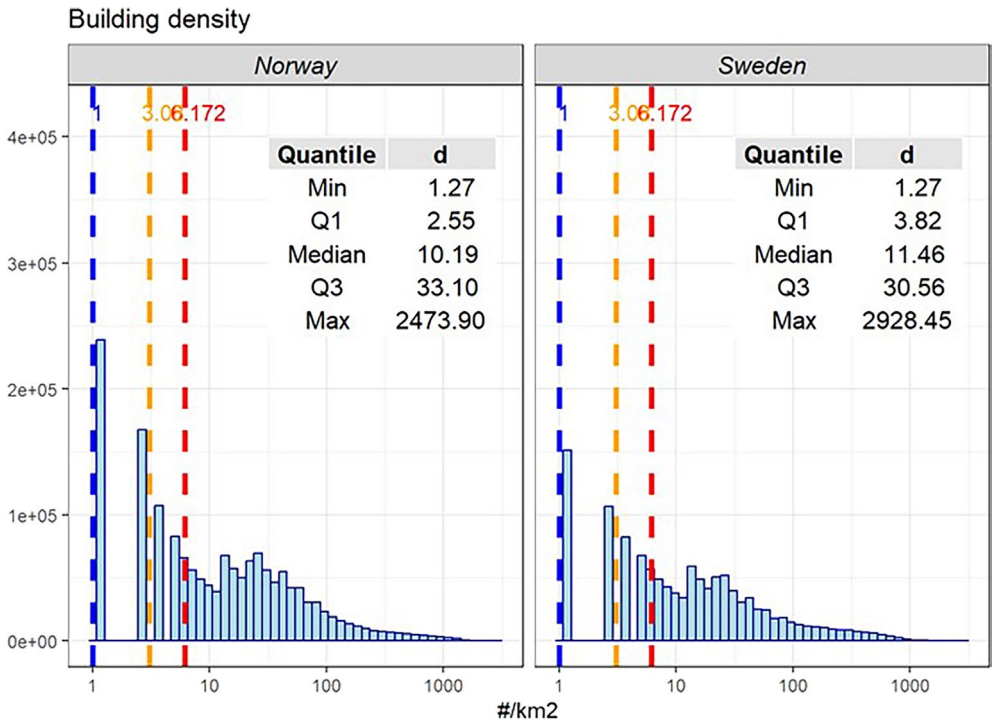

FIGURE 6 | Distribution of building density by country.

building per km^2, with an average WUI area increase of 9.5% for Norway and 5.1% for Sweden. The increase in the classified area for Norway, which has more intermixed WUI, almost doubles the increased area for Sweden, showing a higher dependency of the WUI classification on isolated constructions.

4.3 | Influence of the Fire Component

One of the most controversial parameters included in the definition of WUI is the buffer distance from the vegetation to the infrastructure. This distance is essential to design protection measures around dwellings. It affects the classification of WUI areas (Figure 2) and is linked to the distance that the embers can travel. How the percentage of WUI interface varies with the definition of this value is shown in Figure 9.

An increase of the WUI classified areas is observed when increasing the spotting distance. In almost all the studied situations, there is an initial clear increase of the WUI area when increasing the distance from 200 to 500 m, but this increase is considerably slower when further increasing the distance. There are two exceptions to this. First, when using EFFIS, the percentage is almost constant from 500 m. Second, when using SR16 (national Norwegian), the increase is continuous.

4.4 | WUI Fires in the Scandinavian Peninsula

There were over 9 000 and 51 000 recorded wildfires in Norway and Sweden, respectively, between January 2016 and December 2023. The reporting of these fires to the national authorities (DSB and MSB) is done by the fire brigades, answering to a preestablished form. One of the questions in the form is whether the fire spread outside the original patch of land, the following are the possible answers:

- Detached house
- Other housing
- Commercial buildings
- Garage or other building
- Forest or other open ground
- Grass or another infield
- Tunnel
- Vehicle

From the recorded cases in Norway, 88 fires affected one of the 4 first options. Of these, 12 cases were related to wildfire incidents affecting areas of more than 10 ha. Also of the 88 Norwegian fires, 21 fires affected at least one detached house, 22 affected other housing, only one affected a commercial building and 50 affected garages. During the same period, 180 fire incidents led to the ignition of 262 buildings in Sweden. Eight of those incidents burned an area of more than 10 ha. Of the 158 Swedish fires, 19 affected at least one detached house, 19 affected other housing and the remainder affected garages and other outbuildings. The geographical distribution of wildfires affecting buildings (i.e., 268 wildfires) is shown in Figure 10, where each red dot represents one incident.

