Manaaki Whenua
Landcare Research

Quantifying the historical evolution of green space in New Zealand's cities

Extension: measuring urban green space and vegetation from infrared imagery

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Quantifying the historical evolution of green space in New Zealand's cities

Extension: measuring urban green space and vegetation from infrared imagery

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Summary

Project and client

- The Parliamentary Commissioner for the Environment (PCE) contracted Manaaki Whenua – Landcare Research to investigate the feasibility of using remote sensing to separate green space from impervious surfaces, and measure the coverage of green space[1], using the most recent visual and near-infrared imagery for Hamilton, Auckland, and Wellington.
- A sub-goal was to attempt to separate woody vegetation from grass.

Objectives

- Generate GIS raster images of green space for the three cities.
- Measure the coverage of green space by land-use type, public accessibility, and vegetation type (woody vegetation or grass).
- Compare the results to the population distribution to derive the distribution of green space *per person*, including for the population estimates from the 2018 census.
- Compare the results to those previously reported to estimate the accuracy of the original results gathered from panchromatic imagery.

Methods

A Geographic Information System (GIS)-based approach was used, with the following steps.

1 Generate population statistics for 2018.
2 Acquire the most recent visible and near-infrared (NIR) imagery for each city and make the imagery analysis-ready.
3 Compute indices for identifying green space overall, and for separating woody vegetation from grass.
4 Select a threshold for each index and apply it to generate a green space mask and a woody vegetation mask.
5 Merge the masks with urban land-use (planning zone) information to give green space by land-use type.
6 Create rasters that code green space by land-use type (public open space, private residential space, commercial, transport corridor), accessibility (public or private), and vegetation type (grass or woody vegetation).
7 Calculate the statistics.
8 Document the work in an illustrated report.

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[1] In the original study, green space coverage was defined as the ground area of spaces that are predominantly green, with some impervious surfaces included because it was not possible to consistently exclude them. For this study, green space coverage is defined as the area that is natural surface (bare ground, grass, vegetation) *when seen from above*. This change in definition arises from the inability to determine from aerial imagery whether the ground below tree cover is green or not.

Results

- The infrared imagery available varied widely in quality between the three cities, with Hamilton having the best imagery and Auckland the worst. Hamilton and Wellington's imagery was also very recent (2021), while Auckland's was much older (2011). This was reflected in the quality of the resulting masks and the level of uncertainty in the measured green space coverage.
- Separating green space from impervious surfaces was excellent for Hamilton, somewhat poorer for Wellington, and worst for Auckland. However, in all three cases, a useful mask could be produced.
- Separating woody vegetation from grass and bare ground using an infrared index was more challenging, with considerably higher levels of uncertainty. However, the inferred woody vegetation coverage was in line with expectations when compared to published tree cover[2] estimates.
- The difference between the overall green space measured in this study and that inferred from open space in the previous report varied between cities. For Auckland and Wellington the difference was small (1% or less); for Hamilton the difference was much larger (8.2%).
- Most of the difference in green space coverage was for private/residential areas, owing to the substantial (and increasing) proportion of residential land that is covered in paving. This is somewhat balanced by green space in commercial areas, which was previously discounted.
- Public green space, as previously reported, fell in all three cases by 1.8–3.0% of total area, but this was more than balanced by including the significant green space in the transport corridor, which added 5.4 to 6.5% of total area. This was exacerbated by the inclusion of tree canopy, which is common in the road corridor and was measured as green space.
- The distribution of changes in public, private, and total green space was not uniform. It depended on factors such as where major road corridors (with green space) are routed, the level of development of otherwise of green public spaces, and differences in classification of some commercial green space areas, such as at airports, which were deliberately excluded in the original study on the basis of inaccessibility, but have been included in the measurements for this study.

Conclusions

- Measuring green space directly using visual and NIR imagery is feasible, but the level of accuracy is strongly dependent on the quality of the imagery. Measuring green space directly using visual and NIR imagery can also be used to separate woody vegetation from other green space areas to a useful accuracy, albeit less accurate than the separation of green and grey space (impervious surfaces).
- The total green space measured directly from infrared imagery is close to the total green space reported from the primary subtraction-based analysis for Auckland and Wellington, but is significantly lower for Hamilton.

[2] Tree cover is a subset of woody vegetation so is not directly comparable. It is usually defined as vegetation exceeding a minimum height and crown diameter.

- The amount of private/residential grey space is significant and growing, with the most recent subdivisions losing increasing amounts of green space to driveways and other paving, particularly in Hamilton where, on average, more than 25% of residential section area is paving, roughly doubling the impervious footprint compared to just the building footprint that was subtracted in the primary study. The most recent subdivisions show much higher levels of paving, including new high-density dwelling areas (including in-fill development) in Hamilton that are almost completely covered in buildings and impervious surfaces.
- The transport corridors add significant green space (5.4–6.5% of the city area). Motorway berms, street berms and tree canopy all add significant green space. This effect is very non-uniform, with some suburbs containing substantially more green space in the road corridors than others.
- Commercial and industrial areas can also contain non-trivial amounts of green space, although it is typically very fragmented; this was most pronounced in Auckland (2% of total area).
- Tree canopy cover varied substantially between the three cities: around 38% of Hamilton's green space is woody vegetation, compared to 44% for Auckland and 63% for Wellington (including peri-urban reserves).
- The technique is sufficiently accurate to measure changes in urban composition using modern NIR imagery and could provide a valuable policy and planning tool.

Recommendations

- Use the developed green space masks to train a deep learning model to improve green space detection and apply these to standard RGB[3] aerial imagery.
- Repeat the study for all existing RGB imagery to obtain a clearer picture of how green space is changing over time.
- Further analyse the generated green space masks. This could include measuring and analysing green space coverage by subdivision, based on age, to extract finer-grained insights into how green space in cities is changing.
- Extend the study to other urban areas.

[3] RGB refers to colour imagery consisting of red, green and blue colour bands that are added together by the display device to give the desired colour.

1 Introduction

In 2021 the Parliamentary Commissioner for the Environment (PCE) contracted Manaaki Whenua – Landcare Research to investigate how best to measure changes in the amount of, and distribution of, public and private green spaces in New Zealand cities over time. The method was applied to three cities: Hamilton, Auckland, and the greater Wellington urban area, and for three periods: the 1940s, the 1980s, and 2016 (Martin et al. 2022).

A concern raised by the initial study was the potential over-reporting of green space because it included impervious surfaces, particularly on private (residential) land. Balancing this was the omission of green space in the transport corridor, which was thought to be significant. While these two effects are in opposition and balance each other to some degree, PCE sought to quantify the difference between these two approaches to determine the extent to which the original method is a valid estimate of green space, and whether a more accurate measure can be obtained for the current period using newly available data such as infrared imagery.

2 Background

The objective of the original study was to measure the change in public and private green space in three of the five Tier 1 cities in New Zealand: Hamilton, Auckland, and Greater Wellington (Wellington city, Lower Hutt, Upper Hutt, and Porirua). A second objective was to identify the distribution of urban green space within the three cities and how this has changed over time. This information was then compared to the population distribution to derive the proportion of green space *per person*.

For the purposes of that study, green space consisted of a mixture of natural space (grass, trees, and shrubs) and some types of 'grey' space (paved areas such as playing courts, courtyards and plazas, patios, and driveways). This was largely due to methodological constraints, because only monochromatic imagery was available for the historical periods.

All three study cities now have high-resolution colour imagery available. There is also near-infrared (NIR) imagery available for all three. NIR imagery is routinely combined with RGB colour imagery to compute a normalised differential vegetation index (NDVI) from the NIR and red bands (NDVIr):

$$NDVIr = (NIR - Red)/(NIR + Red)$$

NDVI is commonly used to estimate vegetation density; it is less commonly used to separate green and impervious surfaces, which was the aim of this study.[4] After some experimentation with Wellington's RGB+NIR imagery, we observed that the standard NDVI

[4] Some GIS tools, such as ArcGIS, now include AI-based models for separating green and grey space. However, the underlying models typically require substantial additional training to work well with New Zealand vegetation.

using the red band is a good measure of woody vegetation, but that green space is better separated using a modified index that uses the *blue* band (NDVIb):

$$NDVIb = (NIR - Blue)/(NIR + Blue)$$

This observation was consistent with Auckland City Council's experience. These indices can then be used to separate green from grey space (NDVIb) and woody vegetation from grass (NDVIr) by applying a suitable threshold.

3 Objectives

The objective of this study was to repeat the measurement of green space for the three study cities (Hamilton, Auckland, Wellington) using the most recent infrared imagery available along with the corresponding RGB images. The following outputs were generated for each city:

- green space rasters, categorising green space in three ways:
  - by land use type: commercial/industrial, private residential, public open space, transport corridor, public – peri-urban (Wellington only)
  - by accessibility (private or public)
  - by vegetation type (open ground or vegetated)
- a population layer with statistics by statistical area unit: per-population calculations are presented based on both the original 2013 census meshblock[5] population figures, and the newer 2018 meshblock population figures.

4 Methods

A GIS-based approach was again used to measure green space. In the previous study, green space was inferred by mapping potential green space areas (based on local authority planning maps and visual inspection), and then buildings, roads, and some paved areas were detected and removed. For this new analysis, NIR and colour imagery were used to generate indices that could be used to directly separate green space (including bare ground, grass, and woody vegetation) from grey space (impervious surfaces). These generated 'greenness' rasters, to which a threshold was then applied to separate green and grey space. For each city, a green space mask raster was generated from a combination of RGB and NIR imagery.

The process consists of the following steps.

1 Compute a normalised greenness index = (NIR – blue) / (NIR + blue).

[5] A meshblock is the smallest geographical unit for which statistical data are collected and processed by Stats NZ.

2 Determine a threshold to be used to decide whether each pixel is green space (above threshold) or grey space (below threshold). Use this threshold to generate a binary mask (0 = grey space, 1 = green space).

3 Mask out false positives caused by red roofs by subtracting building footprints from the mask.

A woody vegetation mask was generated in a similar fashion.

