OCTOBER 2020

HOW NEW ZEALAND WILDFIRE OCCURRENCES CORRESPOND WITH FIRE RISK DETERMINED BY THE RURAL-URBAN INTERFACE

FINAL YEAR RESEARCH PROJECT

NATHAN LUFF
UNIVERSITY OF CANTERBURY

Acknowledgements

I would like to thank Professor Rien Visser and Campbell Harvey for their guidance and supervision throughout the entirety of the project. I would also like to acknowledge Grant Pearce and Veronica Clifford from Scion for providing the data on wildfire occurrences and for the experienced advice they were able to offer. Finally, to my classmates for the encouragement and sense of comradery that helped to make the project possible.

Executive Summary

In this report, wildfire occurrence locations were compared with the Rural-Urban Interface (RUI) extent for three case study locations to test the reliability of the RUI as a tool for estimating fire risk. With a global history of severe fire events causing devastation around the world and a likely increase in future fire activity predicted due to climate change, it is important that people have reliable fire management tools for minimizing the effects of wildfire on our communities.

An appropriate method for creating RUI maps was found after a review of the literature, as well as a set of definitions and threshold values that best suited the objective of the study. RUI maps were created for the three case study areas (Rotorua, Christchurch, and Wellington) using the applied method, combining individual building footprints and land cover data to define the RUI extent.

Wildfire occurrence locations were overlaid onto the RUI maps to find the proportion of wildfires that occurred inside the RUI for each case study area. The results showed that a wildfire is 1.9 times more likely to occur inside the RUI.

Maps illustrating the distribution of different vegetation covers (fuel classes) were also created for each case study area to further investigate the effects of different fuel classes on RUI extent. It was found that areas of ‘Cropland & Grassland’ were inevitably included in the RUI extent, suggesting that this can always be assumed.

This study confirms that wildfire risk is highest in RUI areas, however; it also endorses recommendations from previous studies that there is no ‘true’ or ‘best’ representation of the RUI. The most suitable method and parameters should be selected based upon context and availability of data.

Table of Contents

1. Introduction

In recent history, severe wildfire events have affected many countries and communities around the world. In October 2003 the Cedar Fire in San Diego County burned more than 113,000 hectares of land, resulting in the death of 15 people, the destruction of approximately 2227 homes, and $30 million USD in overall damages (Brillinger et al., 2009). More recently, the 2019-2020 Australian bushfire season saw more than 18 million hectares of land burned and 34 people killed, becoming one of the most catastrophic fire events in Australian history (Centre for Disaster Philanthropy, 2020).

Several international studies have predicted an increase in future fire activity due to global warming and climate change (Flannigan et al., 2009; Brown et al., 2004; Pearce & Clifford, 2008; Pearce et al., 2005). This highlights the importance of having effective and updated fire management plans and resources so that future fire events can be mitigated as much as possible.

The most at-risk communities are those that are part of the rural-urban interface (RUI), which is the area of land where people and their development intermix with flammable vegetation (USDA & USDI, 2001). Numerous international studies have developed a methodology for mapping the RUI (Stewart et al., 2007; Lampin-Maillet et al., 2009; Radeloff et al., 2005; Zhang et al., 2008) so it can be used as a tool for estimating wildfire risk.

The rate at which the RUI expands must also be monitored to keep control of the close relationship between RUI area and wildfire ignitions. With such a dynamic environment, it is necessary to have versatile resources in place to enable awareness of any change to the RUI.

This study aims to test the reliability of the RUI as a tool for estimating wildfire risk by comparing the location of actual fire occurrences with the RUI extent for three case study locations. Further investigation will also be carried out to assess the relationship between wildland vegetation fuel type and RUI extent.

2. Literature Review

2.1 Rationale and Context

New Zealand experiences somewhere between four and five thousand vegetation fires per annum (Fire and Emergency New Zealand, 2019), which is a relatively small number when compared internationally. However, a vegetation fire on the Port Hills resulted in the evacuation of more than 1400 residents and the destruction of nine houses on the margin of Christchurch City in 2017 (Langer et al., 2018).

This event is considered one of the biggest, most severe wildfires in recent New Zealand history, and is a reminder that New Zealand landowners are vulnerable to the damaging effects of wildfire events. It also draws attention to the need for effective fire management planning and tools for areas most susceptible to such events. These areas are collectively known as the Rural-Urban Interface (RUI).

Pearce et al. (2014) explain that while there are numerous existing fire risk assessment and mitigation planning systems already operational in New Zealand, none of them specifically focus on or quantify the risk associated with wildfires in the RUI.

2.2 Definition of the Rural-Urban Interface

Since the extent of the RUI is useful for comparison across locations and time periods, it is important to define it using a set of standardized definitions. Despite the extensive literature written on the topic, a commonly accepted definition for the RUI (or WUI – wildland-urban interface – as it is referred to in the United States) is yet to be established (Stewart et al., 2007). The original definition given to the RUI was "any point where fuel feeding a wildfire changes from natural [wildland] fuel to man-made [urban] fuel" (Butler, 1974, cited in (Platt, 2010)). The theoretical understanding of the term progressively evolved until it was formally defined in the US Federal Register as "where humans and their development meet or intermix with wildland fuel." (USDA & USDI, 2001). This general definition has been widely referenced in the literature since its publication. However, the Federal Register definition has not been officially adopted and studies continue to redefine its parameters for different usages and contexts. It is important to note that the RUI refers to a 'community' of rural buildings rather than isolated houses.

The RUI is commonly broken into three contributing components, including human presence, wildland vegetation, and a buffer distance that represents the potential for effects (e.g. wildfire) to cross boundaries and impact neighbouring lands (Stewart et al., 2007). Several studies (Haight et al., 2004; Radeloff et al., 2005; Stewart et al., 2007) define the human presence component by the density threshold value of '>1 structures per 40 acres' (6.17 structures/km^2) set by the Federal Register (USDA & USDI, 2001). Platt (2010) explains that to meet this density threshold, structures in the area must be within a 1,890 ft. (576 m) radius of each other. At this distance, a set of 40-acre square blocks with one structure at the centre of each would be the minimum required density to meet the threshold.

Stewart et al. (2007) define wildland vegetation as "all types of vegetative cover except those that are clearly not wild, such as urban grass, orchards, and agricultural vegetation". For areas that meet the building density threshold, if at least 50% of the area represents wildland vegetation the RUI is classed as Intermix. Also, according to this study, areas that have less than 50% wildland vegetation but are situated within a 1.5-mile (2.4 km) buffer distance (i.e. buffer component) of a 5 km^2 area of at least 75% wildland vegetation are classed as Interface (Figure 1). This buffer distance is representative of the distance an average firebrand can fly and potentially reach a structure (Stewart et al., 2007; Summerfelt, 2003).

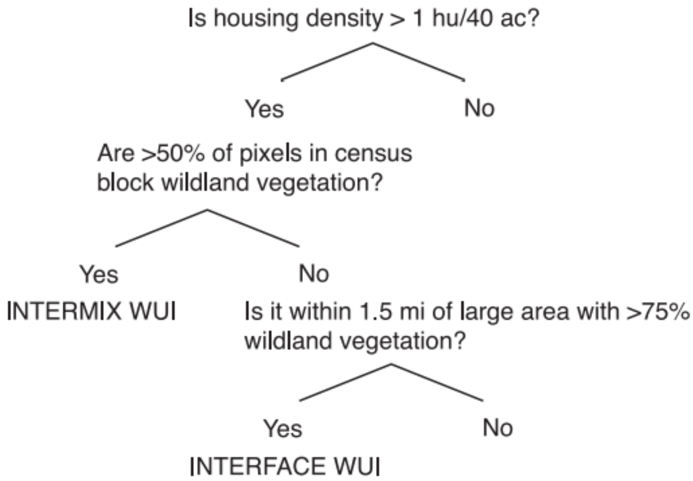

Figure 1: Method for distinguishing between intermix and interface RUI (Stewart et al., 2007)**.**

However, sensitivity analysis carried out by Pearce et al. (2014) found that a buffer distance of 500 m is a more suitable value for New Zealand. The reduced distance represents a more accurate estimate of spotting distances for New Zealand plant species typically found in RUI areas, including gorse, manuka scrub, and pine trees (Pearce et al., 2014). Since this is a New Zealand study, the 500 m buffer distance will be used as a parameter for the RUI mapping method.

A study by Anderson et al. (2008) analysed New Zealand wildfire records from 1991-2007 to determine trends in fire occurrences. The results found that of the total area burned, 54% was made up of grasslands, 40% scrublands, and only 6% forests. In conjunction with these results and at the recommendation of Scion researchers, wildland vegetation will include grassland and scrubland land covers for the purpose of this study.

Two studies (Radeloff et al., 2005; Stewart et al., 2007) conducted a sensitivity analysis to test the robustness of RUI area estimates based on the above threshold values for housing density, vegetation density and buffer distance, both concluding that the values provide a robust RUI assessment (Tables 1 and 2), validating the use of these parameters.

Table 1: Sensitivity analysis of RUI definition thresholds (Radeloff et al., 2005).

Variable	California Area (1000s km^2)	California Houses (100 000s housing units)	North Carolina Area (1000s km^2)	North Carolina Houses (100 000s housing units)	New Hampshire Area (1000s km^2)	New Hampshire Houses (100 000s housing units)
Federal Register definition†	29.3	50.9	55.3	23.2	9.6	4.5
Housing density						
>3.09‡	41.1	51.4	74.0	24.1	13.5	4.6
>12.34	20.7	50.1	33.5	21.3	5.9	4.1
Intermix vegetation						
>25%	30.7	58.0	62.8	27.9	9.7	4.6
>75%	28.6	49.0	47.5	20.6	9.5	4.4
Interface distance						
<4.8 km	33.0	74.7	59.3	28.3	9.7	5.2
<1.2 km	26.4	35.2	52.3	19.8	9.4	3.9
Wildland vegetation						
Upland only†	29.1	50.5	45.4	18.8	9.4	4.0
Forest only†	10.0	6.2	44.8	18.5	9.4	4.0
Minimum WUI†	4.6	3.8	5.0	2.8	5.0	2.8
Maximum WUI†	46.5	79.1	83.1	28.1	13.6	5.4

† See *Methods: WUI definition and assessment* for definition.
‡ Housing units per km^2.

Table 2: Sensitivity analysis of RUI definition thresholds (Stewart et al., 2007).