The percentage of these fires that would be located in WUI classified areas depending on the different studied parameters are shown in Tables 7 and 8. In this classification, the larger classified areas observed when using the EFFIS map agrees with the

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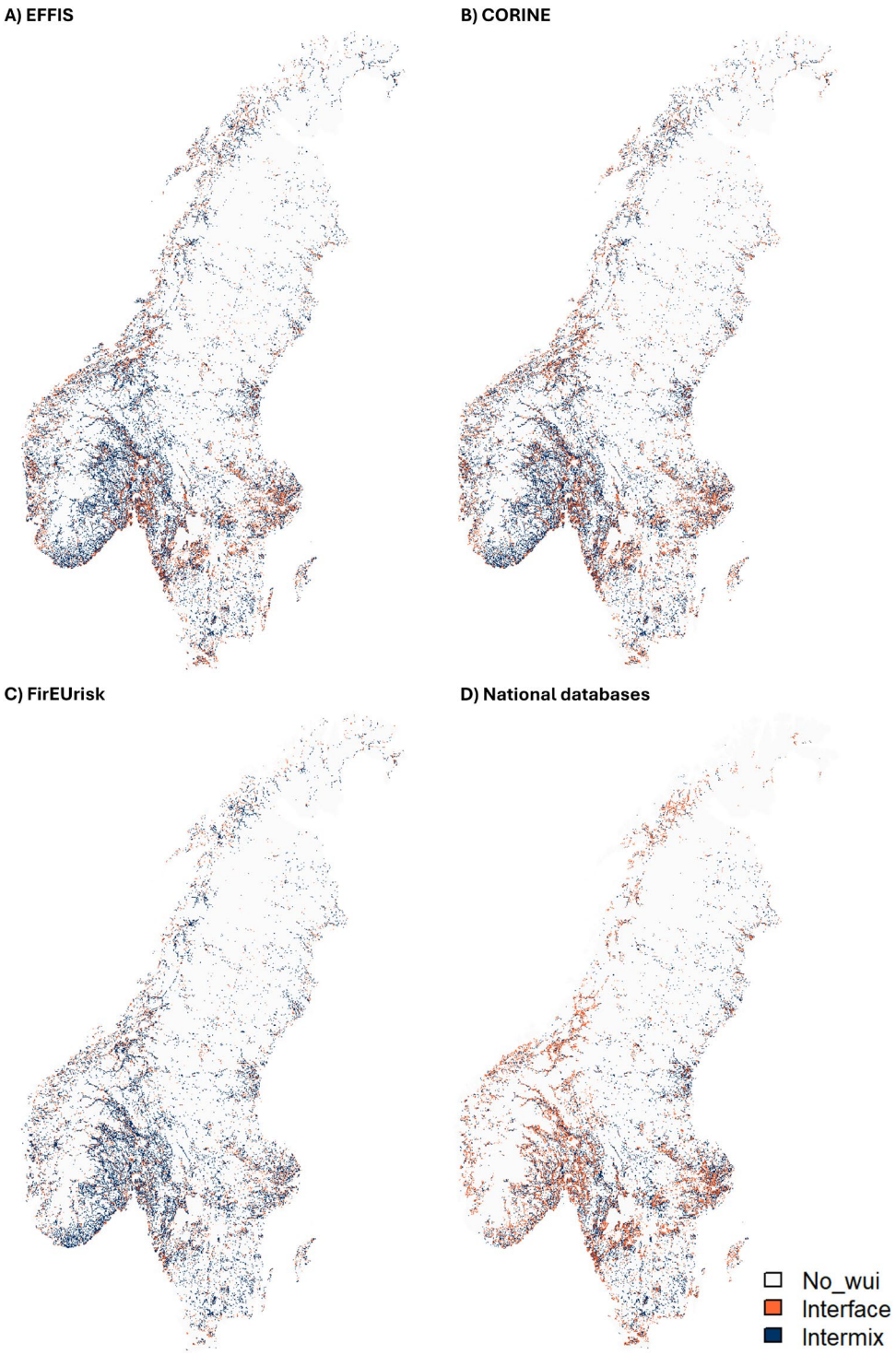