1 Compute the normalised vegetation index = (NIR – red) / (NIR + red).

2 Determine a threshold to be used to decide whether each pixel is woody vegetation (above threshold) or open green space (bare ground, grass; below threshold). Use this threshold to generate a binary mask (0 = not woody vegetation, 1 = woody vegetation).

3 Combine the vegetation mask with the green space mask to give a three-class raster (0 = grey space, 1 = grass/bare ground, 2 = woody vegetation).

4.1 Imagery

For each city the most recent imagery that included NIR capture was used. Table 1 summarises the imagery used.

Table 1. Details of the near-infrared aerial mosaics

City	Year taken	Image type and resolution
Hamilton	2021	TIFF (NIR +RGB), 0.2m
Auckland	2010/2011	Jpeg (NIR+GB), 0.5m
Wellington	2021	TIFF (NIR+RGB), 0.3m

4.2 Selecting the thresholds

The selection of the threshold for each mask has a significant effect on the resulting measurements. Three approaches were tried.

1 Inspect a histogram of the index values and look for a cut point that separates the two distributions (impervious surfaces versus natural surfaces; open grass versus woody vegetation).

2 Try several thresholds and inspect the resulting masks for a balance of false positives and negatives.

3 Use machine learning to select the threshold.

In practice the viability of each method depended on the image quality. NIR imagery is generally lower quality than RGB, with the infrared signal 'bleeding' outward into adjacent areas, particularly when these areas have high RGB values. This results in a tendency to over-report green space. Conversely, shadows are challenging because the signal for all channels becomes weak, and the resulting differential index value is unreliable. Further, in some imagery, the shadows had a blue colour cast, causing the greenness index to be biased toward under-reporting. These issues make visual selection of an appropriate threshold challenging.

4.2.1 Selecting a threshold from the index histograms

The greenness and vegetation indexes ideally follow a bimodal distribution, whereby the two classes are cleanly separated with no overlap, giving an obvious threshold value. In practice the two classes tend to overlap, and this is exacerbated by issues with image quality. Figure 1 shows the greenness and vegetation histograms for Hamilton, Auckland, and Wellington. (Noise to the left of each chart is caused by reflections off water and can be ignored.)

For an NDVIb index, because the main distribution is clearly bimodal, the mid-point minimum can be selected as the threshold. This gives threshold values of around 0.0 for Hamilton, 0.2 for Auckland, and 0.1 for Wellington. These could potentially be used as threshold values.

For separating woody vegetation from grass using NDVIr the situation is far less clear, with only Wellington showing obvious evidence of a further bimodal distribution in the range of index values representing woody vegetation, with the mid-point minimum at around 0.3.

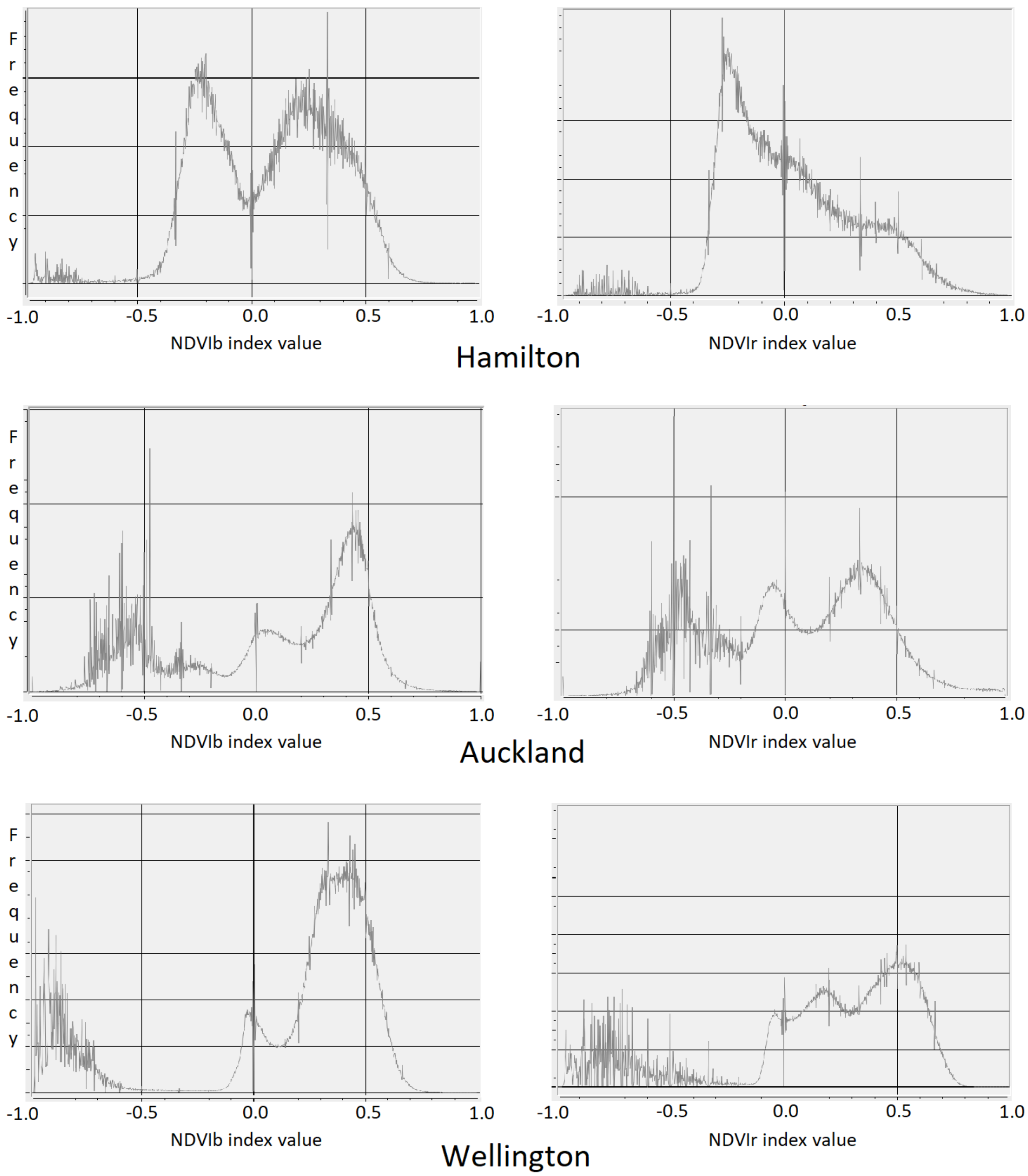


Figure 1. NDVIb (green space) and NDVIr (woody vegetation) indices for each city.

4.2.2 Selecting the threshold through visual inspection of generated masks

An alternative approach is to threshold the indices at several values and visually inspect the results for accuracy. This was carried out for the NDVIb (green versus grey space) threshold for all three cities. For Hamilton, the threshold selected from the histogram of 0.0 gave excellent results, whereas for Auckland and Wellington the masks appeared visually most accurate when the threshold was 0.05 higher than the value suggested by the histograms (0.25 and 0.15, respectively).

For Auckland and Wellington the manually selected thresholds were most likely both higher than the histogram suggested because these thresholds minimised over-reporting of green space owing to obvious 'bleed' in the infrared layer from green areas to neighbouring grey space, without overly adding obvious dropout from vegetation shadows and bare land. This problem is worst in Auckland, significant in Wellington, and almost non-existent in Hamilton (due to its superior infrared image quality). However, this must be balanced with the tendency for tree shadows to be under-reported; this issue gets worse as the threshold is raised and is more difficult to gauge visibly. There is also potential bias from viewing only a localised sample of the resulting mask.

Figure 2 shows examples of the imagery from each city, where the red band represents the NIR channel. As can be seen, the NIR channel is indistinct in both the Auckland and Wellington images, with the entire grey space showing elevated infrared levels for Auckland, and the NIR signal 'bleeding' into the road edge for Wellington. In contrast, the Hamilton NIR signal is much stronger and more accurate, with crisp edges between the green and grey spaces. As a result, selecting the threshold using visual inspection cannot be considered reliable for either Auckland or Wellington.

Auckland **Wellington** **Hamilton**

Figure 2. Examples of (NIR, green, blue) imagery.

4.2.3 Selecting the threshold using machine learning

We investigated whether a more accurate model for mapping RGB+NIR could be inferred from the data by training a machine learning model to classify each mask pixel as green or grey based on its image and index pixel values. The process was as follows.

- Identify representative areas representing various examples of green and grey space:
  - non-woody vegetation green space: parks, golf courses, lawns, and farmland, including bare ground and shaded areas
  - woody vegetated green space, including bush, private trees, and trees in parks
  - impermeable space, including roads, buildings, and other concrete areas such as parking lots.
- Extract an image for each area, giving thousands of sample pixel values for green and grey space.
- Extract the image pixel values, and add the following computed features:
  - normalised values (divide the channel value by the average of all channels)

- NDVIb.
- Infer a model for the data using various machine learning algorithms.
- Use the generated models to infer mask layers and visually assess their accuracy.

Figure 3 plots histograms of index values for the NDVIb for the sampled pixels, showing how the values are distributed for green and grey space. The histograms show good separation of grey and green space index values for Wellington and Hamilton. For Auckland, the two distributions have significantly more overlap, suggesting separating the two classes will be less accurate for Auckland and the threshold point less well defined.