	California	Colorado	Florida	Michigan	North Carolina	New Hampshire	Washington	Average
Original WUI								
Area (1,000,000 ac)	7.23	1.98	6.97	5.84	13.66	2.38	3.75	—
Housing (100,000 HUs)	*50.9*	*8.4*	*25.9*	*9.7*	*23.2*	*4.5*	*12.0*	—
Percent change in response to parameter changes (percent change in area, *percent change in housing units*)								
Housing density (original, >1 HU/40 ac)								
>1 HU/ 80 ac	40.6	71.7	39.8	62.3	34.0	40.0	36.9	46.5
	1.0	*3.0*	*1.9*	*6.7*	*3.7*	*3.9*	*2.0*	*3.2*
>1 HU/ 20 ac	−29.2	−39.6	−33.7	−45.6	−39.4	−39.0	−29.8	−36.5
	−1.5	*−3.3*	*−3.2*	*−9.7*	*−8.3*	*−7.4*	*−3.3*	*−5.2*
Intermix vegetation density (origina,l >50% of pixel)								
>25% of pixel	4.9	5.4	11.1	47.4	13.7	0.6	6.4	12.8
	14.0	*5.8*	*17.8*	*57.1*	*20.3*	*2.6*	*22.5*	*20.0*
>5% of pixel	−2.3	−2.3	−8.2	−18.5	−14.1	−0.8	−3.8	−7.1
	−3.7	*−1.9*	*−6.2*	*−20.3*	*−11.5*	*−1.4*	*−8.2*	*−7.6*
Interface buffer size (original, 1.5 mi)								
3.0 mi	12.6	10.0	13.7	12.1	7.4	1.2	9.4	9.5
	46.7	*33.3*	*49.0*	*19.9*	*21.7*	*15.7*	*29.3*	*30.8*
0.75 mi	−9.9	−8.5	−9.6	−6.8	−5.3	−1.8	−7.5	−7.1
	−3.7	*−24.1*	*−27.9*	*−13.5*	*−14.7*	*−13.5*	*−20.2*	*−20.7*
Vegetation (original all wildland vegetation)								
Upland only	−0.6	0.2	−12.7	−30.8	−17.9	−1.8	−0.6	−13.9
	−0.8	*0.2*	*−71.5*	*−3.6*	*−18.8*	*−9.9*	*−1.9*	*−20.0*
Forest only	−65.9	−57.6	−20.7	−37.9	−18.8	−1.9	−19.5	−39.3
	−87.8	*−76.2*	*−86.8*	*−4.3*	*−20.3*	*−11.0*	*−31.0*	*−51.0*
WUI scenarios[a] (simultaneous changes)								
Maximum	58.9	91.2	64.3	134.2	50.4	41.3	52.8	70
Extent	*55.5*	*39.3*	*61.4*	*79.0*	*20.9*	*19.8*	*45.4*	*46*
Minimum	−84.3	−80.7	−94.4	−83.1	−50.9	−48.0	−52.9	−71
Extent	*−92.5*	*−83.4*	*−95.5*	*−75.7*	*−22.9*	*−37.9*	*−55.3*	*−66*

[a] Maximum extent: housing density > 1 HU/80 ac, intermix vegetation density >25%, interface buffer 3 mi, vegetation all wildland; minimum extent: housing density > 1 HU/20 ac, intermix vegetation density > 75%, interface buffer 0.75 mi, vegetation forest only.
Note: Figures in italics give percent change in housing units.

2.3 Review of Existing RUI Mapping Methods

Since the RUI is the interface of human development with wildland vegetation, it can be computed by finding the spatial intersection of wildland vegetation with areas of appropriate building density. Throughout the literature, a significant number of international studies have developed their own adaptations of RUI definitions and mapping techniques. Pearce et al. (2014) tested the application of four methods for spatially identifying RUI areas.

Three of these methods (Zhang et al., 2008; Haight et al., 2004; Theobald & Romme, 2007) use census meshblock data for housing density together with vegetation land cover data to identify the RUI and define its categories. Meshblocks are aggregations of point-based features that are bounded by physical features such as roads and streams, causing large variation in size and limited resolution in more rural areas (Bar-Massada et al., 2013). This zonal approach provides a useful gauge to the extent of RUI areas, although the variable nature of the data itself brings limitations to the precision of density values.

The limitations of census-block data are due to the size of each unit depending on housing density, trending towards larger units where houses are more widely spread. This can result in large census blocks being excluded from the RUI when it contains a small area of clustered homes that is outweighed by large uninhabited spaces (Stewart et al., 2009).

In response to this problem, Theobald & Romme (2007) used ancillary data to alter the census-block boundaries by removing public land and water land cover (i.e. rivers, lakes, etc.) from the building density calculation. The use of this process is based on the assumptions that buildings are not located on water and that public land contains no private housing.

Similarly, Stewart et al. (2007) made their definition of wildland vegetation more specific by the inclusion and exclusion of appropriate vegetation types according to their definition of wildland vegetation.

The fourth tested method (Lampin-Maillet et al., 2009) combines individual building footprint data with vegetation cover data to identify the RUI based on precise building locations and further classify it using the distance between buildings and vegetation structure. Pearce et al. (2014) suggest that the Lampin-Maillet method provides a better description of the true RUI area compared to the meshblock-based approaches; however, the building footprint data was not available for every New Zealand region at the time their report was published. Since then, a comprehensive national building footprint data layer has been developed and made available, permitting a precise estimation of the RUI in New Zealand and avoiding the use of subjective definitions based on zonal density. The Lampin-Maillet method is so thorough in its identification of RUI buildings that it will recognize the most isolated of dwellings that fit the method criteria. However, the premise of a RUI map is to identify the communities that are at risk due to the close proximity of vegetation fuels. Therefore, including individual homes makes the RUI classification less useful for targeting appropriate communities for fire safety programs and will put a strain on the budget constraints of fire managers (Bar-Massada et al., 2013).

Building footprint data methods such as the Lampin-Maillet method avoid the need for removal of public land or water areas because they are based on the precise distance between structures and vegetation, rather than an aggregated density value per census-block.

Bar-Massada et al. (2013) have developed a hybrid method that utilizes the building density threshold from the zonal approach but calculates building density values based on building footprint data as opposed to meshblock data, resulting in the inclusion of appropriate communities only. This technique computes the density of structures and wildland vegetation of a 'neighbourhood' around each map cell within a radius *r* by using a moving window analysis to create a series of raster maps, which are then combined to form the RUI map. A notable advantage of this method is that only two different datasets are required to determine the RUI (building footprint and vegetation cover).

To assess the sensitivity of RUI extent to the neighbourhood radius size *r*, Bar-Massada et al. (2013) tested and compared 10 values of *r* ranging from 100 to 1000 m. The results showed that the choice of neighbourhood size *r* had a significant effect on the subsequent RUI extent (Figure 2). To be consistent with the density threshold published in the Federal Register (USDA & USDI, 2001), the maximum radius of 576 m recommended by Platt (2010) will be used as *r*.

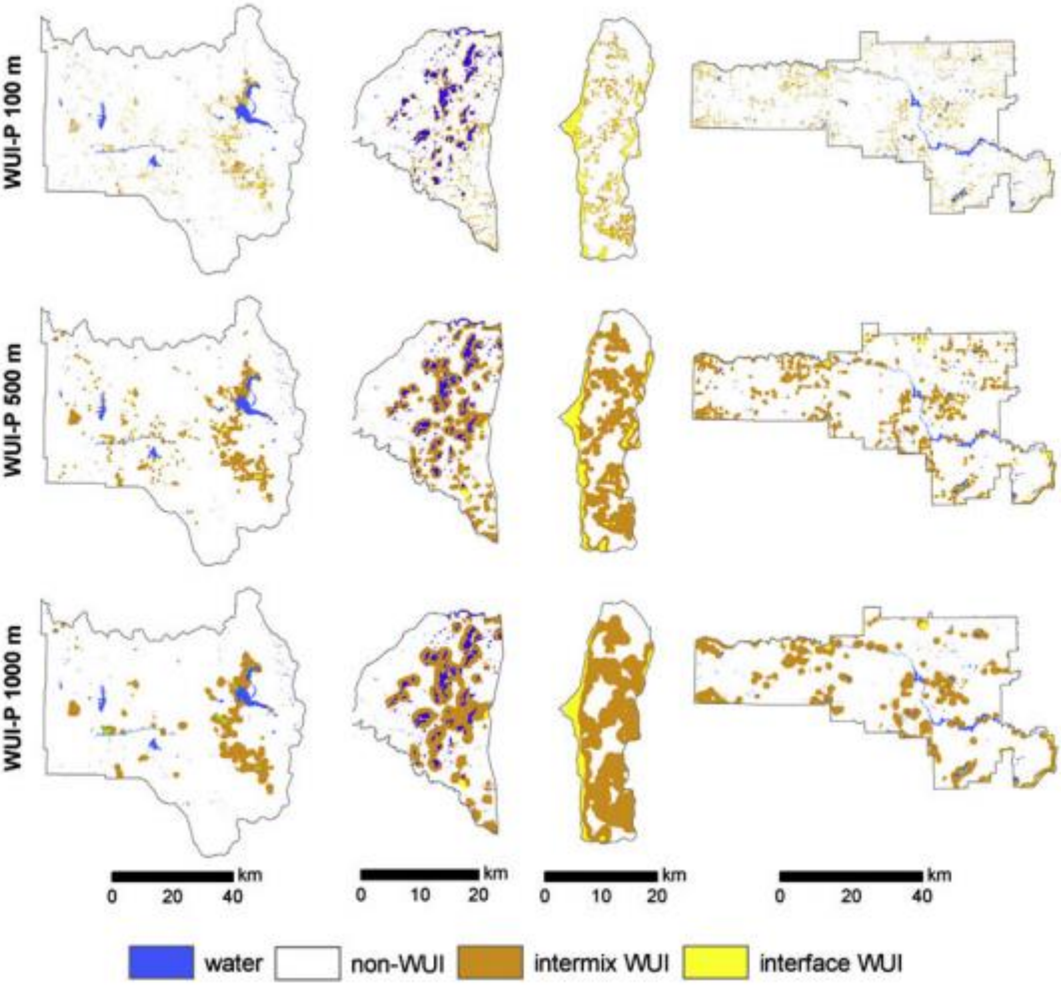

Figure 2: Spatial results of sensitivity analysis comparing different values of neighbourhood size *r* (Bar-Massada et al., 2013).

A study in Canada extended the RUI concept to address potentially vulnerable industrial/ commercial buildings and infrastructure that are not typically included in the RUI (Johnston & Flannigan, 2018), based on the importance of industrial values that can also be affected by wildfire. They produced two new maps identifying the intersection of industrial structures and infrastructure with wildland vegetation.

More specific methodology has been developed to explicitly identify RUI areas of high wildfire risk. Haas et al. (2013) developed a method that intersects human population data with a wildfire simulation model to create a risk-based map that highlights the magnitude and likelihood of wildfire occurrence in the RUI. Similarly, Lu et al. (2010) linked land cover data with historical wildfire records to create a map that compares wildfire risk levels for different RUI areas (Intermix vs Interface).

Despite the extensive range of RUI mapping techniques present in the literature, it is widely agreed that there is no single method that satisfactorily produces a 'true' or 'best' representation of the RUI area over a region or country (Pearce et al., 2014). Choosing the right method depends on the purpose for which each method was developed and the quality of data and analysis on which it is based (Stewart et al., 2009). It is therefore important that all assumptions and limitations associated with any method should be made explicit following its implementation.

2.4 Impact of RUI Growth

A study in the United States found that human activity is responsible for the cause of approximately 80% of all wildfires (Nagy et al., 2018). As the RUI represents areas where humans (and their activity) meet flammable vegetation, it therefore creates an area of significantly increased wildfire ignition risk.

A study in Central Spain showed that spatial patterns of wildfire ignition are strongly associated with areas of human activity, with proximity to roads and urban areas being the most influential factors (Romero-Calcerrada et al., 2008). This evidence is further supported by Lampin-Maillet et al. (2009), who found that fire ignition density was twice as high in RUI areas. This suggests that as the RUI expands, so will the number of wildfire ignitions (Radeloff et al., 2018).