FIGURE 7 | Alternative WUI maps by vegetation and building density of 3.08 buildings per km^2.

largest number of fires located in WUI areas. In the best-case scenario, with 1 building per km^2 using the EFFIS map, 67.9% of the listed fires are located in classified areas, compared to the worst case (National, d200), where 67.2% of the listed fires are located outside WUI areas.

When looking at the building density existing in the areas where these incidents have initiated, it is observed that more than 20% of them were located in areas with no building, and 28% with less than 3 buildings per km^2 (Table 9). Considering the procedure used to determine the building density, as well as the inexact location of the fires (based on the fire truck locations), this suggests that all these fires are located in areas with isolated buildings. If we look at the threshold commonly used for WUI definitions (6.17 buildings per km^2), we see that around 30% of the fires affected buildings located in areas with lower building densities. This shows the need of considering this threshold when defining the concept of WUI.

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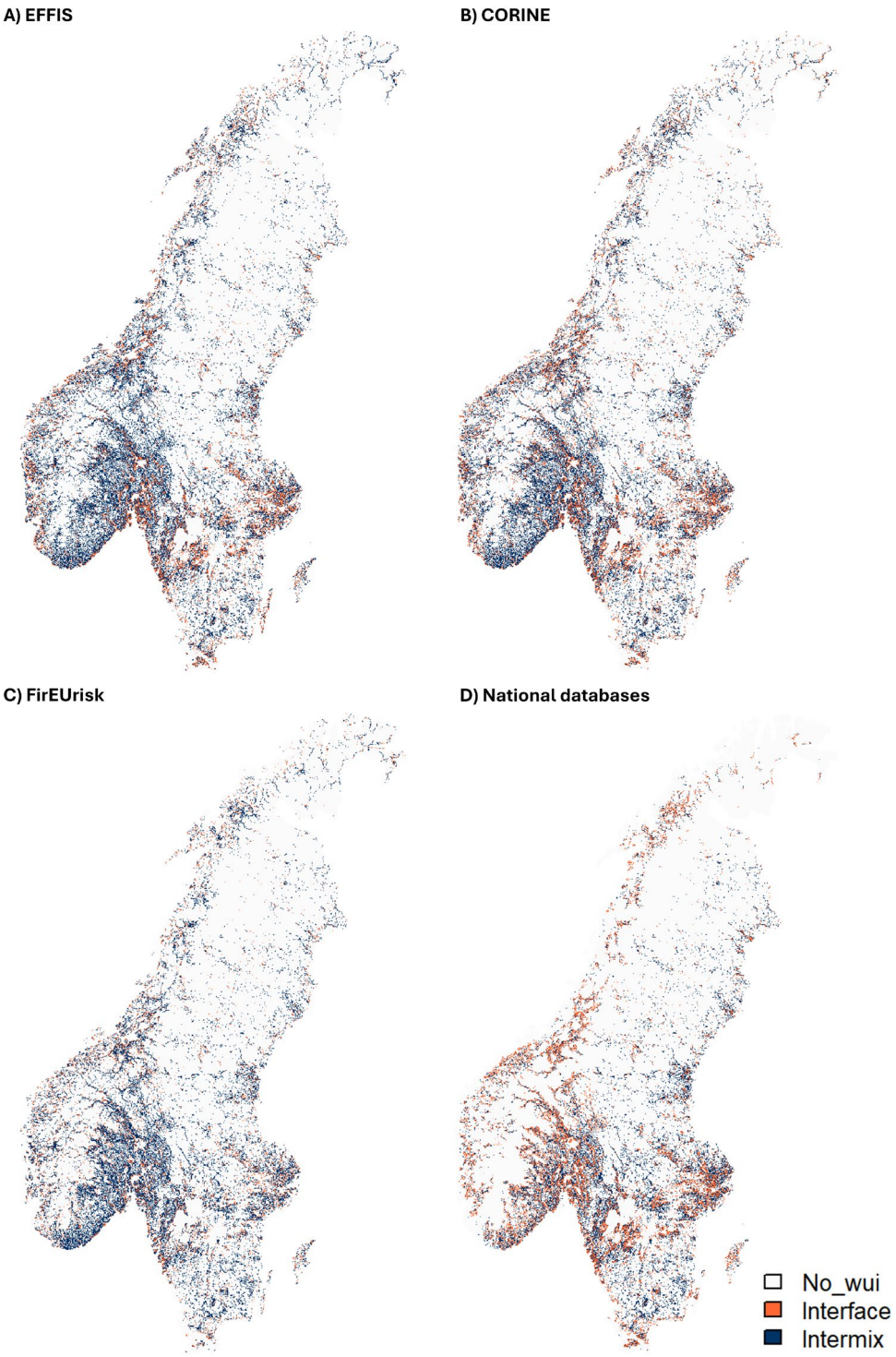