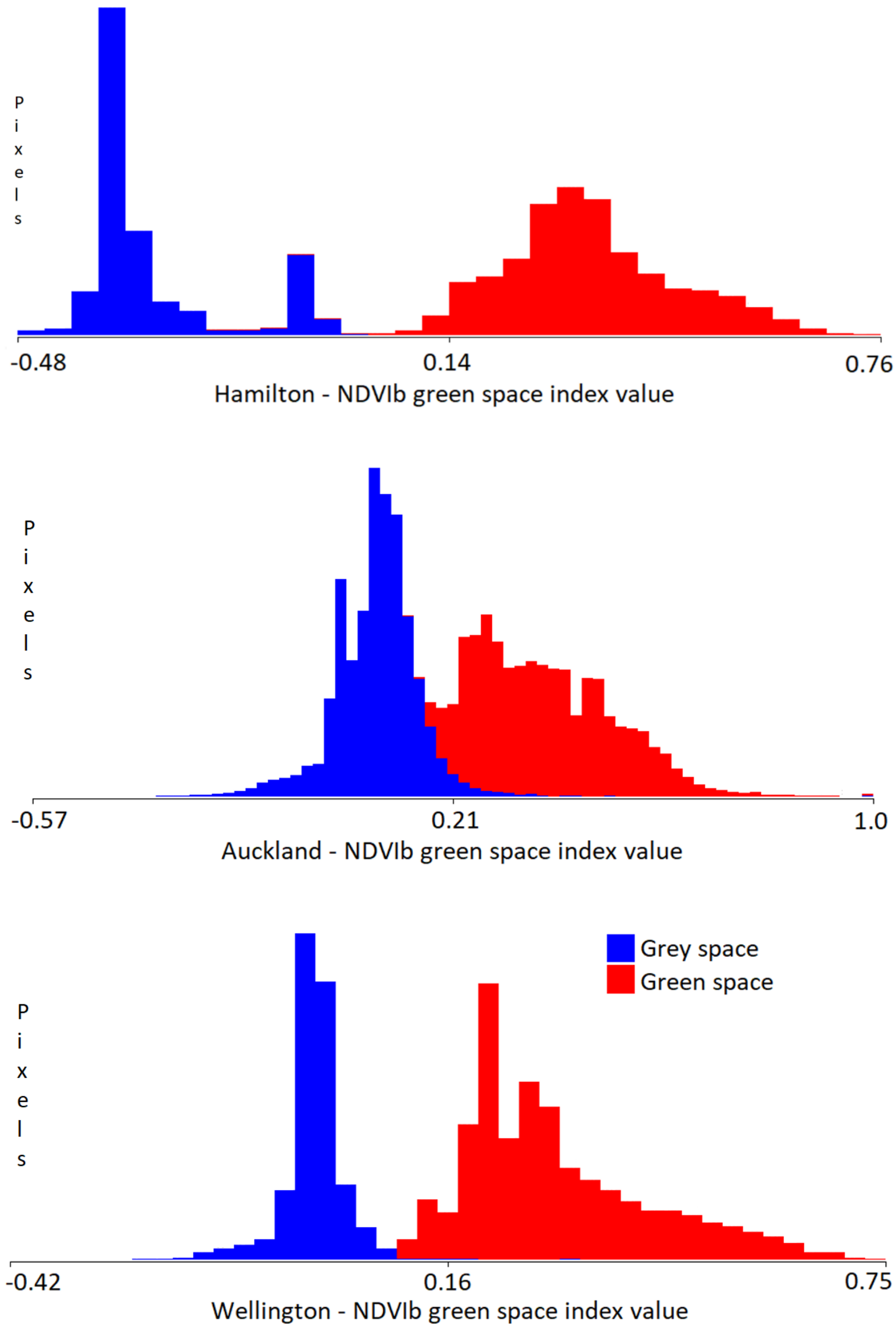


Figure 3. Frequency histograms of green space index values, separated by class.

Several models were tested using a combination of NDVIb, the raw pixel values, and normalised pixel values. Models inferred using all these features produced high-accuracy scores during training but overfitted the data, resulting in poor masks when applied across the entire city.

We then inferred models using NDVIb alone, which simply selects the threshold. We selected the best NDVIb-based model, trained using logistic regression and an entropy-based model, separately. These two approaches have quite different learning biases: whereas logistic regression iteratively refines the fit of the logistic function to the data points and then selects the threshold from the function's zero crossover point, the entropy method directly selects the threshold that maximises global entropy.

As a consequence, logistic regression is more sensitive to the shape of the two distributions near the threshold, whereas entropy is more sensitive to the overall sample bias. In practice, the two methods gave consistent, but different estimates for the thresholds. Table 2 shows the resulting thresholds.

Table 2. NDVIb thresholds selected and their cross-validation accuracies

City	NDVIb threshold: logistic regression (accuracy)	NDVIb threshold: entropy (accuracy)	NDVIb threshold: visual inspection
Hamilton	0.01 (99.65%)	0.02 (99.64%)	0.0
Auckland	0.20 (96.77%)	0.17 (96.89%)	0.25
Wellington	0.10 (99.7%)	0.09 (99.7%)	0.15

The selected thresholds were essentially the same as those selected from the histograms, suggesting the bimodal minimum is the most probabilistically accurate threshold. The Wellington and Hamilton models had high levels of cross-validation accuracy (>99%) compared to Auckland, reflecting the overlapping distributions (probably caused by the poorer image quality).

It should be noted that this approach is limited by the quality of the sample selection: poor selection may introduce bias. During the experiment it was noted that shadows are a strong source of noise and are almost impossible to classify owing to their lack of reliable channel values. Similarly, the infrared signal for bare ground is indistinguishable from that for impermeable surfaces. Including either shadows or bare ground biases the model according to their sample size, so they were removed from the sample set. Because logistic regression is less sensitive to overall bias, it was used to select the machine learning-based thresholds for the NDVIb threshold mask.

4.2.4 Threshold sensitivity

Selecting the threshold is a critical step, and changing this value has a non-trivial effect on the measured green space. Table 3 shows the total green space reported for a variety of threshold values for each city. Note that each city is different due to non-standard normalisation of the imagery. The numbers reported are before building footprints were removed, then the coverage for the selected best model is reported at the bottom of the table with building footprints masked out.

Table 3. Total green space versus NDVIb threshold

Threshold	Hamilton % green space	Auckland % green space	Wellington % green space
0.35		40.4	
0.3		48.5	
0.25		54.6 (visual selection)	59.7
0.2		60.4 (machine learning selection)	65.5
0.15			70.2 (visual selection)
0.1			74.7 (machine learning selection)
0.01	47.3 (machine learning selection)		
0.0	47.6 (visual selection)		
Selected models with buildings removed	Visual: 46.0 Machine learning: 46.3	Visual: 51.2 Machine learning: 55.8	Visual: 68.2 Machine learning: 72.1
Originally inferred and reported	54.2	56.8	71.8

Comparing the machine learning versus manually selected thresholds suggests a potential error from inaccurate threshold selection of around 3.9% for Wellington, 4.6% for Auckland, and less than 1% for Hamilton.

4.2.5 Separating woody vegetation from grass

Figure 4 plots histograms of NDVIr and NDVIb for sampled pixels of woody vegetated and grassed areas for the three cities. Unlike the distributions for green versus grey space, the NDVIb and NDVIr histograms showed no clear bimodal separation of woody vegetation versus grass. Also, trying to decide the threshold based on visual inspection of the resulting masks was extremely challenging, because the level of under-reporting (shadows) versus over-reporting (inclusion of lush/long grass) could not be easily judged. We therefore relied solely on the machine learning threshold selection.

Of the two indices, NDVIr has less overlap between the classes; this is particularly apparent for Hamilton, which has the best NIR imagery. We therefore used the NDVIr index. We repeated the machine learning experiments, this time separating trees and grass using the NDVIr index. Table 4 shows the results.

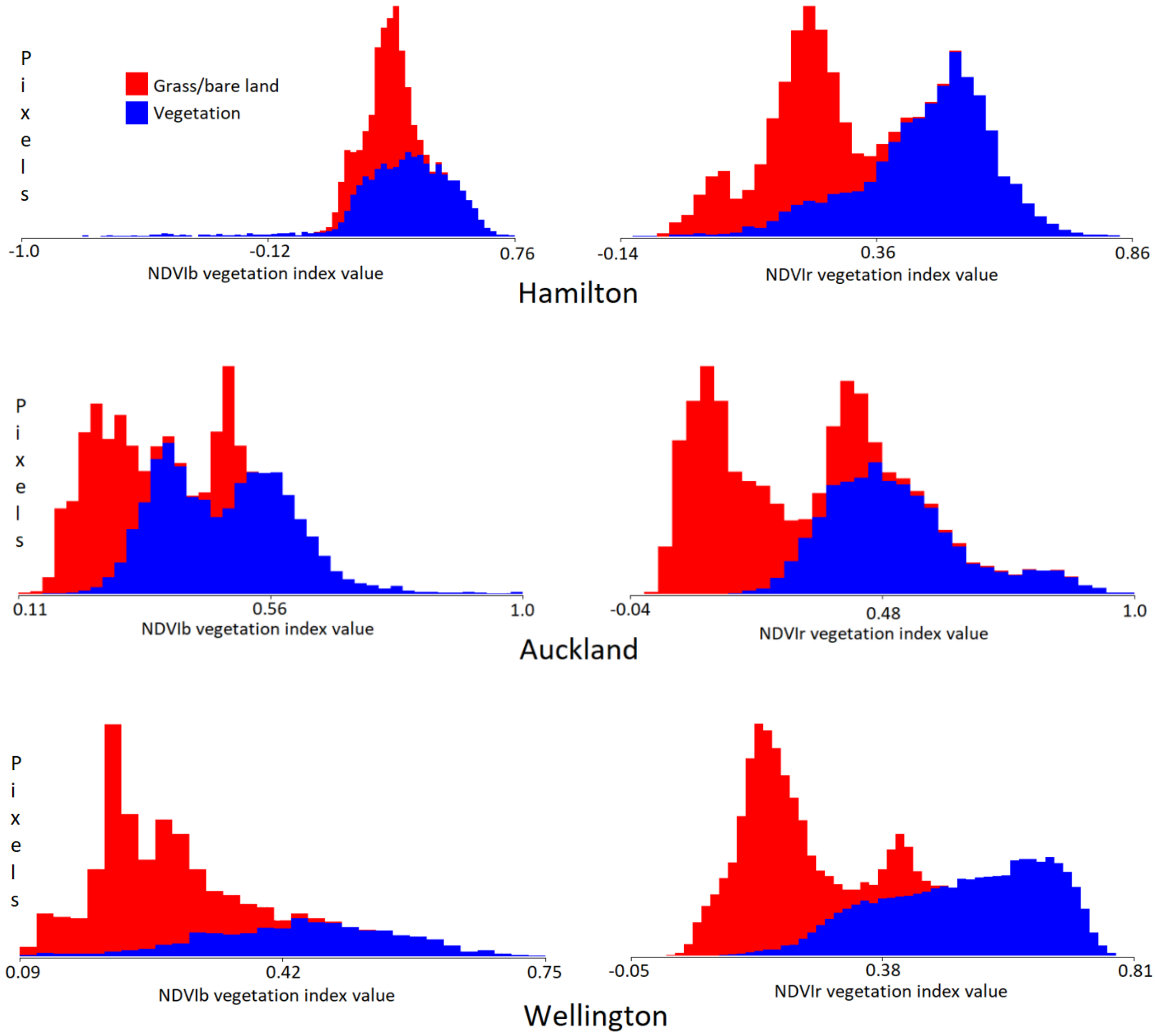


Figure 4. NDVIb and NDVIr histograms of index values.