Radeloff et al. (2018) revealed that the RUI area in the United States grew by 33% from 1990 to 2010. Of this increase, 97% of the new RUI areas were a result of the construction of new homes. This result suggests that RUI growth is strongly propelled by social and economic reasons, including the affordability of rural houses (or lifestyle blocks) that provide ready access to nature and recreation while being only a short distance from urban settings.

In 1998, New Zealand had a total of just over 100,000 lifestyle properties. By 2011 this number had risen to 175,000 (an increase of 75%) (Andrew & Dymond, 2013). Furthermore, the population of rural areas with moderate urban influence (the RUI) in New Zealand is projected to increase by 21% between 2001 and 2021, compared with a national average of 16% (Bayley & Goodyear, 2005).

As is evident in the population projections, migration to rural land is very popular in New Zealand. Jakes et al. (2010) found that landowners who had recently moved to rural areas were less prepared for a wildfire event than long-term lifestyle block owners due to a lack of experience coming from an urban setting.

RUI growth is also present through urban fringe developments (e.g. Port Hills), which again puts less experienced suburban landowners into high-risk areas. Langer et al. (2018) suggest that these communities require special focus by fire managers to ensure residents are aware of the risk of wildfires and that fire management is appropriate to their context.

It is important that RUI growth is monitored so that fire managers become aware of new changes to the high-risk environment, enabling them to interact appropriately to audiences of different experience.

3. Objectives

The objective of this study is to test the reliability of the rural-urban interface (RUI) as a tool for estimating wildfire risk by comparing the location of actual fire occurrences with the RUI extent for three case study locations. Further investigation will also be carried out to assess the relationship between wildland vegetation fuel type and RUI extent.

The results of this study will provide fire management authorities with an insight for how much more likely it is for a wildfire to occur inside the RUI, enabling fire management and prevention strategies to be better prioritized for high fire risk zones.

4. Methodology

4.1 Data

Following the methodology, three datasets were used:

1. Structure location data was obtained from the ‘NZ Building Outlines’ dataset, which provides vector building footprints of all structures larger than or equal to 10 square meters observed in aerial imagery (Figure 3) (Land Information New Zealand, 2020).

Figure 3: Example of building footprints used to generate RUI maps.

2. Vegetation cover data was obtained from the 'LCDB v4.0' dataset, which contains vector data showing a thematic classification of New Zealand's land cover (Land Resource Information System, 2020).

3. Wildfire occurrence records were provided by V. Clifford (Scion), including a combination of data collected from 1990 – 2008 by the Department of Conservation (DOC) and from 2012 – 2018 by Fire and Emergency New Zealand (FENZ).

GIS software ArcGIS 10.7 was used to process the data and create maps according to the following method.

4.2 Method

4.2.1 Creating the RUI map

After reviewal of the methods outlined in the literature review and assessment of the intended implementation and availability of data, the most appropriate mapping technique was determined to be the Bar-Massada method (Bar-Massada et al., 2013). The following steps are based on this method; however, the specific ArcGIS model was adapted to suit New Zealand context and data accessibility (Figure 18 in Appendix).

A detailed explanation of the technical procedure developed for this study is described below.

Step 1: Create Building Density Raster (R1) – where each cell[1] represents whether the building density threshold of 6.17 buildings/km^2 is met. The number of buildings within a 576 m radius of the cell decides whether the cell meets the building density threshold. This calculation was iterated through each cell in the case study area.

a) First, the building footprint data layer must be converted from polygon to point format using the *Feature To Point* tool.

[1] 1 cell = 30x30 m

b) Next, the building points are put into the *Point Statistics* tool to create a raster in which each cell value represents the total number of points within the neighbourhood radius *r*.

c) Using the *Raster Calculator* tool, the raster cell values (*N*) are recalculated to get the building density *d* (buildings/km^2) using the equation[2]:

$$d = \frac{N}{\pi r^2} \times 1{,}000{,}000 \qquad [1]$$

d) The resulting density raster is then reclassified using the *Reclassify* tool so that the call value is 1 for cells that had a density greater than 6.17 buildings/km^2 and 0 otherwise.

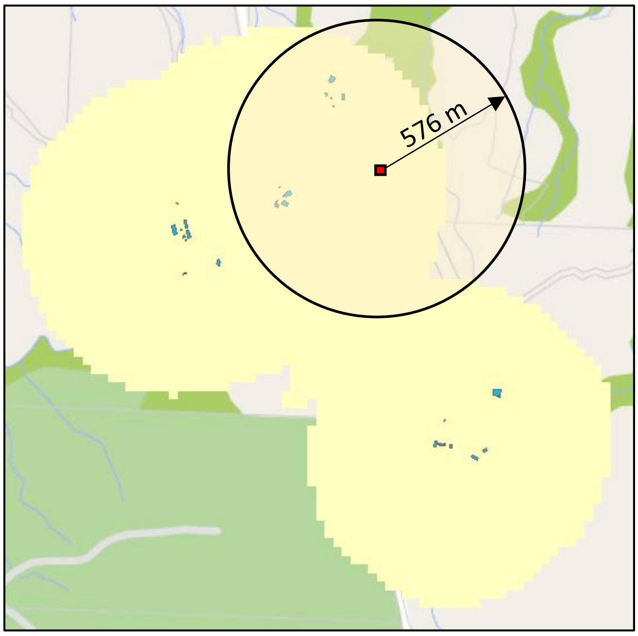

Figure 4: Example showing how building density is calculated for each cell using the moving window analysis. Yellow areas meet the required building density threshold (>6.17 buildings/km^2).

Step 2: Create Intermix Vegetation Cover Raster (R2) – Where each cell represents whether the wildland vegetation density of 50% is met. Table 3 shows which specific land covers from the LCDB classification were counted as wildland vegetation.

a) The LCDB layer is converted to raster format using the *Feature To Raster* tool.

b) Using the *Reclassify* tool, the raster is reclassified so that the cell value is 1 for cells that are classed as wildland vegetation and 0 otherwise (according to Table 3).

[2] 1,000,000 = correction factor to get density in km^2.

c) The reclassified wildland vegetation raster is put into the *Focal Statistics* tool to create a raster in which each cell value represents the sum of original cell values within the neighbourhood radius *r.*

d) Using the *Raster Calculator* tool, the cell values are recalculated to represent the percentage vegetation cover (*%*) within the neighbourhood radius *r* using the equation[3]:

$$\% = \frac{N}{\pi r^2/900} \times 100 \quad [2]$$

e) The vegetation percentage raster is reclassified using the *Reclassify* tool so that cells with ≥ 50% vegetation are assigned a value of 1, while cells < 50% are assigned 0.

Table 3: Reclassification of LCDB land cover types for wildland vegetation raster.

Wildland Vegetation (1)	Non-Wildland Vegetation (0)
Indigenous Forest	Built-up Area (Settlement)
Exotic Forest	Urban Parkland / Open Space
Deciduous Hardwoods	Surface Mine / Dump
Forest - Harvested	Transport Infrastructure
Short-rotation Cropland	Sand / Gravel
Orchard / Vineyard / Other Perennial Crops	Gravel / Rock
High Producing Exotic Grassland	Landslide
Low Producing Grassland	Permanent Snow / Ice
Tall Tussock Grassland	Alpine Grass / Herbfield
Depleted Grassland	Lake / Pond
Herbaceous Freshwater Vegetation	River
Herbaceous Saline Vegetation	Estuarine Open Water
Flaxland	
Fernland	
Gorse / Broom	
Manuka / Kanuka	
Matagouri / Grey Scrub	
Broadleaved Indigenous Hardwoods	
Sub Alpine Shrubland	
Mixed Exotic Shrubland	

[3] 900 = area of one cell (30 m resolution).

Step 3: Create Interface Vegetation Cover Raster (R3) – Where each cell is distinguished based on whether it is within the buffer distance of 500 m of large areas of wildland vegetation.

a) A copy of the LCDB vector layer is reclassified using the *Reclassify* tool according to Table 3.
b) Using the *Dissolve* tool, the contiguous polygons in the LCDB layer are joined together to create polygons representative of patches of continuous wildland vegetation.
c) The area of each polygon is calculated and appended to the attribute table.
d) Using *Select By Attributes*, all polygons with an area less than 5 km^2 are removed from the layer.
e) A 500 m buffer is applied around each of the remaining polygons using the *Buffer* tool.
f) Using the *Feature To Raster* tool, the buffered polygon layer is converted to raster form.
g) The resulting raster is then reclassified using the *Reclassify* tool so that all cell values are 1 (representing the wildland vegetation footprint + 500 m radius).

Step 4: Combine all 3 Raster Layers to Create RUI Map

a) R1 is combined with R2 to create raster T1 using the *Combinatorial Or* tool, which creates a different cell value for each unique combination of input values. The cell values are classified appropriately (Figure 5).
b) The resulting raster is combined with R3 to create another raster (T2) with a value for each combination using the *Combinatorial And* tool. The cell values are classified appropriately (Figure 6).
c) The symbology of T2 is edited so that only the Intermix and Interface RUI types are visible.
d) T2 is overlaid onto the imagery of the elected study area.

Rowid	VALUE	COUNT	R1	R2	RUI Type
0	0	299580	0	0	Non-RUI
1	1	731101	1	0	Possible Interface
2	2	306283	0	1	Non-RUI
3	3	166833	1	1	Intermix

Figure 5: Input value matrix and classification for step 4a.

Rowid	VALUE	COUNT	R1,R2	R3	INTERFACE
0	0	299580	0	0	No
1	1	731101	1	1	Yes
2	2	306283	2	1	No
3	3	166833	3	1	No

Figure 6: Input value matrix and classification for step 4b.