FIGURE 8 | Alternative WUI maps by vegetation and building density of 1 building per km^2.

5 | Discussion

The obvious differences between the Scandinavian peninsula and other parts of the world produce a clear need for studying the way of classifying WUI in this area. The influence of the three components of the WUI definition (vegetation, population and spotting distance) are analysed, and through this process the need to select appropriate parameters becomes evident.

Starting with vegetation, it becomes obvious that shrubs, tall dry grass and fields constitute the most hazardous vegetation types for buildings in Scandinavia [34]. Therefore, one may discuss the vegetation criterion in the classical WUI definition further: tall grass is considered 'combustible', while the arable land is considered 'noncombustible'. It is also necessary to differentiate grasslands from lawns, which is the single most important feature for building protection [32], when mapping the WUI. Maps that do not consider all the fire prone vegetation might produce WUI

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TABLE 5 | WUI and no WUI distribution of areas for different building densities thresholds in Norway.

Norway	Building density	No WUI (%)	WUI		
			Interface (%)	Intermix (%)	Total (%)
National	3.08	86.5	8.4	5.1	13.5
Corine		79.7	7.3	13.0	20.3
EFFIS		79.0	6.3	14.8	21.0
FirEURisk		83.7	4.4	12.0	16.3
National	1.00	82.0	10.2	7.8	18.0
Corine		72.5	8.8	18.6	27.5
EFFIS		71.4	6.8	21.8	28.6
FirEURisk		77.5	5.6	16.9	22.5

TABLE 6 | WUI and no WUI distribution of areas for different building densities thresholds in Sweden.

Sweden	Building density	No WUI (%)	WUI		
			Interface (%)	Intermix (%)	Total (%)
National	3.08	88.7	5.0	6.3	11.3
Corine		89.3	4.5	6.1	10.7
EFFIS		89.2	4.2	6.7	10.8
FirEURisk		91.0	2.5	6.5	9.0
National	1.00	85.4	5.8	8.8	14.6
Corine		86.0	5.3	8.6	14.0
EFFIS		85.8	4.8	9.3	14.2
FirEURisk		88.0	2.0	8.9	12.0