Table 4. NDVIr thresholds selected and their cross-validation accuracy

City	NDVIr threshold: logistic regression (accuracy)	NDVIr threshold: entropy (accuracy)	NDVIr threshold: visual/histogram inspection
Hamilton	0.30 (88.57%)	0.35 (88.17%)	0.33
Auckland	0.36 (83.55%)	0.27 (86.20%)	0.4
Wellington	0.34 (87.6%)	0.28 (89.14%)	0.3

The accuracies for this task are substantially lower than for green versus grey space, and the difference between the logistic regression and entropy-based models is greater, reflecting the level of uncertainty about where to set the threshold. Table 5 lists the resulting vegetation cover using the two methods.

Table 5. Vegetation cover for each of the candidate thresholds

City	Vegetation cover: logistic regression threshold	Vegetation cover: entropy threshold	Vegetation cover: visual/histogram threshold
Hamilton	(NDVIr ≥ 0.30) 17.34%	(NDVIr ≥ 0.35) 14.67%	(NDVIr ≥ 0.33) 15.4%
Auckland	(NDVIr ≥ 0.36) 24.60%	(NDVIr ≥ 0.27) 36.96%	(NDVIr ≥ 0.4) 15.24%
Wellington	(NDVIr ≥ 0.34) 45.25%	(NDVIr ≥ 0.28) 50.67%	(NDVIr ≥ 0.3) 49%

We then visually inspected the resulting masks from the logistic regression model and the entropy-based model. For Wellington and Auckland there were significant visual differences between the various thresholds, and in both cases the threshold selected by logistic regression was considered to give the best result, with the entropy-based thresholds significantly over-reporting vegetation. For Hamilton, the differences between the masks generated by the three thresholds were minimal. We therefore again used the thresholds selected by logistic regression to generate the masks.

4.3 Calculate statistics

The statistics (by Stats NZ statistical area unit[6]) polygon layer generated for the previous research was extended using the same methods to include the following additional information for each city from this extension study:

- green space percentage coverage from the NDVIb-derived mask: public, private, and total green space
- green space per person, using the population densities previously calculated from the 2013 census
- population and population density estimates generated from the 2018 census
- green space per person, using the population densities calculated from the 2018 census.

Table 6 lists the full set of fields provided.

The imagery used for this study comes from different dates from either the 2013 or the 2018 census, and the dates are also different from the original study (which was used to calculate the city boundary for this study). This introduces the following potential sources of error.

- The building footprint may have changed, particularly from new development.
- The city boundary may have changed, meaning the densities are overestimated.

[6] Statistical area units are non-administrative areas intermediate in size between meshblocks and territorial authorities. In an urban location, an area unit is often a collection of city blocks, while in rural situations area units may be equated to localities or communities. https://datafinder.stats.govt.nz/layer/27771-area-unit-2017-generalised-version/

These issues were also present in the previous study, which used the 2013 census and 2016 imagery.

Table 6. Data field definitions for the population statistics layer

Field group	Field name	Description
Originally reported open space statistics	POP_2013	Population – 2013 census
	AREA	Area (m^2 or km^2)
	DENS_2013	Population density – 2013 census
	PU_OS_16	Public open space – 2016 imagery
	PR_OS_16	Private open space – 2016 imagery
	TT_OS_16	Total open space – 2016 imagery
	PU_OS_P13	Public open space per person – 2013 census
	PR_OS_P13	Private open space per person – 2013 census
	TT_OS_P13	Total open space per person – 2013 census
Measured green space (infrared)	PU_GS_YY	Public green space – YY imagery
	PR_GS_YY	Private green space – YY imagery
	TT_GS_YY	Total green space – YY imagery
Measured green space – 2013 census	PU_GS_P13	Public green space per person – 2013 census
	PR_GS_P13	Private green space per person – 2013 census
	TT_GS_P13	Total green space per person – 2013 census
Measured green space statistics – 2018 census	POP_2018	Population – 2018 census
	DENS_2018	Population density – 2018 census
	PU_GS_P18	Public green space per person – 2018 census
	PR_GS_P18	Private green space per person – 2018 census
	TT_GS_P18	Total green space per person – 2018 census
Differences between 2016 open space reported and measured green space	PU_GS_DIFF	Public green space difference
	PR_GS_DIFF	Private green space difference
	TT_GS_DIFF	Total green space difference

5 Results

The change in method, from inferring green space from open space to measuring the green space directly, led to differences in the total public, private, and overall green space. Table 7 summarises these changes.

Table 7. Green space summary and comparison to the previous results for all three cities

City	Public green space % (previous, change)	Private green space % (previous, change)	Total green space % (previous, change)
Hamilton	21.6 (18.6, +3.0)	24.4 (35.6, –11.2)	46.0 (54.2, –8.2)
Auckland	24.7 (20.5, +3.2)	30.6 (36.2, –5.6)	55.3 (56.8, –1.5)
Wellington – excluding peri-urban reserves	31.2 (26.1, +5.1)	33.1 (37.4, –4.3)	64.3 (63.5, +0.8)
Wellington – all reserves	46.6 (43.0, +3.6)	25.6 (28.9, –3.3)	72.2 (71.8, +0.4)

Overall:

- total green space for Wellington is almost unchanged, with increases in public green space from inclusion of the transport corridor almost exactly balancing losses in private green space from paving
- for Auckland the difference is larger, but still small (–1.5% of total city area), for the same reasons as Wellington
- Hamilton's total green space changes significantly (–8.2% of total area), mainly due to a much larger loss of private green space.

As with the previous study, Hamilton has significantly less green space coverage than either Auckland or Wellington. Wellington has the highest green space proportion, both with and without the inclusion of peri-urban reserves.

The distribution of green space throughout the city also changes, dominated by three factors:

- the location of motorways, which add substantial public green space
- patterns of intensification and new development, which remove substantial areas of green space
- the amount of commercial green space present, which was largely excluded from the previous study.

Figure 5 illustrates the changes in total green space by statistical area for the three cities. Hamilton shows the largest change, as expected from the large drop in total green space. For Wellington and Auckland the change is less, with gains and losses approximately balanced, in line with the minimal total green space change.

Figure 5. Differences in total green space distribution.

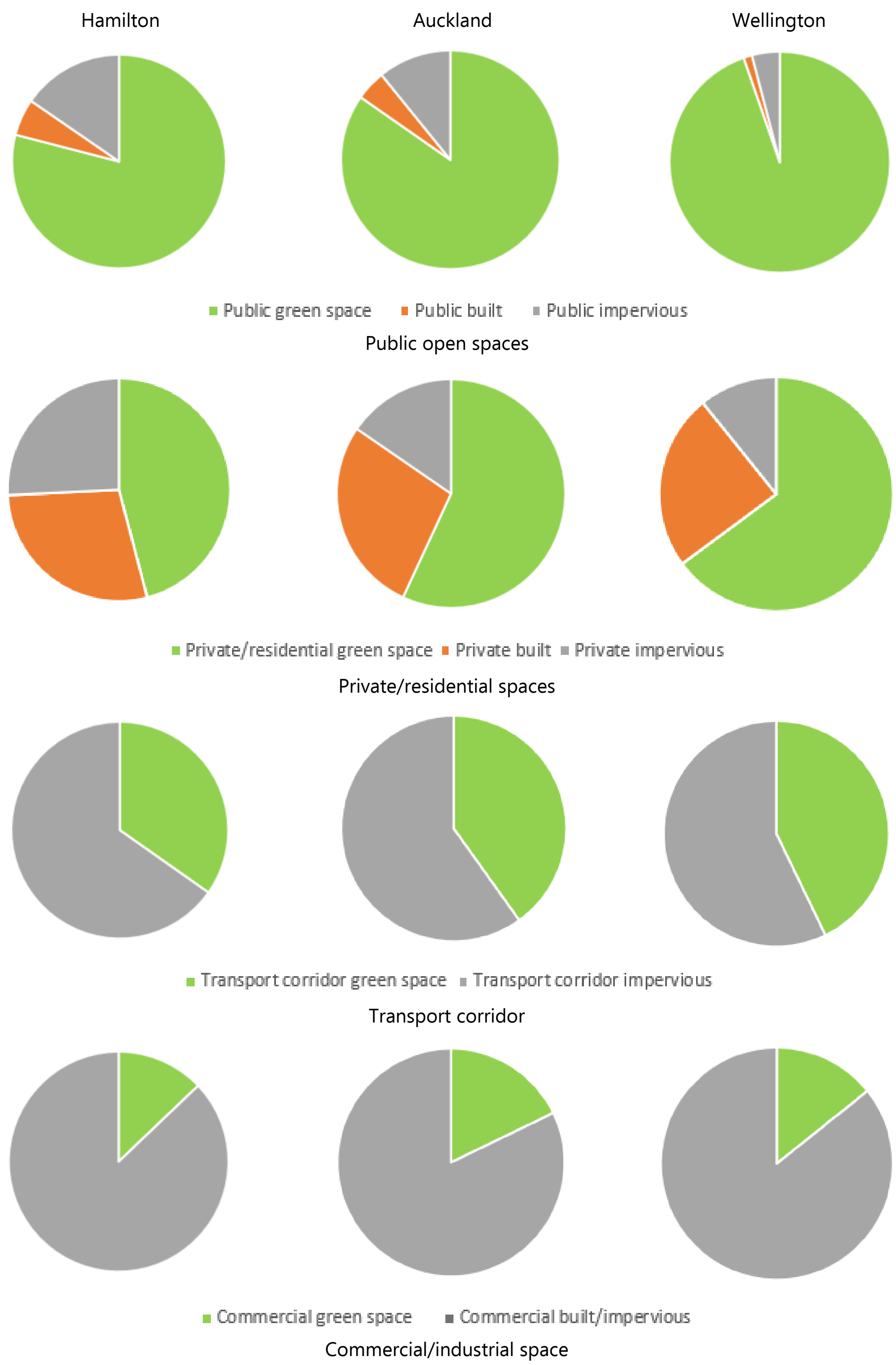


Figure 6. Breakdown of usage types into green, grey, and built space.