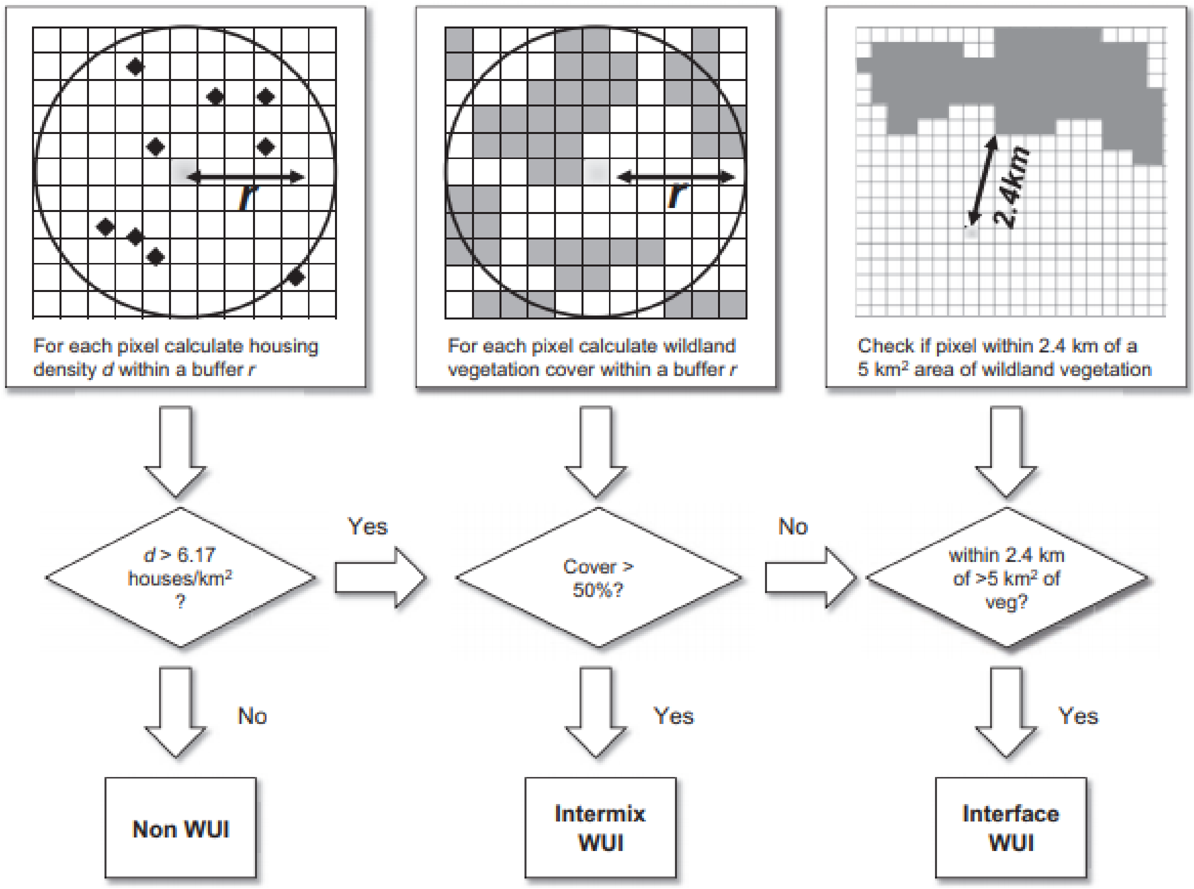

Figure 7: A flowchart illustrating steps 1-4 (Bar-Massada et al., 2013).

4.2.2 Calculating RUI Extent and Number of Wildfire Occurrences

Once the RUI maps had been created, the RUI extent was calculated using the following equation:

$$RUI\ extent\ (\%) = \frac{Area\ of\ identified\ RUI}{Total\ area} \times 100 \qquad [3]$$

The areas of large waterbodies such as lakes and oceans were subtracted from the total area value because it is not possible for them to be classified as RUI, therefore it would skew the results if they were included.

The wildfire occurrence data was then overlaid onto the RUI maps and the number of wildfires that occurred within the RUI zones (Intermix and Interface) and in Non-RUI areas was recorded.

The likelihood of a wildfire occurring inside the identified RUI extent was calculated by the equation:

$$Likelihood = \frac{Wildfires\ inside\ RUI\ (\%)}{RUI\ extent\ (\%)} \qquad [4]$$

4.2.3 Investigating the effects of Wildland Vegetation Fuel Type

To investigate the relationship between wildfire occurrences and different fuel types, land cover types from the LCDB layer were categorised into three wildland vegetation classes (based on fuel type), including 'Cropland and Grassland', 'Scrub and Scrubland' and 'Forest' (Table 4).

Table 4: Categorizing land cover types from the LCDB data set into wildland vegetation classes.

Wildland Vegetation Class	Land Cover
Forest	Indigenous Forest
	Exotic Forest
	Deciduous Hardwoods
	Forest - Harvested
Cropland & Grassland	Short-rotation Cropland
	Orchard / Vineyard / Other Perennial Crops
	High Producing Exotic Grassland
	Low Producing Grassland
	Tall Tussock Grassland
	Depleted Grassland
	Herbaceous Freshwater Vegetation
	Herbaceous Saline Vegetation
	Flaxland
Scrub & Shrubland	Fernland
	Gorse / Broom
	Manuka / Kanuka
	Matagouri / Grey Scrub
	Broadleaved Indigenous Hardwoods
	Sub Alpine Shrubland
	Mixed Exotic Shrubland

The RUI maps were then overlaid onto the reclassified LCDB layers and the proportion of RUI for each class was computed using ArcGIS software. The reclassified LCDB layer was then overlaid with the wildfire occurrence records and the number of points above each wildland vegetation class was recorded.

5. Results & Analysis

5.1 Generated Maps

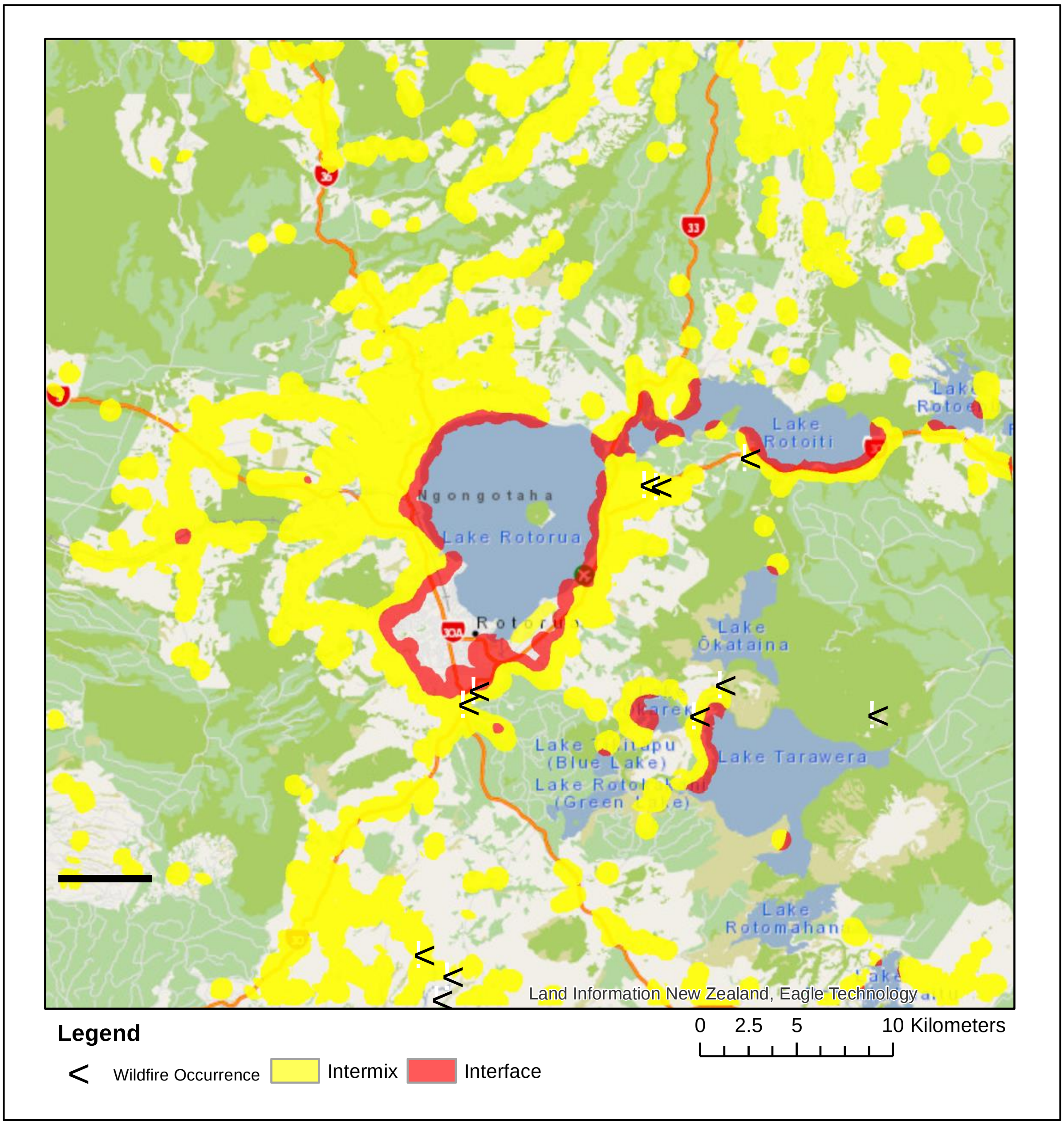

Figure 8: RUI extent for the Rotorua case study area showing Intermix and Interface RUI zones and wildfire occurrence locations.

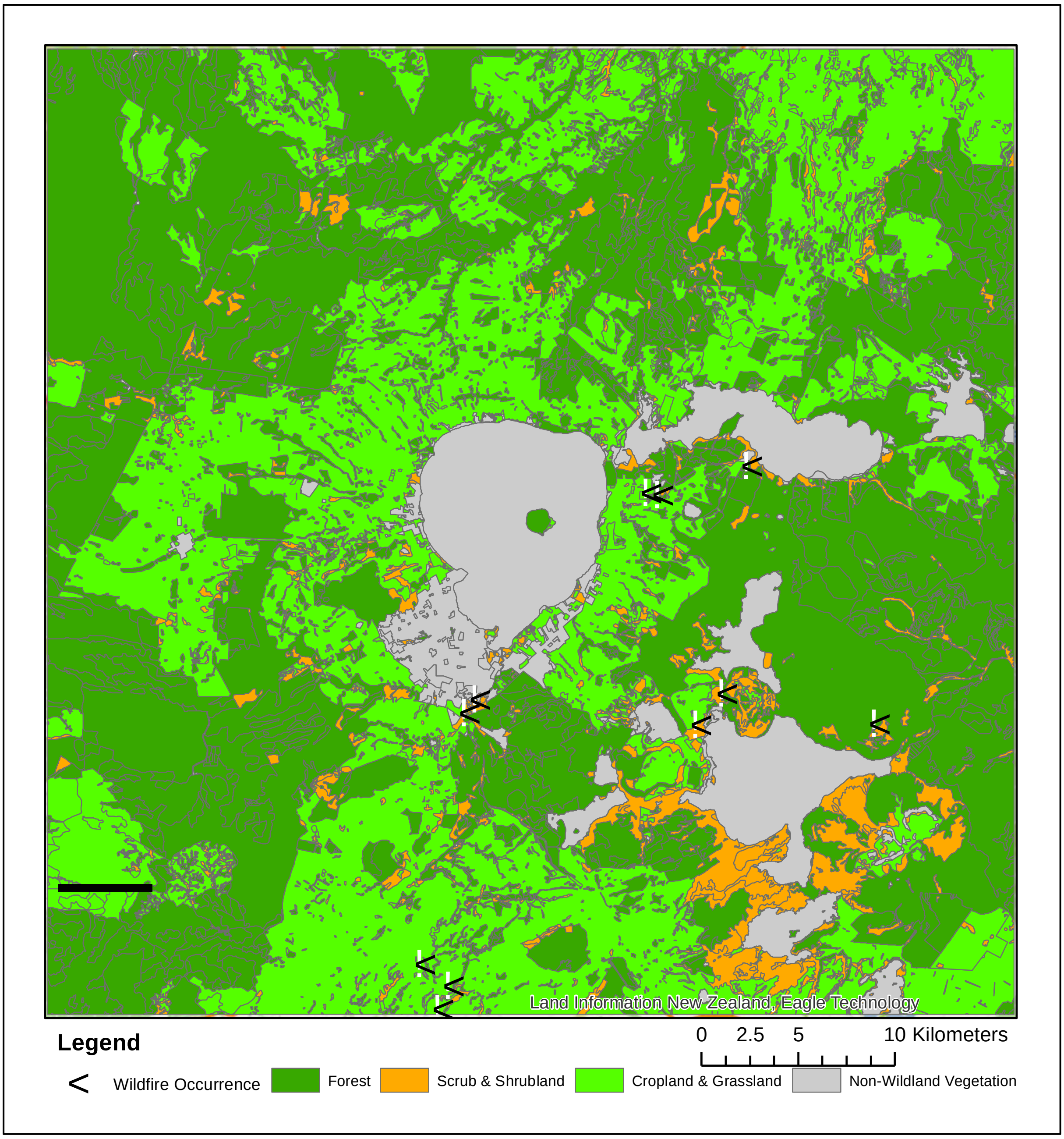

Figure 9: Map for the Rotorua case study area showing the extent of the three wildland vegetation fuel classes and wildfire occurrence locations.