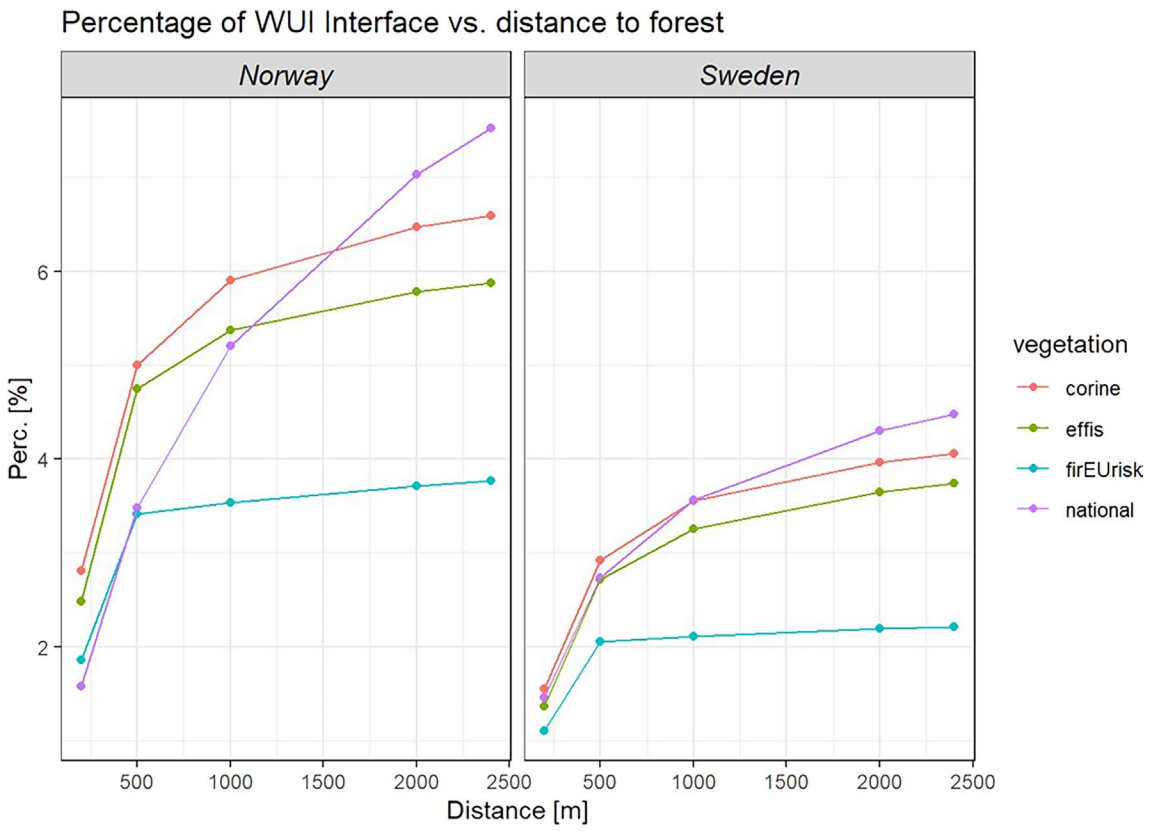

FIGURE 9 | Percentage of WUI interface by vegetation map and distance to large vegetation areas.

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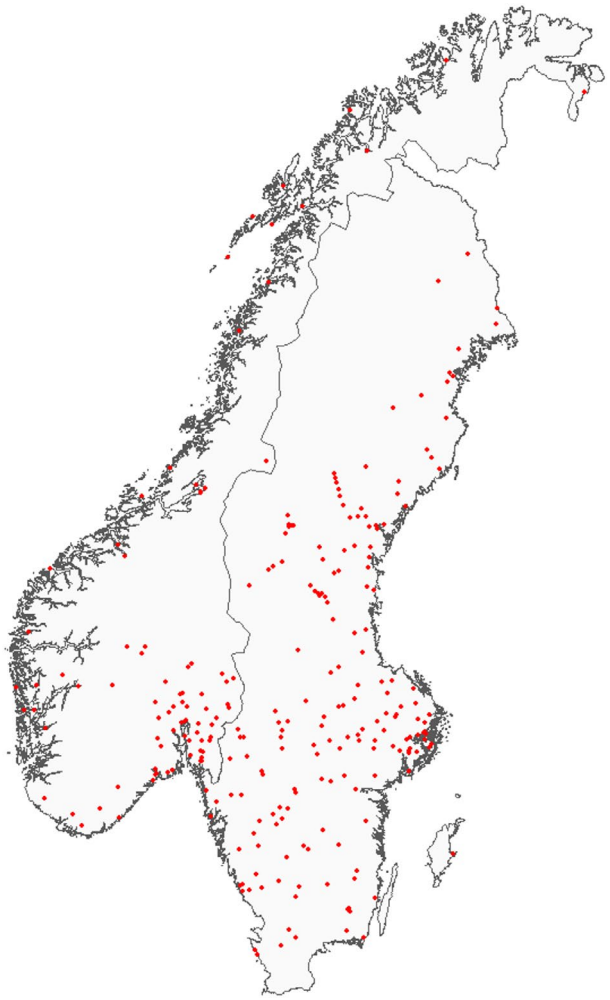