In the previous study building footprints were detected, enabling a comparison of the built and unbuilt space. In this study we have further separated open space into green and grey space. Figure 6 shows the breakdown of spaces for each of the major usage types (public open space, private/residential spaces, commercial/industrial spaces, and the transport corridor).

The most striking difference between the three cities is that Hamilton's private/residential space has a significantly larger proportion that is paved. Commercial areas and transport corridors are similar for the three cities, while the proportion of impervious surfaces in public open spaces is much lower for Wellington because of its large peri-urban reserves, with Hamilton again having the largest proportion covered in buildings and impervious surfaces.

Table 8 summarises the public, private and total green space per person for each city, using the 2018 census for Hamilton and Wellington to more closely match the date of the imagery (2021), but using the 2013 census (used for all three cities in the original study) to more closely match the older date of the imagery (2011).

Table 8. Green space per person for the three cities

City	Public green space m^2 per person (previous, change)	Private green space m^2 per person (previous, change)	Total green space m^2 per person (previous, change)
Hamilton (2018 census)	101 (102, –1)	118 (194, –76)	219 (295, –76)
Auckland (2013 census)	108 (89, +19)	133 (157, –24)	241 (247, +6)
Wellington – excluding peri-urban reserves (2018 census)	158 (140, +18)	167 (201, –34)	325 (341, –17)
Wellington – all reserves (2018 census)	305 (299, +6)	167 (201, –34)	472 (499, –27)

In all three cases private green space per person falls, with Hamilton experiencing the largest fall of $76m^2$ per person, a reduction of almost 40% compared to the previous study. In contrast, Auckland and Wellington saw reductions of 15% and 17% of private green space per person. The reductions result from a combination of the removal of paved areas and an increase in population density (Hamilton's population density rose from 18 people per hectare in 2013 to 21 people per hectare in 2018, a 13% increase).

Public green space per person rose for Auckland and Wellington from the inclusion of road berms, and remained almost unchanged in Hamilton. Overall green space per person fell by over 25% for Hamilton and around 5% for Wellington, but remained almost unchanged for Auckland.

5.1 Hamilton

5.1.1 Revised green space totals

Hamilton's green space was mapped using 2021 imagery with a spatial resolution of 0.2 m. This is a higher spatial resolution than the imagery available for Auckland or Wellington, and the quality of the NIR band was demonstrably the best of the three cities, with far less bleed. As a result, the green space and vegetation maps are likely to be more accurate.

The green space index for Hamilton was thresholded at 0.0, giving total green space cover of 46%, compared to 54.2% previously reported (an 8.2% decrease). This suggests the original method may have over-reported green space, although some of this difference is caused by additional development. There is some 'dropout' in the new mask caused by shadows and areas of bare earth, but it appears to be minimal.

The city-wide green space was then filtered by open-space classification to compute the amount of green space of each type. The resulting coverages are listed in Table 9.

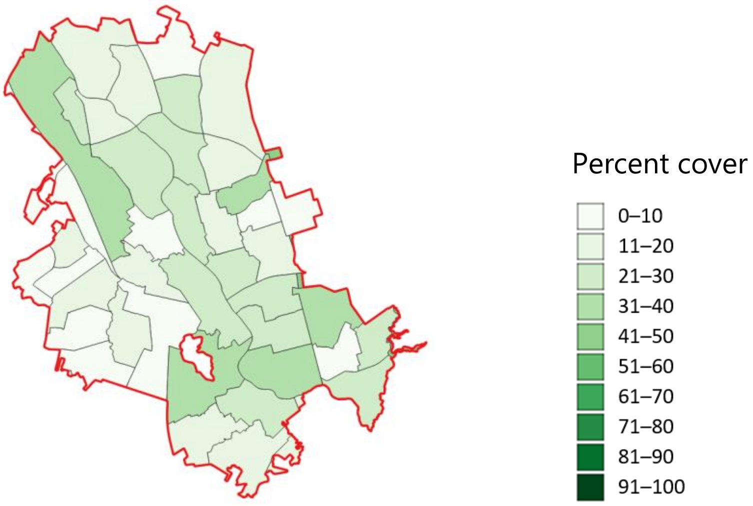
Table 9. Hamilton green space, by usage type

Classification	2021 analysis (direct detection) %	2016 analysis (subtraction-based) %	Inferred (extra) grey space (% of open space)
Public open spaces	15.6	18.6	3.0 (16%)
Private/residential	22.8	35.6	12.8 (36%)
Commercial/industrial	1.6	0	–1.6
Transport corridor	5.4	0	–5.4
Water (Waikato river)	0.6	0	–0.6
Total	**46.0**	**54.2**	**8.2**

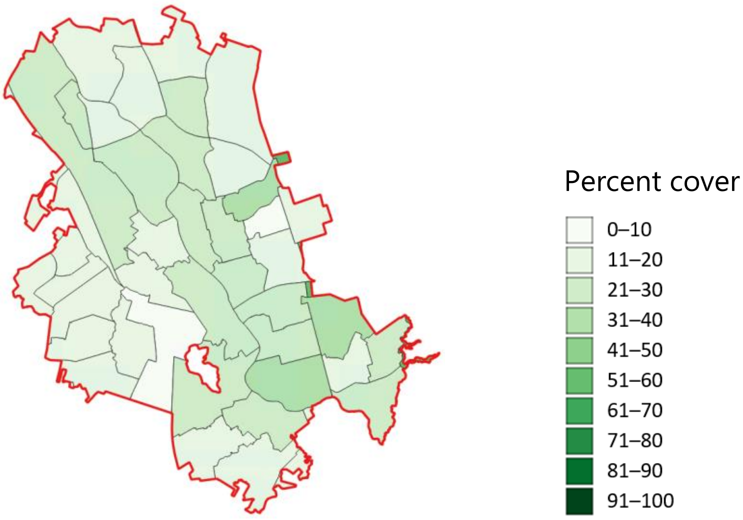
The new mask suggests that around 16% of public open space and 36% of private residential space (excluding the area taken up by the building footprint) is sealed.

5.1.2 Revised green space distribution

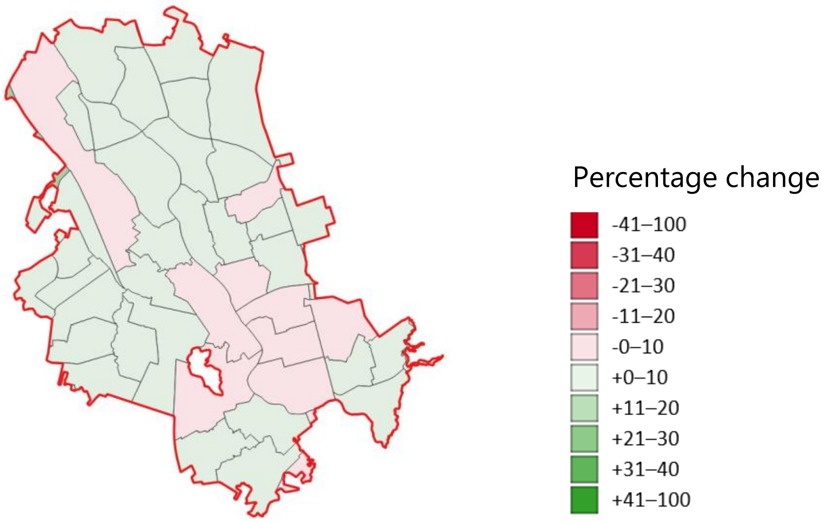
Figure 7–9 compare the new green space distribution with the previously reported open space and show the differences. Overall, the pattern of total green space distribution is largely unchanged, but the overall level of greenness is lower, with most areas experiencing a decrease in green space compared to the original study, and some areas seeing a significant reduction.