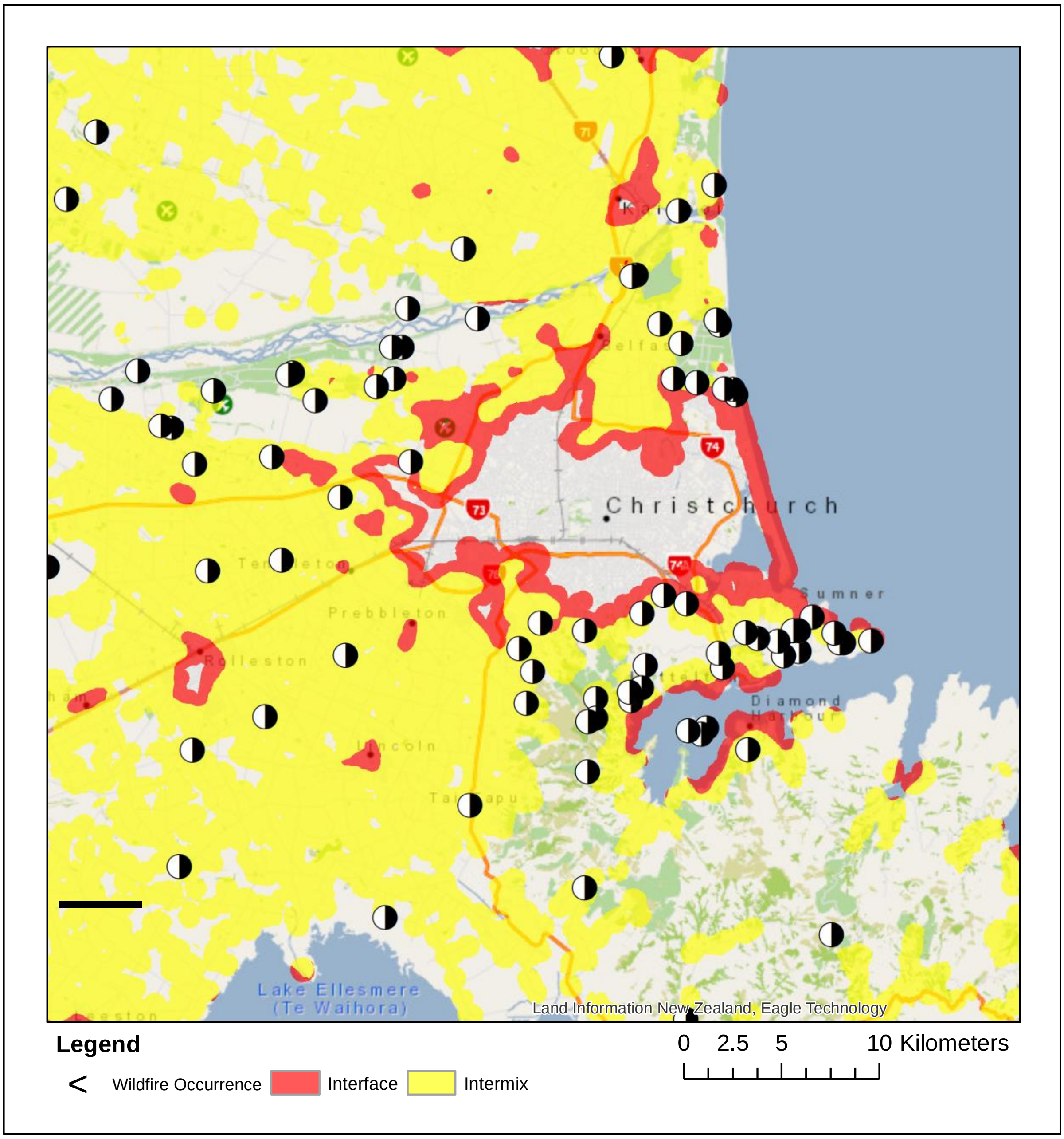

Figure 10: RUI extent for the Christchurch case study area showing Intermix and Interface RUI zones and wildfire occurrence locations.

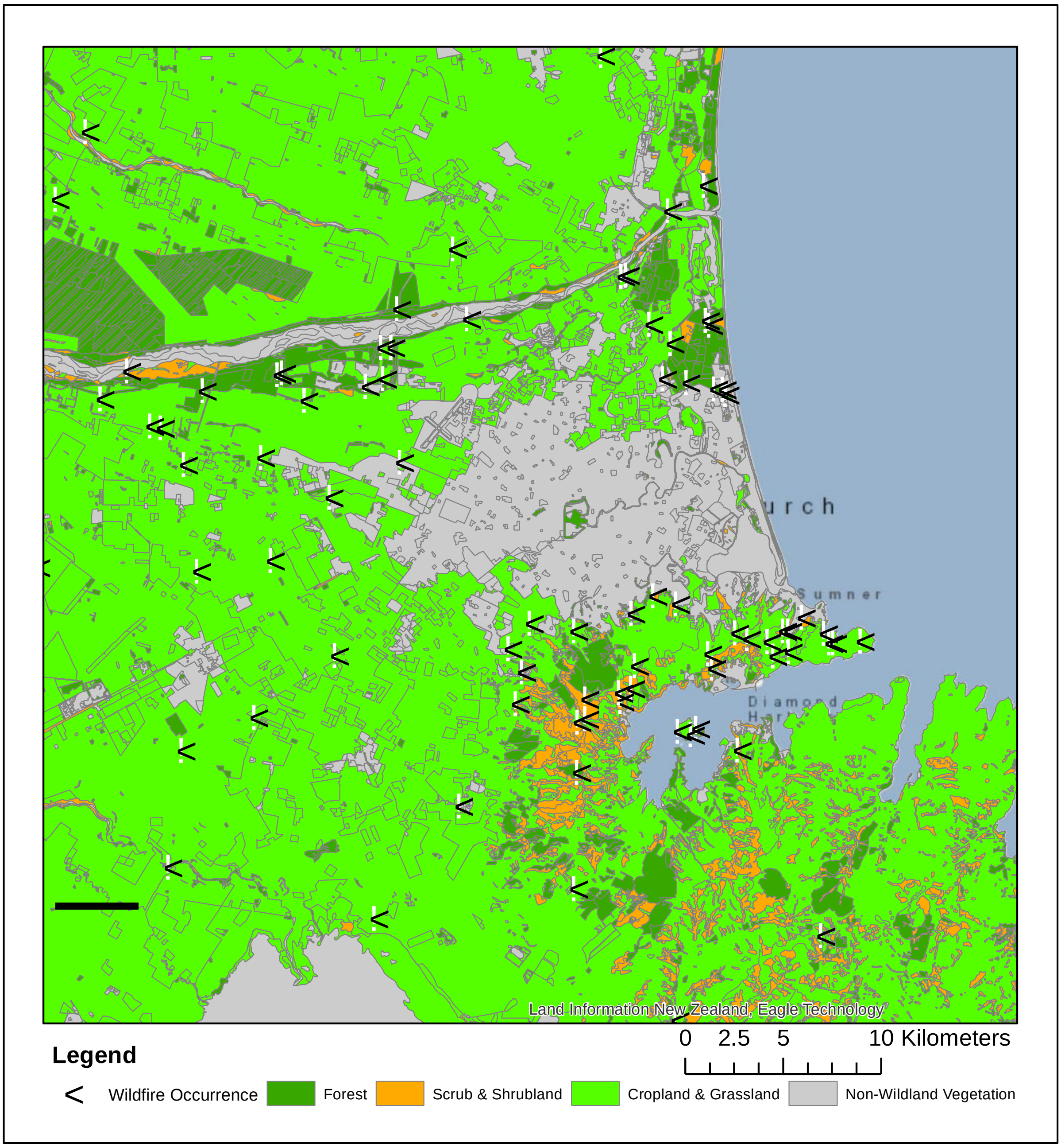

Figure 11: Map for the Christchurch case study area showing the extent of the three wildland vegetation fuel classes and wildfire occurrence locations.

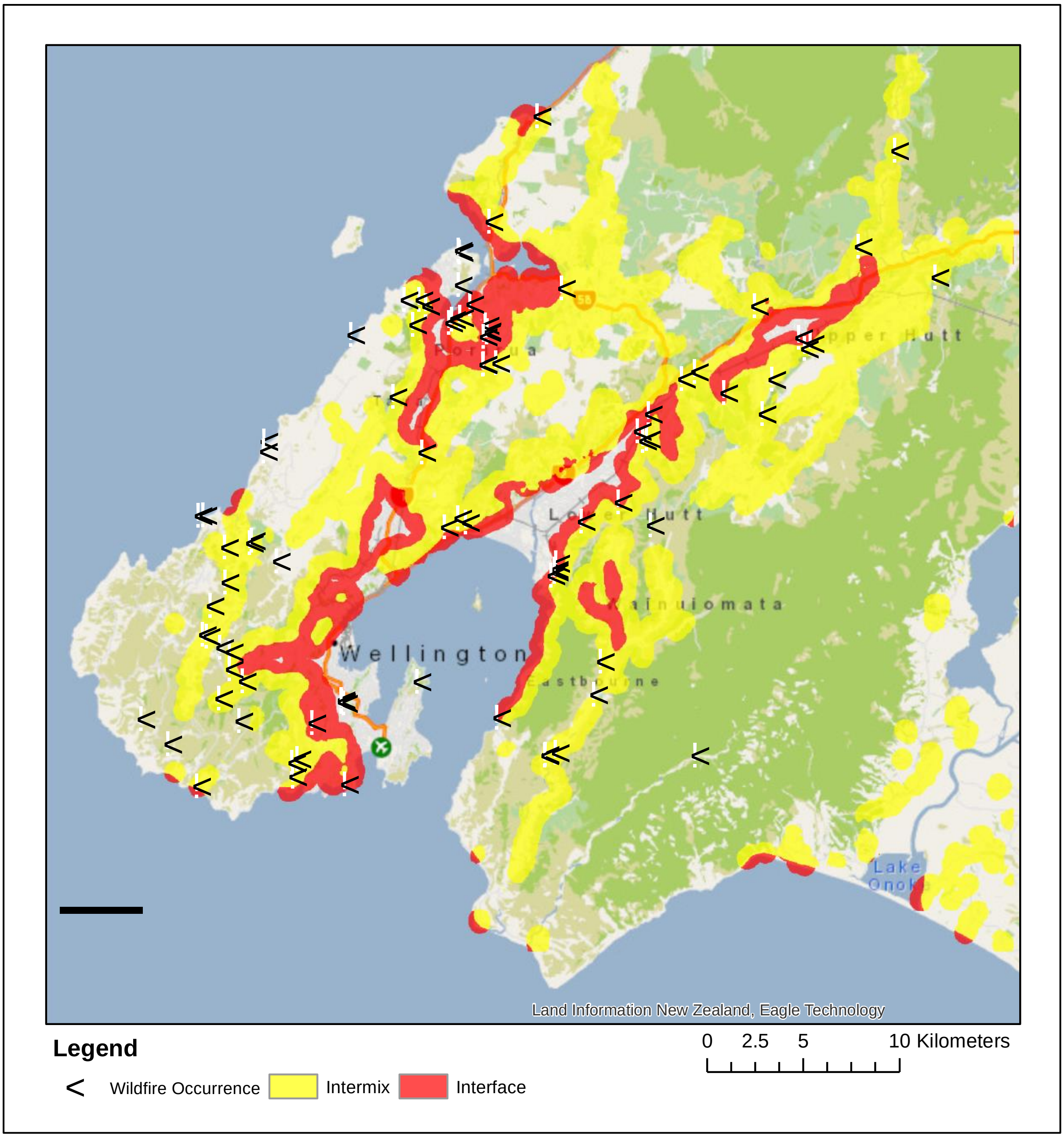

Figure 12: RUI extent for the Wellington case study area showing Intermix and Interface RUI zones and wildfire occurrence locations.