FIGURE 10 | Geographical distribution of wildfires affecting buildings (i.e., 268 wildfires), where each red dot represents one incident.

maps with classified areas that do not accurately represent the risk. A clear example of this is the national map used in Norway (SR16), which only includes three species of trees, considering that the area covered by vegetation in the country is smaller; hence, the areas at risk are also decreased.

Another important point is the map raster resolution. The larger the resolution, the least precise the results will be. However, low resolutions are difficult to access and to work with. Therefore, a balance between both should be considered when choosing the maps to be used.

In this study, four maps have been analysed: two vegetation maps and two fuel maps. The EFFIS map considers more vegetated area in both countries. When using this map, the percentage of land classified as WUI intermix is the largest for both countries since the percentage of vegetation considered flammable is larger.

A question to be raised is how much the vegetation propensity to ignite varies depending on the season. Vegetation/fuel maps do not vary with the seasons; however, the influence of weather in Scandinavia is considerable, making some vegetation prone to ignite during some times of the year, but not probable during others. On the other hand, changing WUI classifications

TABLE 7 | Percentage of fires affecting infrastructures in Norway and Sweden that would be located in WUI classified areas depending on the buffer distance and the vegetation/fuel map.

	D200	D500	D1000	D2000	D2400
EFFIS					
No WUI	60.1	46.3	41.0	38.4	37.3
Interface	10.1	23.9	29.1	31.7	32.8
Intermix	29.9	29.9	29.9	29.9	29.9
Corine					
No WUI	61.2	48.5	44.4	40.3	39.6
Interface	13.1	25.7	29.9	34.0	34.7
Intermix	25.7	25.7	25.7	25.7	25.7
National					
No WUI	67.2	57.8	55.2	50.4	48.1
Interface	12.3	21.6	24.3	29.1	31.3
Intermix	20.5	20.5	20.5	20.5	20.5
FirEUrisk					
No WUI	62.7	56.3	56.3	56.3	56.3
Interface	9.0	15.3	15.3	15.3	15.3
Intermix	28.4	28.4	28.4	28.4	28.4

depending on the season can also be difficult in terms of regulations related with these areas.

When focusing on the building density, it has been observed that the population distribution in these countries does not follow the same pattern as other places, such as southern Europe. Northern Europe typically has distribution with more isolated buildings, or communities that are considerably less dense. This change in the distribution shows that the 6.17 buildings per km^2 commonly used to determine the location of WUI does not cover the observed WUI fire problem of northern Europe. When using a population density of 1 building per km^2, which is a better fit for Norway and Sweden, the area classified as WUI considerably increases. If this criterion is used, all the buildings will be covered in the WUI definition, ensuring their inclusion in wildfire risk planning activities. However, there are costs associated with using this classification compared with using the current 6.17 #/km^2. A complete cost–benefit analysis would be necessary in this case to determine the pros and cons of this decision.

The last parameter studied is the spotting distance, the distance that embers are expected to travel, which should be accounted for in order to have a protective area around the constructions. The determination of the spotting distance has attracted high attention in the last years, but there is no existing model that could be implemented for all types of vegetation. It has been observed that not only burning woodlands can transmit embers, but bushes and shorter vegetation also transmit embers in a shorter range (50 to 100 m). Additionally, this distance not only depends on the type of vegetation but also on the climatic conditions,

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TABLE 8 | Percentage of fires affecting infrastructures in Norway and Sweden that would be located in WUI classified areas depending on the building density and the vegetation/fuel map.