Public green space inferred from open space, as previously reported

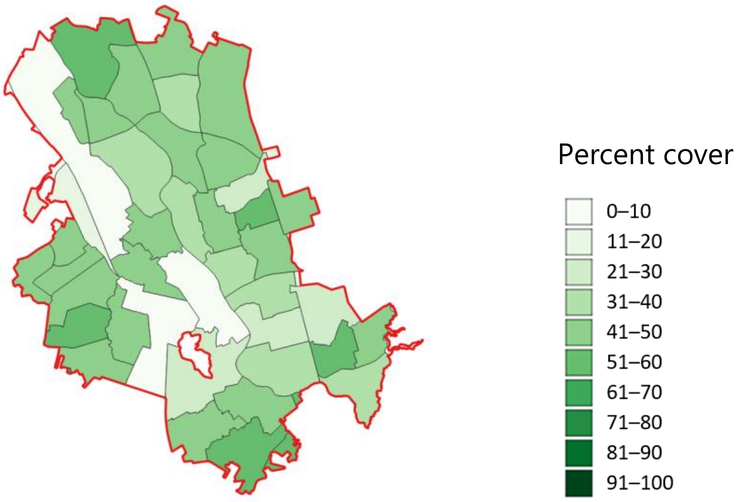


Public green space measured directly from infrared imagery

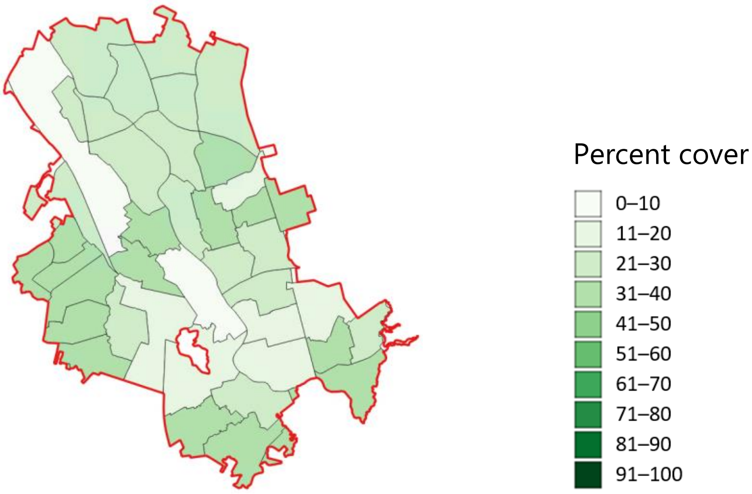


Difference between inferred and measured public green space

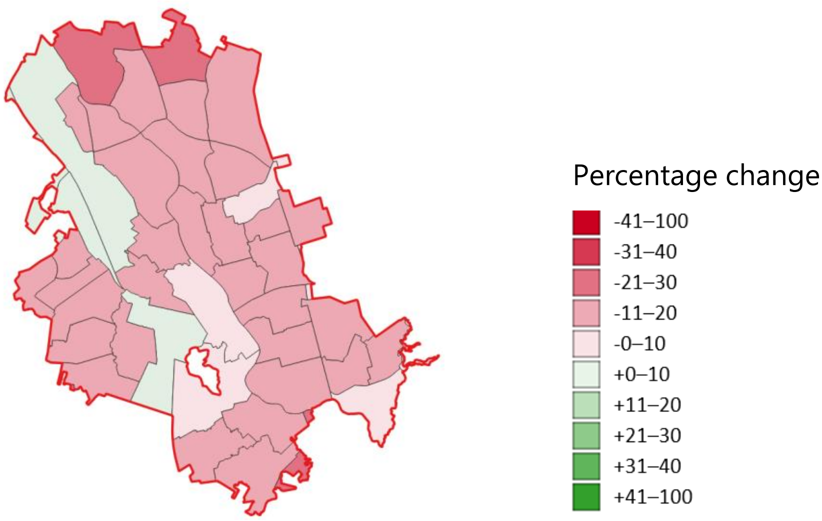
Figure 7. Hamilton public green space distribution.



Private green space inferred from open space, as previously reported

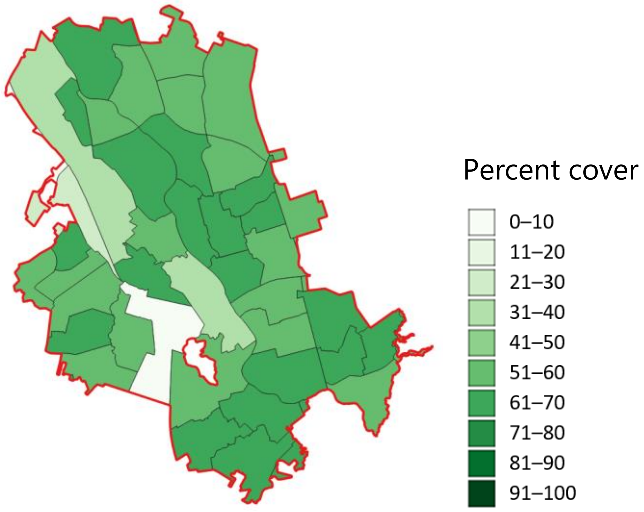


Private green space measured directly from infrared imagery

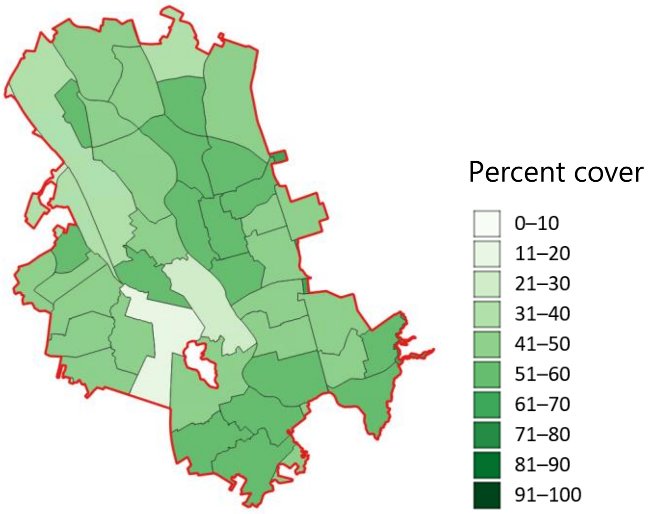


Difference between inferred and measured private green space

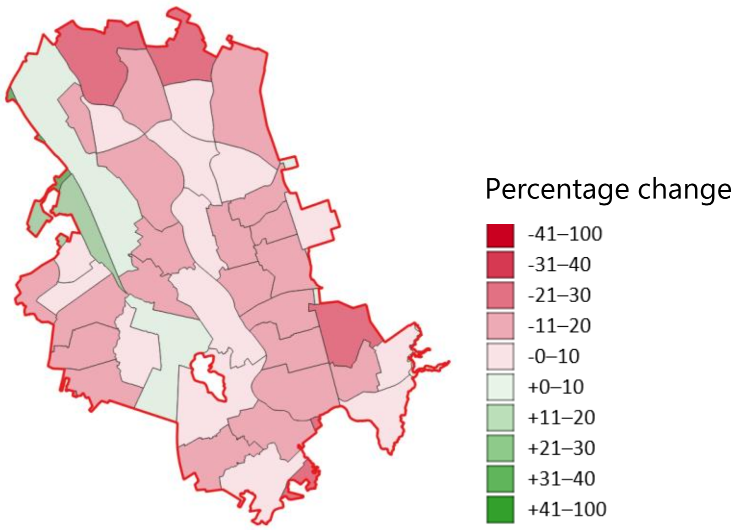
Figure 8. Hamilton private green space distribution.



Total green space inferred from open space, as previously reported



Total green space measured directly from infrared imagery



Difference between inferred and measured total green space

Figure 9. Hamilton total green space distribution.

Compared to the primary subtraction-based analysis, public green space directly measured using NIR increased in most areas, with 14 areas experiencing an increase of 5% or more. This increase is entirely due to the addition of green space in the transport corridor, with areas close to motorways (including Fairview Downs, Rototuna, Chedworth, and Pukete) showing the largest increases. In contrast, public green space decreased in 10 areas, although only two of these (university and Naylor) were by more than 2% of the total area. In both cases a small water body was included in the original measured green space, and a significant portion of the university is paved parking space. Naylor also has significant parking areas in and around Hamilton Gardens, and there appears to be a new motorway being built to the right of Hamilton cemetery, which has resulted in a significant area of green space being lost. Overall, public green space appears to have been well represented in the original study.

Private green space shows a much larger difference between the two studies, with many areas experiencing a reduction of more than 10% of total area. Three areas show a reduction of more than 20% (Sylvester and Horsham Downs in the north, Peacocke in the south). Some of this change is due to further development that has occurred between 2016 and 2021. For example, Sylvester (on the northern boundary) has seen a significant reduction in green space (Figure 10). This area also shows a large reduction in private green space in Figure 8, although, as can also be seen in Figure 10, this new subdivision has a high proportion of paved area, so the green space previously reported would have been significantly overestimated. This is true for all three areas showing the largest reductions.

Figure 10. An area in Sylvester under development in 2016 (left) and 2021 (right).

More generally, the loss of typically around 10% of total area is a combination of the exclusion of impervious surfaces (including swimming pools) and additional in-fill building. Figure 11 shows a typical example of both effects in the suburb of Insoll: the main loss of green space is from sealed driveways and parking areas, but some in-filling is also apparent.

Figure 11. Insoll aerial image (left), previous private green space mask (middle), and new green space mask (right).

Recent subdivisions show an increasing density, with a corresponding greater loss of green space to impervious surfaces (this effect is more marked in Hamilton than in Auckland or Wellington). Figure 12 compares the built versus impervious footprint in an area in Horsham Downs.

Figure 12. New subdivision in Horsham Downs: aerial image (left), original public green space mask (middle) and new green space mask (right), showing the extent of impervious surfaces.

Four Hamilton areas showed an increase in private open space compared to the previous study (Burbush, Rotokauri, Te Rapa, and Frankton Junction). All four are dominated by commercial zones, and the difference is small (4–7%).

5.1.3 Woody vegetation cover

We generated a woody vegetation mask by computing a standardised vegetation index and applying a threshold, chosen by logistic regression, of 0.3. The resulting green mask suggested a total tree canopy cover of around 17%, with the remaining green space area (29%) being grass or bare ground. There is some dropout due to shadows and non-green trees (yellow, red), but there is also some corresponding false positive cover from shadows and lush grass. We were unable to find a published figure of total tree cover in Hamilton to check this result – published figures refer to indigenous cover only. Figure 13 shows green space by vegetation type compared to the aerial image. The overall vegetation pattern visually matches the aerial image very well.