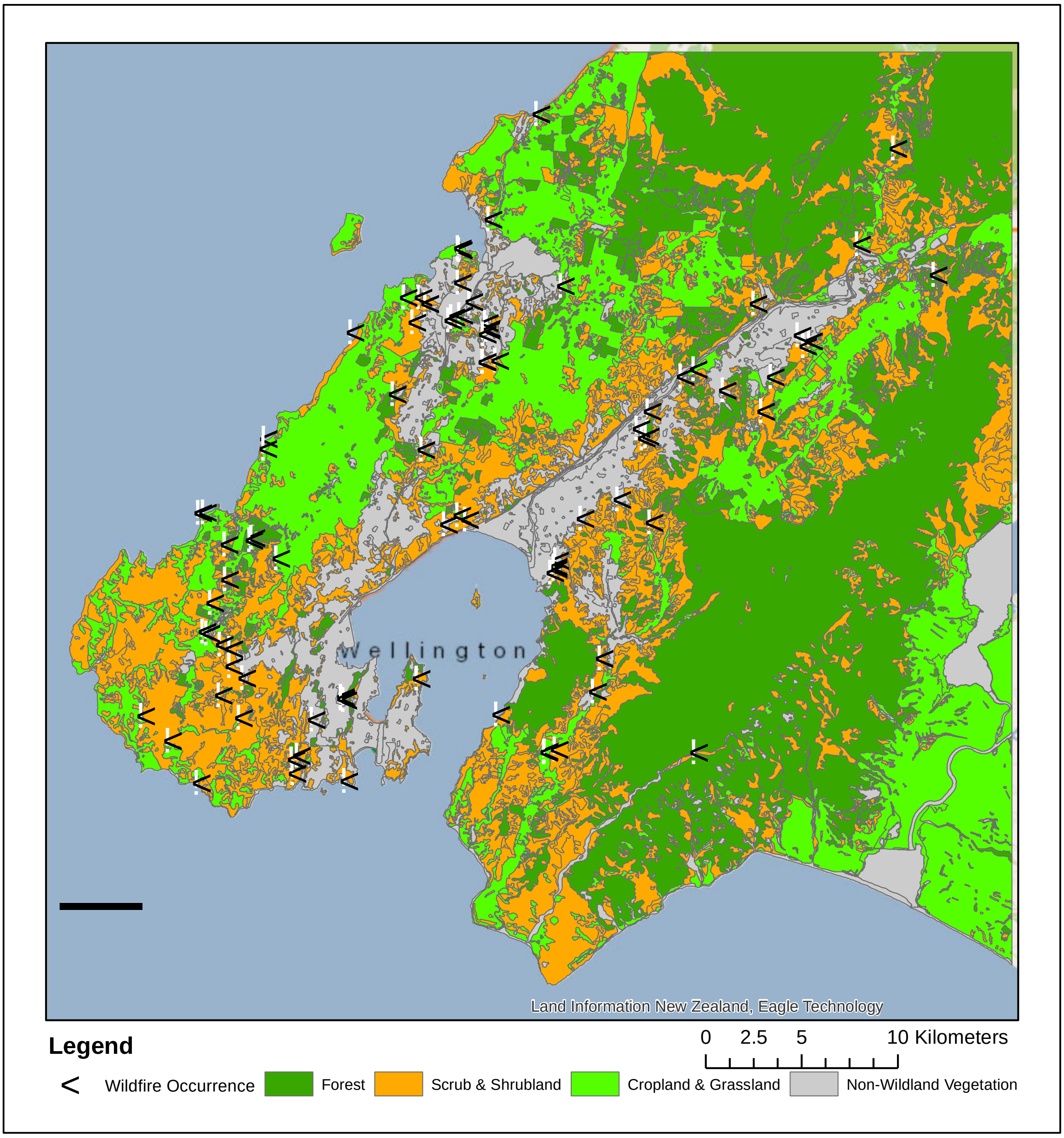

Figure 13: Map for the Wellington case study area showing the extent of the three wildland vegetation fuel classes and wildfire occurrence locations.

5.2 Comparing RUI Spatial Extent with Wildfire Occurrences

The proportion of each case study area identified as RUI is shown in Figure 14. For the Rotorua case study, 25% of the area was classified as Intermix RUI, while 2% was classified as Interface RUI. The results were similar for the Wellington case study, where 24% of the area was classified as Intermix RUI and 8% was classified as Interface RUI. The results for the Christchurch case study identified a much larger RUI extent, with 53% of the area classified as Intermix RUI and 8% as Interface RUI.

On average, 40% of each case study area was identified as RUI. 34% was classified as Intermix RUI and 6% was classified as Interface RUI.

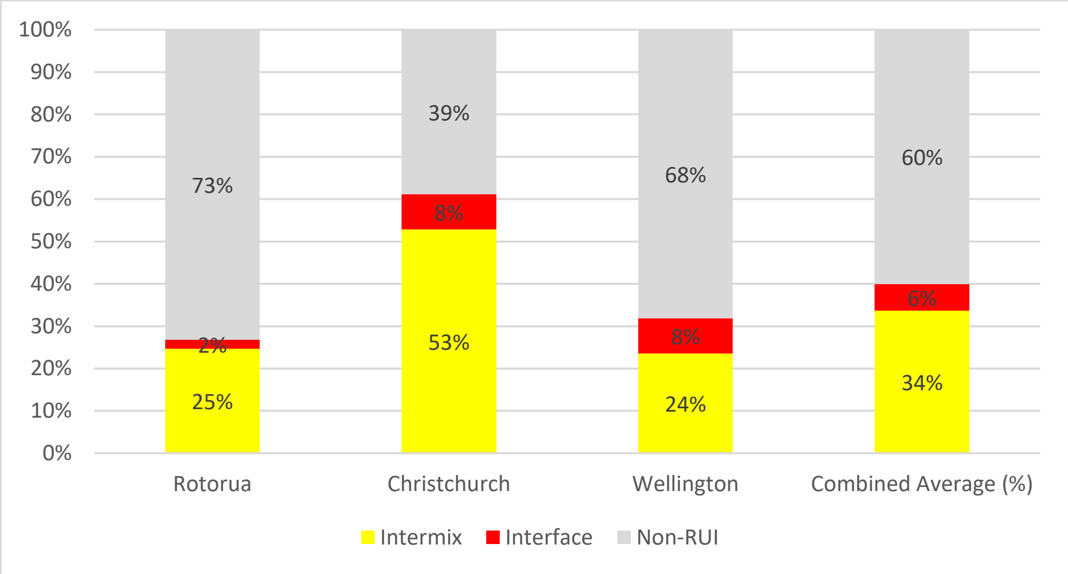

Figure 14: Identified RUI extent for each case study area and a combined average for all three case study areas.

Figure 15 shows that 8 out of 11 wildfire occurrences were inside the identified RUI extent for the Rotorua case study area, all of which occur in the Intermix RUI zone. The results for the Christchurch case study area show that 56 out of 81 wildfire occurrences were inside the identified RUI extent. 50 of these occurred in the Intermix zone, while 6 occurred inside the Interface zone. The results for the Wellington case study area show that 70 out of 90 wildfire occurrences were inside the identified RUI extent. 58 of these occurred in the Intermix zone, while 12 occurred inside the Interface zone.

Figure 15 also shows the combined average for all three case study areas. 74% of wildfire occurrences were inside the collective identified RUI extent. 64% occurred in the Intermix zone, while 10% occurred in the Interface zone.

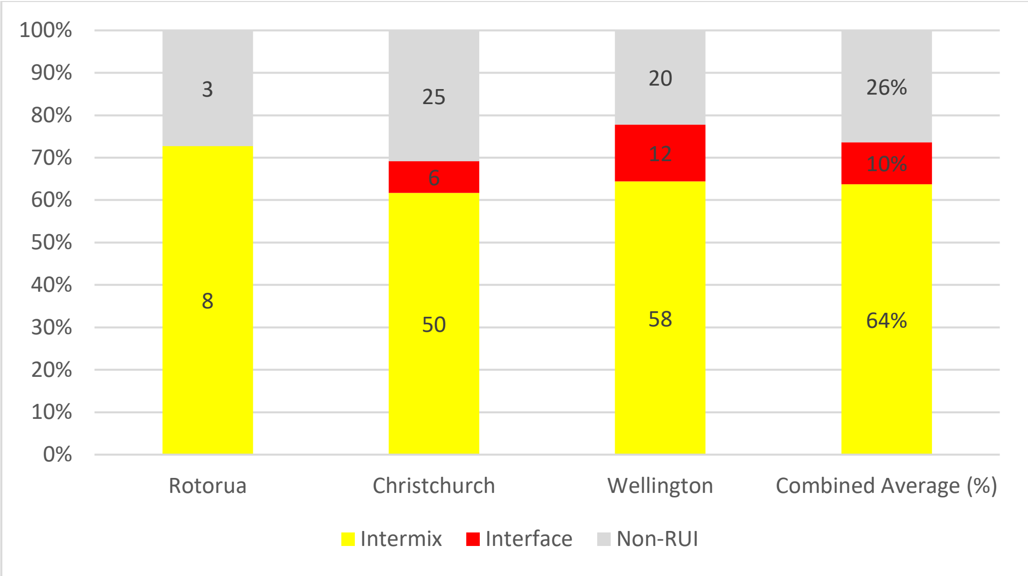

Figure 15: Wildfire occurrences per RUI class for each case study area and the combined average of all three areas.