	EFFIS	Corine	National	FirEUrisk
1 #/km^2				
No WUI	32.1	34.3	42.5	51.5
Interface	34.7	36.2	33.2	16.0
Intermix	33.2	29.5	24.3	32.5
3.08 #/km^2				
No WUI	36.2	38.4	47.0	55.6
Interface	33.2	35.1	31.7	15.3
Intermix	30.6	26.5	21.3	29.1
6.17 #/km^2				
No WUI	37.3	39.6	48.1	56.3
Interface	32.8	34.7	31.3	15.3
Intermix	29.9	25.7	20.5	28.4

TABLE 9 | Building density of the areas where fires affecting infrastructures have originated.

Building density [#/km [2]]	Wildfires		
	Number	Percentage [%]	Cumulative [%]
[0,1)	62	23.1	23.1
[1,3)	13	4.9	28.0
[3,6)	3	1.1	29.1
[6,10)	11	4.1	33.2
[10,20)	31	11.6	44.8
[20,50)	50	18.7	63.4
[50,100)	40	14.9	78.4
[100,500)	39	14.6	92.9
[5001,700]	19	7.1	100.0

mainly wind speed and direction, as well as on the intensity of the fire. For Nordic countries, the average wind speed, as well as the number of days with high wind speeds per year are relatively high. This influence should be included when discussing the spotting distance, making more necessary a larger distance when classifying WUI.

This analysis shows that the existing WUI classifications available provide much lower areas than those obtained when using regional knowledge. Therefore, it is essential to define the WUI accordingly to ensure safe areas. However, a complete cost–benefit analysis should be done to understand the costs that a more conservative approach could incur in the implementation of the expected rules for WUI areas.

6 | Conclusions

There is an obvious need for mapping the WUI in Northern Europe to design prevention and protection measures in these areas against the expected increase in wildfire risk in the coming years. When looking at the distribution of vegetation and buildings in Norway and Sweden, it can be observed that the WUI is scattered over the region, and the highest concentration is found in the southern part of both countries, where the largest percentage of population is located.

However, the use of different resources to delimit these areas (vegetation/fuel maps), as well as changing the thresholds from the definitions show a large variation in the results. The vegetation/fuel map used, building density and buffer distance are key parameters that need to be well-defined and pre-established to ensure the correct classification of WUI areas. The building density is key to define the WUI zones in these areas, showing that for a more realistic representation, considering all the existing buildings would be the safest approach, while the most used building density of 6.17 buildings per km^2 misrepresents the reality and leaves a high number of dwellings potentially at risk without being classified.

It has been observed that the selection of these parameters is area-dependent and needs to take into consideration the specific characteristics of the study zone. The types of vegetation and the area vegetated, as well as the distribution of dwellings in the area need to be defined in advance to ensure a correct classification.

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Conflicts of Interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript andthere is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

Data Availability Statement

The data that support the findings of this study are openly available in:

Geofabrik GmbH at https://www.geofabrik.de/.

Map data copyrighted OpenStreetMap contributors at https://www.openstreetmap.org/.

EFFIS (© European Union) at https://forest-fire.emergency.copernicus.eu/applications/data-and-services.

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Corine Land Cover 2018 at https://land.copernicus.eu/en/products/corine-land-cover.

NIBIO - Norwegian Forest Resource at https://www.nibio.no/tema/skog/kart-over-skogressurser/skogressurskart-sr16.

Swedish National Land Cover at https://www.naturvardsverket.se/en/services-and-permits/maps-and-map-services/national-land-cover-database/.

FirEURisk Europe fuel map (Aragoneses, Garcia, and Chuvieco 2022) at https://edatos.consorciomadrono.es/dataset.xhtml?persistentId=doi:10.21950/YABYCN.

The data from the wildfires datasets are available under request to the *Norwegian Directorate for Civil Protection (DSB)* and the *Swedish Civil Contingencies Agency (MSB)*.

The R scripts used in this article can be found at https://github.com/javiereliomedina/wui_definition_neur.

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