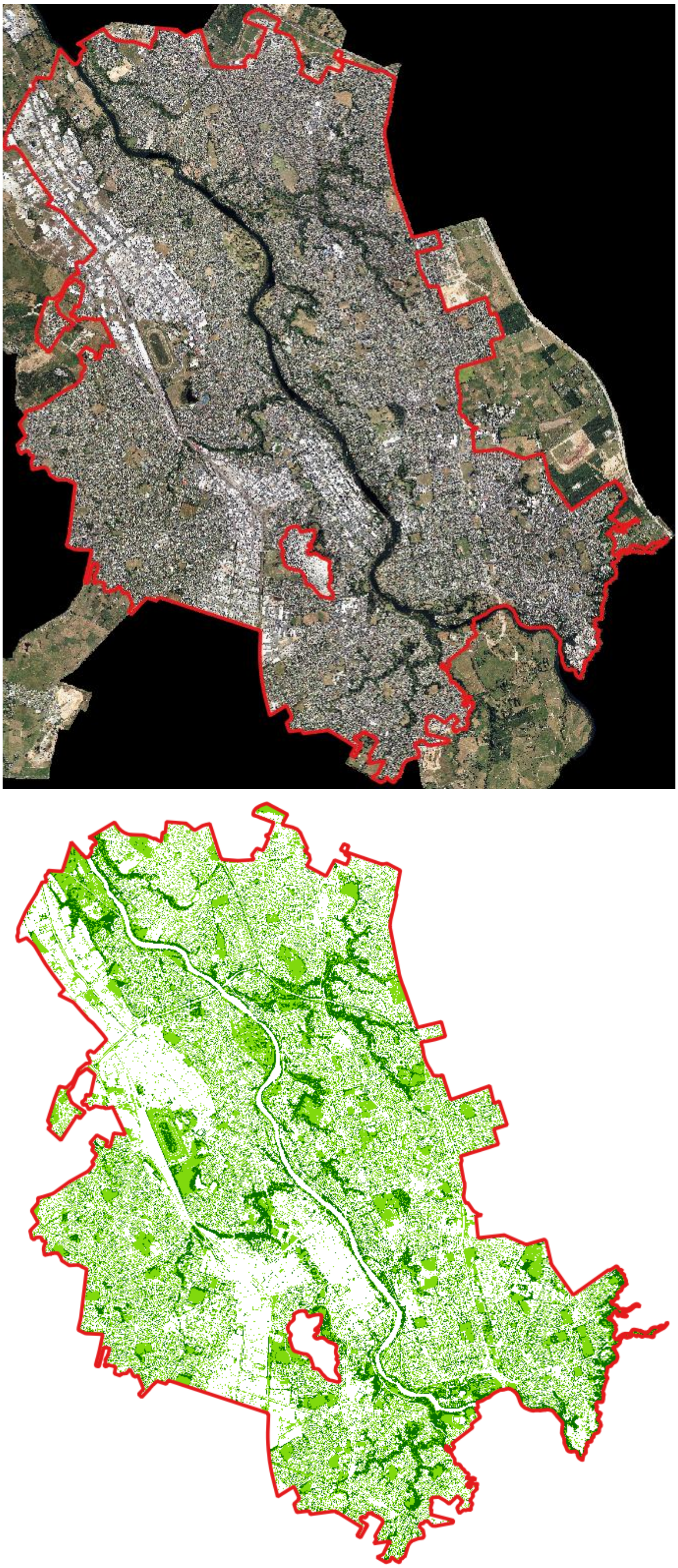


Figure 13. Hamilton aerial image (left) and corresponding vegetation mask (right: light green = grass, dark green = woody vegetation).

5.2 Auckland

5.2.1 Revised green space totals

Total green space was measured by creating a green space mask based on RGB+NIR imagery, and then computing the mean value for the entire area within the previously selected 2016 urban boundary. The NDVIb index was thresholded using logistic regression at 0.20, and the built footprint subtracted. This mask classified 55.3% of the area within the chosen 2016 boundary as green space. This is close to the 56.8% coverage originally reported.

The city-wide green space was then filtered by open space classification to calculate the amount of green space for each usage type. Figure 14 shows an example of the classified mask, and the resulting coverages are listed in Table 10.

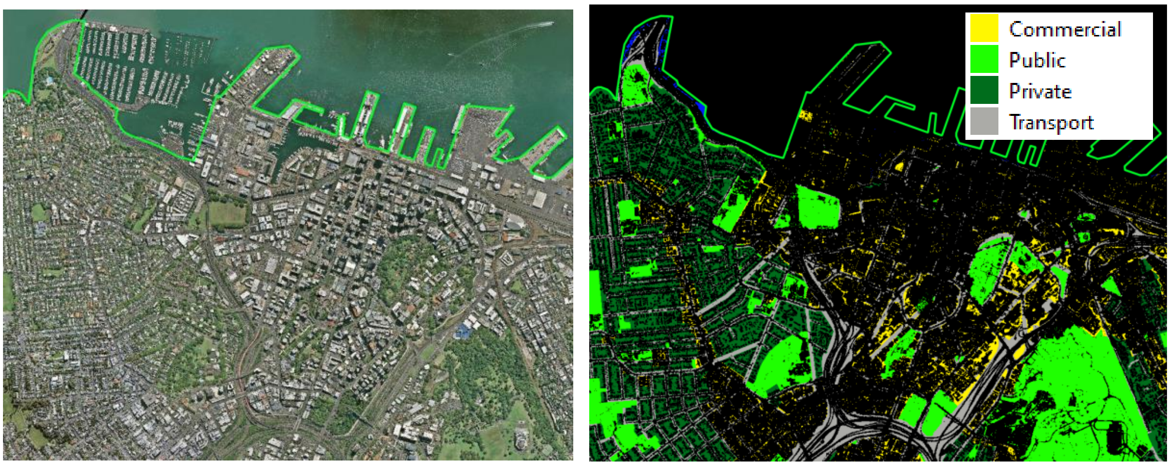


Figure 14. Auckland CBD (left) and matching green mask (right), coloured by open space class.

Table 10. Auckland green space, by usage type

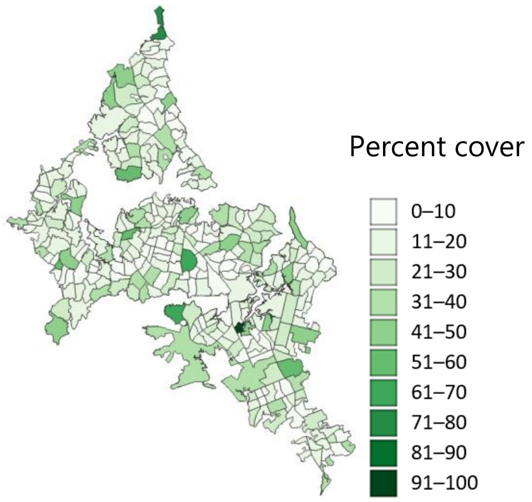
Classification	2011 analysis (direct detection) %	2016 analysis (subtraction-based) %	Inferred (extra) grey space (% of reported value)
Public open spaces	18.2	20.5	2.3 (11.2%)
Private/residential	28.5	36.2	7.7 (21.3%)
Commercial/industrial	2.1	0	–2.1
Transport corridor	6.5	0	–6.5
Overall	55.3	56.8	1.5

The largest difference observed was a loss of private/residential green space of 7.7 percentage points, suggesting that around 21% of private/residential unbuilt space is paved, which is significantly lower than the 36% estimated for Hamilton. Balancing this loss partially is the green space that exists in the commercial areas, which was previously excluded, of 2.1%.

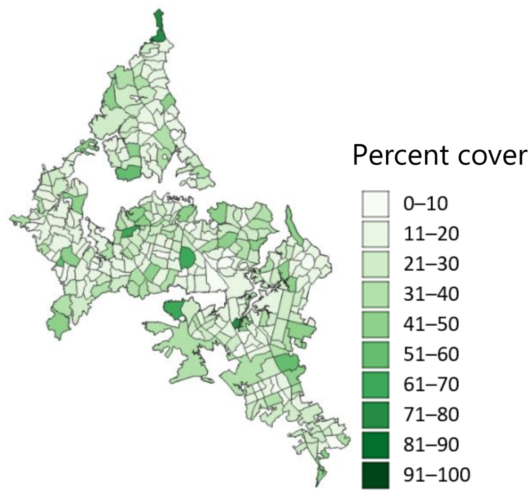
Similarly, there is some loss of green space in the public open space areas (2.3%, around 11% of the public open space areas, compared to 16% for Hamilton); however a significant proportion of this is likely to be dropout from shadows. In contrast, the transport corridor adds 6.5% of green space coverage.

5.2.2 Revised green space distribution

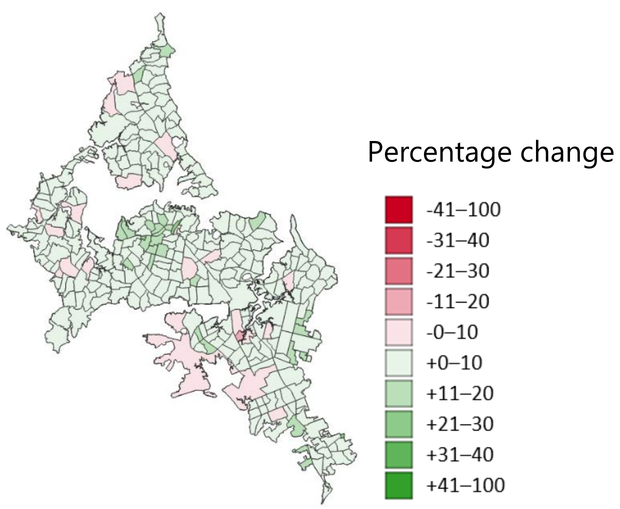
Figure 15–17 show the distribution of public, private, and total green space around Auckland city: as estimated from open space in the previous study, as measured from the infrared-based green mask, and the difference. Public green space is lost from some areas and gained in others. Overall, the amount of change is small. Private green space is reduced up to 10% for most areas. A significant number of areas show a larger reduction of 11–20%, while a small number show an increase. The overall effect on *total* green space is that more than half of the areas experience a reduction in green space, with some showing reductions of over 10%. A small number of areas show a modest overall increase.