The likelihood of a wildfire occurring in the RUI can be inferred by comparing Figures 14 and 15. For the Rotorua case study, 8 out of 11 wildfires occurred inside the identified RUI extent. However, only 27% of the total area was identified as RUI. The results therefore suggest that a wildfire is 2.7 times more likely to occur inside the RUI for this case study area. Similar results were found for the Wellington case study area, where 70 out of 90 wildfires occurred inside the identified RUI. However, only 32% of the total area was identified as RUI. The results therefore suggest that a wildfire is 2.4 times more likely to occur inside the RUI for this case study area. The Christchurch case study area had conflicting results, where 56 out of 91 wildfires occurred in the identified RUI, but 61% of the total area was identified as RUI. The results therefore suggest that a fire is about equally (only 1.1 times more) likely to occur inside the RUI than it is outside the RUI for the Christchurch case study.

Overall, 74% of wildfires occurred inside the identified RUI extent on average for the three case study areas, while 40% of the total area was identified as RUI. Therefore, the combined results from all three case study areas suggest that a wildfire is 1.9 times more likely to occur inside the RUI.

5.3 Comparing Effects of Wildland Vegetation Fuel Classes

The distribution of wildland vegetation fuel classes over the identified RUI extent for each case study area is shown in Figure 16. For the Rotorua case study, a major proportion (69%) of the identified RUI was classed as Cropland & Grassland, while 18% was classified as Forest, 4% as Scrub & Shrubland, and 9% was classified as Non-Wildland Vegetation. The results from the Christchurch case study area were similar, with 82% of the identified RUI classed as Cropland & Grassland, 5% as Forest, 2% as Scrub & Shrubland, and 12% classified as Non-Wildland Vegetation. The RUI extent for the Wellington case study area had a more even spread of fuel classes, with 33% classified as Cropland & Grassland, 30% Scrub & Shrubland, 13% Forest, and 25% classified as Non-Wildland Vegetation.

Figure 16 also shows the combined average distribution of wildland vegetation fuel classes for all three case study areas. Cropland & Grassland was the most extensively represented fuel class, accounting for 68% of the identified RUI. The other two fuel classes were relatively similar, with Forest and Scrub & Shrubland making up 10% and 8% of the identified RUI, respectively. An average of 14% of the total RUI area was identified in areas of Non-Wildland Vegetation.

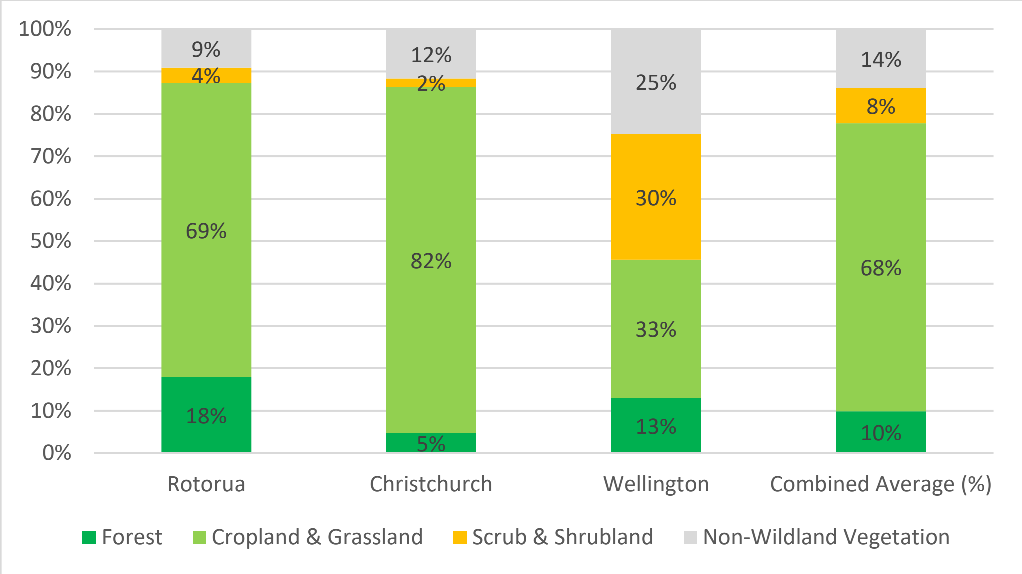

Figure 16: Distribution of wildland vegetation fuel classes over the identified RUI extent for each case study area and all three areas combined.

Figure 17 shows the number of wildfires that occurred on each wildland vegetation fuel class for each case study area. The wildfire occurrences were fairly evenly distributed for the Rotorua case study, with 3 out of 11 wildfires occurring on the Forest fuel class, 2 on Cropland & Grassland, 5 on Scrub & Shrubland, and 1 that occurred on Non-Wildland Vegetation. The results from the Christchurch case study show that a significant amount of the wildfires (53 out of 81) occurred on the Cropland & Grassland fuel class, while 12 occurred on Forest, 7 on Scrub & Shrubland, and 9 on areas of Non-Wildland Vegetation. Interestingly, the Wellington case study had a significant number of wildfires (49 out of 90) occurring on the Scrub & Shrubland fuel class, while 10 occurred on Forest, 11 on Cropland & Grassland and 20 occurred on Non-Wildland Vegetation.

Figure 17 also shows that on average, 36% of wildfires occurred on Cropland & Grassland for the three case study areas, while 34% occurred on Scrub & Shrubland, 14% on Forest, and 16% on areas of Non-Wildland Vegetation.

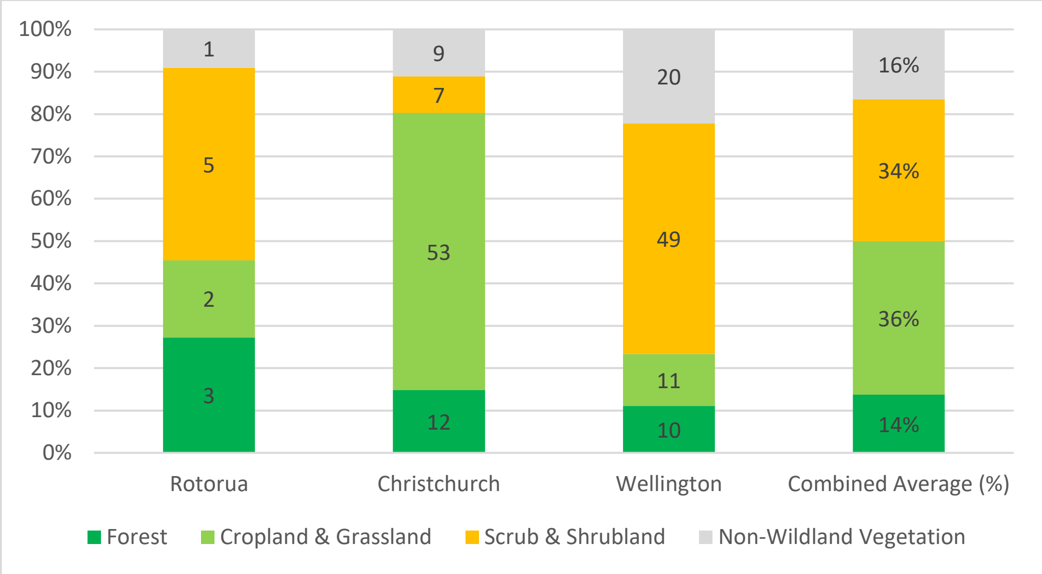

Figure 17: Wildfire occurrences per each wildland vegetation fuel class for each case study area and all three areas combined.

The relationship between wildfire occurrences and wildland vegetation fuel class can be inferred by comparing Figures 16 and 17. The Rotorua case study shows no positive correlation between the two variables, as even though 69% of the identified RUI extent is made up of Cropland & Grassland, only 2 out of 11 wildfires occurred on this fuel class. In contrast, the Christchurch case study shows a more positive relationship, with 82% of the identified RUI classed as Cropland & Grassland corresponding to 53 of 81 wildfires occurring on this fuel class. While 49 out of 90 wildfires occurred on Scrub & Shrubland in the Wellington case study, this has no apparent link to wildland vegetation fuel class, as Scrub & Shrubland accounted for only 30% of the identified RUI extent.

Overall, a significant amount (68%) of the area identified as RUI was made up of the Cropland & Grassland fuel class on average for the three case study areas. There is no apparent correlation between this result and the number of wildfire occurrences per area, as an average of only 36% of wildfires occurred on Cropland & Grassland. A similar number of wildfires (34%) occurred on Scrub & Shrubland, which only accounted for 8% of the total identified RUI for the three case study areas.

6. Discussion

The objective of this study was to test the reliability of the rural-urban interface (RUI) as a tool for estimating wildfire risk by comparing the location of actual fire occurrences with the RUI extent for three case study locations. The likelihood of a wildfire occurring inside the identified RUI area for each of the three case study areas and an overall average likelihood were found by the results of the study.

The overall combined result from the three case studies was that a wildfire is 1.9 times more likely to occur in the RUI. This is the expected outcome, as by definition the RUI is an area of increased wildfire risk. Interestingly, the results showed that a wildfire was only 1.1 times more likely to occur inside the RUI for the Christchurch case study, which is significantly less than the likelihood for the Rotorua and Wellington case studies (2.7 and 2.4 times more likely, respectively). It appears that this is due to the larger RUI extent identified for the Christchurch study (61% of the total case study area), compared to the 27% and 32% RUI extent identified for Rotorua and Wellington. As seen by equation 4 in the methods section, an increase in RUI extent will result in a decreased likelihood of a wildfire occurring inside the identified RUI. Christchurch's larger RUI extent is likely due to the high coverage of the Cropland & Grassland wildland vegetation fuel class to the West and North of Christchurch City, which represents agricultural land-use commonly seen in the Canterbury region.

This relationship between wildland vegetation fuel class and RUI extent can be further explained by the Rotorua case study. As can be seen on the wildland vegetation fuel class map for Rotorua (Figure 9), forests make up a large proportion of the total case study area. However, the results showed that forests only account for 18% of the area identified as RUI. This is likely to be due to the low building density in forested areas not meeting the building density threshold to be classified as RUI. Cropland & Grassland covers a similarly large portion of the total case study area; however, it accounts for a much larger percentage of the area identified as RUI (69%). The most likely reason for this is that a significant proportion of the Cropland & Grassland area is made up of agricultural land which is typical of the New Zealand rural landscape. Agricultural areas including farms contain multiple buildings in close proximity to each other such as farmhouses, milking sheds, and horse stables that are likely to meet the building density threshold. Coupled with the fact that farms operate on extensive areas of continuous grassland, it is inevitable that these areas will be identified as part of the RUI extent.

In support of this comment, the maps produced for all three case study areas (Figures 8 - 13) show that areas of Cropland & Grassland greatly correspond to areas identified as RUI. This suggests that Cropland & Grassland areas can be assumed to always create an area of RUI, which therefore brings the question of whether or not it is useful to include this wildland vegetation fuel class in the RUI mapping algorithm. Even though 54% of the total area burned by wildfires in New Zealand is over grassland (as mentioned in the literature review), it may be more useful to exclude this land cover from the RUI mapping method so that attention can be focussed on areas of less predictable fire risk.

The method from Bar-Massada et al. (2013) was chosen to create the RUI maps for this study because of its improved accuracy in identifying at-risk communities of a specified building density compared with meshblock-based methods. On the other hand, it also has a more conservative approach to the inclusion of isolated buildings compared with other building footprint methods, such as the method by Lampin-Maillet (2009). The integration of the building density threshold avoids isolated individual buildings being included in the RUI mapping algorithm, meaning only at-risk communities of a reasonable size are identified inside the RUI.

The threshold values and parameters used for the method in this study were based on recommendations from previous international studies. Therefore, the maps and results in this study only provide a generic, universal representation of how the RUI extent should appear. To reiterate what was mentioned in the literature review, it is important to note that no single method (or set of parameters) can produce a 'true' or 'best' representation of the RUI. When analysing the RUI, the most suitable method (or set of parameters) should be selected based upon the context and purpose of the investigation and the quality and availability of data. For example, the building density threshold could be adjusted to exclude smaller communities such as rural towns and building-dense farms. The resulting map would then only identify high-risk areas of larger populations such as cities and larger towns.

One limitation that may have affected the results of this study is the incomplete nature of the wildfire occurrence data. Fires that were not attended by DOC staff, or not on DOC land are likely to be missing from DOC records, therefore it is likely that not all New Zealand fires were recorded by the DOC database. The FENZ fire records are a more complete set; however, wildfires recorded in the FENZ database are referenced to the street address of the property (likely a small distance from the letterbox), not necessarily at the actual location the fire started. Also, the DOC data is a record of fires from 1990 – 2008 only, while the FENZ data only consists of fires that occurred between 2012 and 2018.

Another limitation is the relatively small sample sizes of wildfire occurrences used for each case study, especially Rotorua. The data was the best of what was available; however, the sample size was restricted by the size of the available dataset, which could have affected the reliability of the results.

Further research should be undertaken to investigate the relationship between building density and specific land covers. Having an estimate for the average building density for specific land covers will enable a more suitable building density threshold to be used in the mapping algorithm, allowing fire management authorities to create maps better suited to the context of specific management issues.

7. Conclusion

The damaging effects of wildfire events are a serious issue for communities throughout New Zealand, and fire activity is predicted to increase in the future due to the effects of climate change, changes in land use, and an expanding rural-urban interface. It is therefore important that people have reliable fire management tools for minimizing the effects of wildfire on our communities.

The aim of this study was to test the reliability of the rural-urban interface (RUI) as a tool for estimating wildfire risk by comparing the location of actual fire occurrences with the RUI extent for three case study locations. The results of this study have confirmed that wildfire risk is highest in RUI areas, suggesting an urgent need for special attention and prioritisation in fire management in these areas. It was also found that areas of the Cropland & Grassland fuel class were inevitably included in the RUI extent using the applied method due to the nature of continuous agricultural land typical of the New Zealand rural landscape. This observation reiterates the recommendations from previous studies that there is no 'true' representation of the RUI, and that the most suitable method and set of parameters should be selected based upon context and availability of data.

8. References

Anderson, S., Doherty, J., & Pearce, G. (2008). Wildfire in New Zealand from 1991 to 2007. *NZ Journal of Forestry, 53*(3), 19-22.

Andrew, R., & Dymond, J. (2013). Expansion of lifestyle blocks and urban areas onto high-class land: an update for planning and policy. *Journal of the Royal Society of New Zealand, 43*, 128-140.

Bar-Massada, A., Stewart, S. I., Hammer, R. B., & Mockrin, M. H. (2013). Using structure locations as a basis for mapping the wildland urban. *Journal of Environmental Management, 128*, 540-547.

Bayley, A., & Goodyear, R. (2005). *New Zealand: An Urban/Rural Profile.* Statistics New Zealand.

Brillinger, D. R., Autrey, B. S., & Cattaneo, M. D. (2009). Probabilistic risk modeling at the wildland urban interface: the 2003 Cedar Fire. *Environmetrics, 20*, 607-620.

Brown, T. J., Hall, B. L., & Westerling, A. L. (2004). The Impact of Twenty-First Century Climate Change on Wildland Fire Danger in the Western United States: An Applications Perspective. *Climatic Change, 62*, 365-388.

Centre for Disaster Philanthropy. (2020). *2019-2020 Australian Bushfires.*

Fire and Emergency New Zealand. (2019). *Fire and Emergency Annual Report 2019.*

Flannigan, M., Stocks, B., Turetsky, M., & Wotton, M. (2009). Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology, 15*(3), 549-560.

Haas, J., Calkin, D., & Thompson, M. (2013). A national approach for integrating wildfire simulation modeling into Wildland Urban Interface risk assessments within the United States. *Landscape and Urban Planning, 119*, 44-53.

Haight, R. G., Cleland, D. T., Hammer, R. B., Radeloff, V. C., & Rupp, T. S. (2004). Assessing Fire Risk in the Wildland-Urban Interface. *Journal of Forestry*, 41-48.

Jakes, P., Kelly, L., & Langer, L. (2010). An exploration of a fire-affected community undergoing change in New Zealand. *The Australian Journal of Emergency Management, 25*(3), 48-53.

Johnston, L. M., & Flannigan, M. D. (2018). Mapping Canadian wildland fire interface areas. *International Journal of Wildland Fire, 27*, 1-14.

Lampin-Maillet, C., Jappiot, M., Long, M., Bouillon, C., Morge, D., & Ferrier, J.-P. (2009). Mapping wildland-urban interfaces at large scales integrating housing density and vegetation aggregation for fire prevention in the South of France. *Journal of Environmental Management, 91*, 732-741.

Land Information New Zealand. (2020). NZ Building Outlines [Dataset]. Retrieved May 11, 2020, from https://data.linz.govt.nz/layer/101290-nz-building-outlines/

Land Resource Information System. (2020). LCDB v4.0 [Dataset]. Retrieved July 28, 2020, from https://lris.scinfo.org.nz/layer/48412-lcdb-v40/

Langer, L., Pearce, G., & Wegner, S. (2018). The urban side of the Wildland-urban interface – a new fire audience identified following an extreme wildfire event in Aotearoa/New Zealand. *Advances in Forest Fire Research 2018*, 859-869.

Lu, Y., Carter, L., & Showalter, P. (2010). Wildfire Risk Analysis at the Wildland Urban Interface in Travis County, Texas. *Geotechnologies and the Environment, 2*, 203-277.

Nagy, R. C., Fusco, E., Bradley, B., Abatzoglou, J., & Balch, J. (2018). Human-Related Ignitions Increase the Number of Large Wildfires across U.S. Ecoregions. *Fire, 1*(1), 1-14.

Pearce, G. H., & Clifford, V. (2008). Fire weather and climate of New Zealand. *NZ Journal of Forestry, 53*(3), 13-18.

Pearce, G. H., Mullan, A. B., Salinger, M. J., Opperman, T. W., Woods, D., & Moore, J. R. (2005). *Impact of Climate Change on Long-term Fire Danger.* NZFSC - Niwa/Scion.

Pearce, H., Langer, E., Harrison, D., & Hart, M. (2014). *Describing Wildfire Prone Areas in the New Zealand Context: Final Report.* Scion.

Platt, R. V. (2010). The Wildland–Urban Interface: Evaluating the Definition Effect. *Journal of Forestry*, 9-15.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. f. (2005). The Wildland-Urban Interface in the United States. *Ecological Applications, 15*(3), 799-805.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Ber-Massada, A., . . . Stewart, S. I. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *PNAS, 115*(13), 3314-3319.

Romero-Calcerrada, R., Novillo, C., Millington, J., & Gomez-Jimenez, I. (2008). GIS analysis of spatial patterns of human-caused wildfire ignition risk in the SW of Madrid (Central Spain). *Landscape Ecology, 23*, 341-354.

Stewart, S. I., Radeloff, V. C., Hammer, R. B., & Hawbaker, T. J. (2007). Defining the Wildland-Urban Interface. *Journal of Forestry*, 201-207.

Stewart, S., Wilmer, B., Hammer, R., Aplet, G., Hawbaker, T., Miller, C., & Radeloff, V. (2009). Wildland-Urban Interface Maps Vary with Purpose and Context. *Journal of Forestry*, 78-83.

Summerfelt, P. (2003). The Wildland/Urban Interface: What's Really At Risk? *Fire Management Today, 63*(1), 4-7.

Theobald, D. M., & Romme, W. H. (2007). Expansion of the US wildland–urban interface. *Landscape and Urban Planning, 83*, 340-354.

USDA & USDI. (2001). Urban Wildland Interface Communities Within the Vicinity of Federal Lands That Are at High Risk From Wildfire. *Federal Register, 66*(3), 752-753.

Zhang, Y., He, H. S., & Yang, J. (2008). The wildland–urban interface dynamics in the southeastern U.S. from 1990 to 2000. *Landscape and Urban Planning, 85*, 155-162.

Appendix

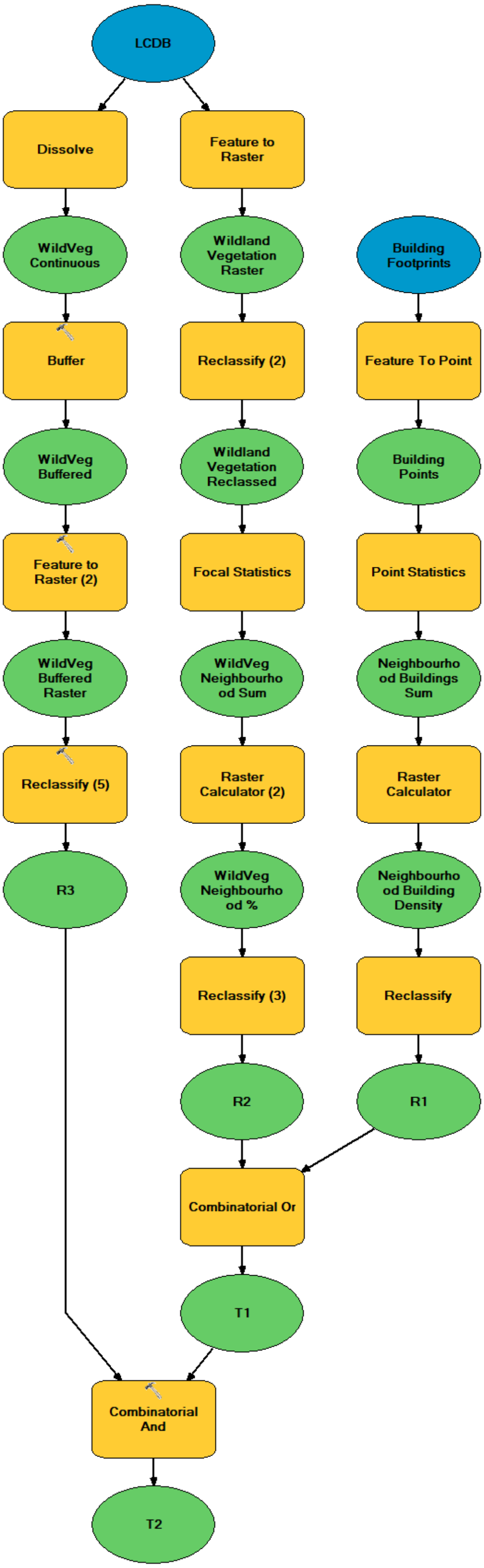

Figure 18: ArcGIS model for the complete mapping method (steps 1-4).