Public green space inferred from open space, as previously reported

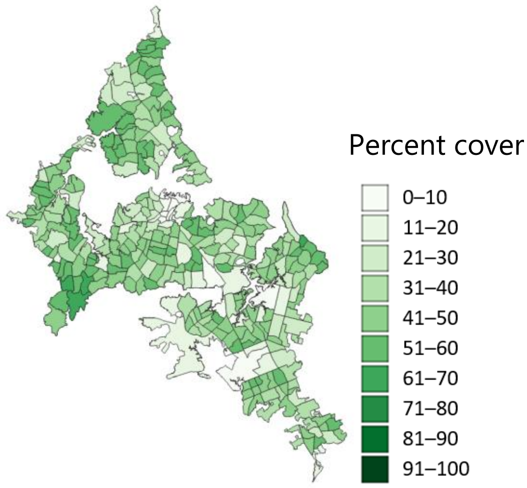


Public green space measured directly from infrared imagery

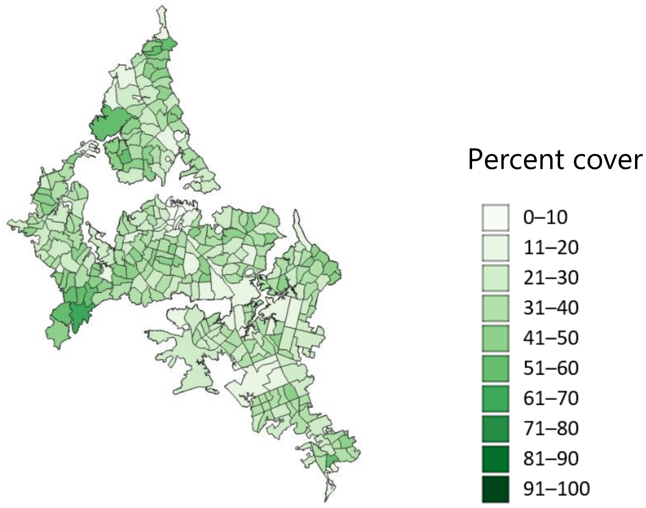


Difference between inferred and measured public green space

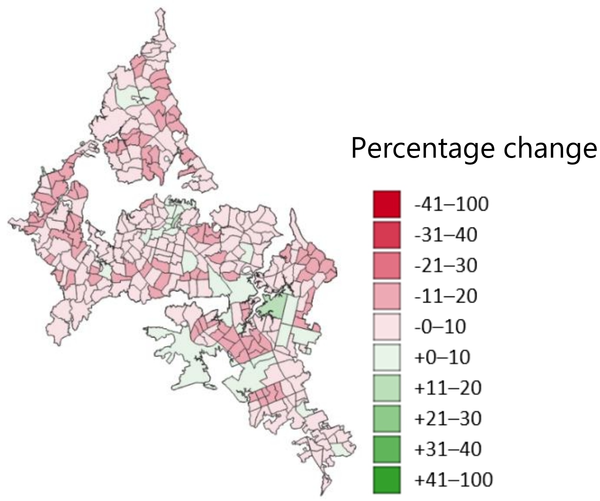
Figure 15. Auckland public green space distribution.



Private green space inferred from open space, as previously reported

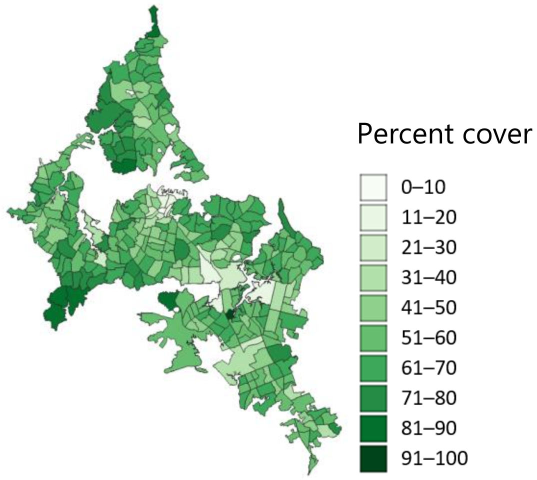


Private green space measured directly from infrared imagery

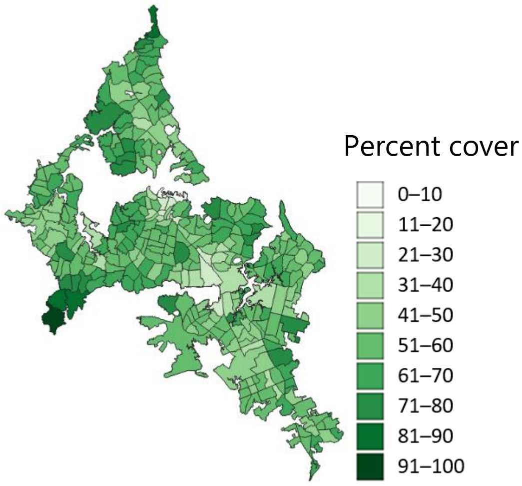


Difference between inferred and measured private green space

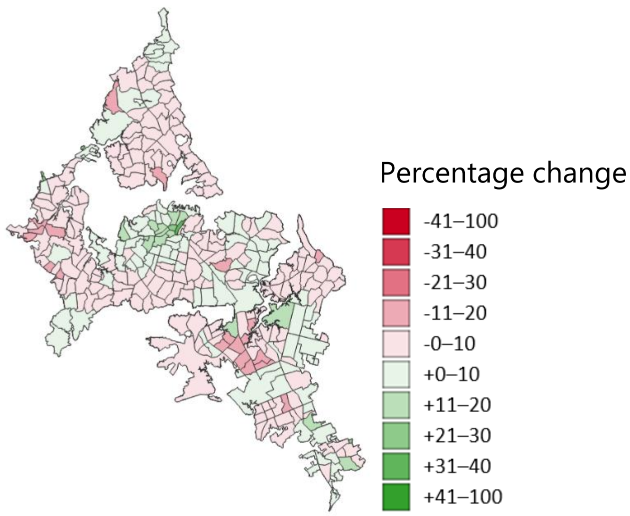
Figure 16. Auckland private green space distribution.



Total green space inferred from open space, as previously reported



Total green space measured directly from infrared imagery



Difference between inferred and measured total green space

Figure 17. Auckland total green space distribution.

Public green space increased significantly for several statistical areas. All of these are because green space, especially on motorways, has now been included in the road corridor. In contrast, other areas saw a reduction caused by paving. Figure 18 shows an example of this. Grafton West (left of picture centre) saw the largest increase in public green space (+20% of total area) because large areas of green space in the motorway corridor (previously excluded from analysis) are now included. In contrast, Grafton East (right of picture centre) saw a reduction in public green space of almost 6% of total area because much of the public open space (Auckland City Hospital) is paved.

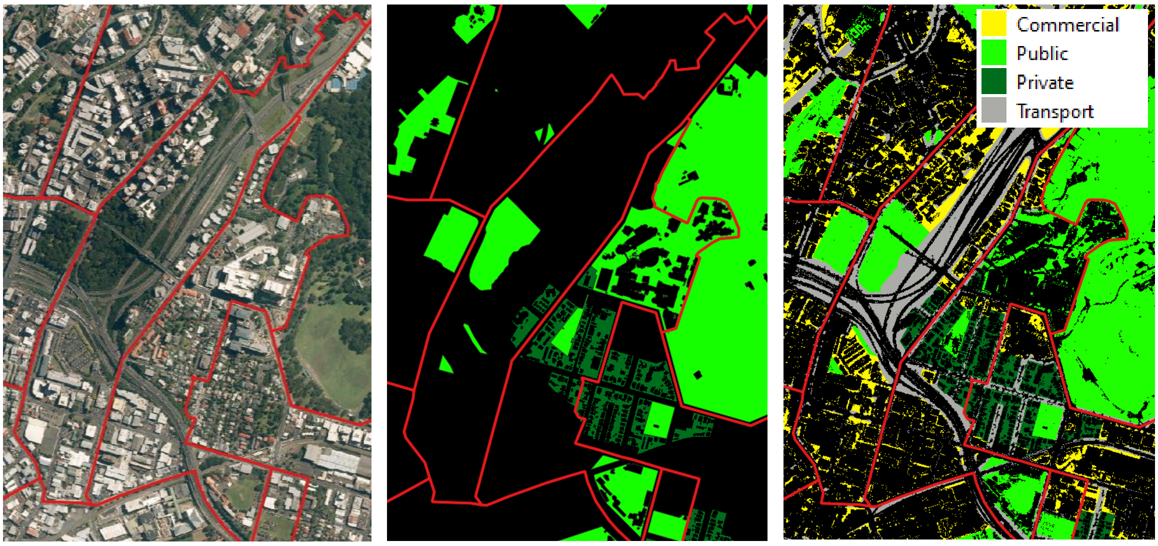


Figure 18. Grafton West and East aerial image (left), previous (subtraction-based) green space mask (middle), and new (directly measured) green space mask (right), coloured by green space class.

Many areas showed a substantial reduction in private green space. However, some areas experienced an increase because green space within the commercial areas, previously excluded, was now counted; although these areas are only small, there are many of them and they add up to a significant area. The greatest increase was in Highbrook, as shown in Figure 19.

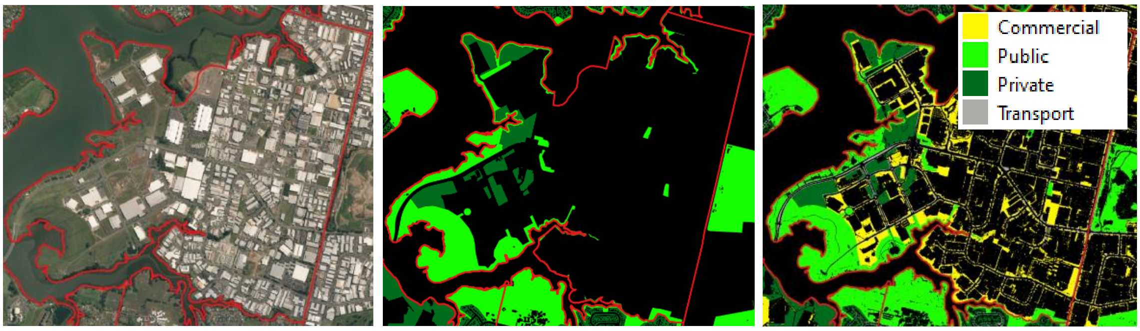


Figure 19. Highbrook aerial image (left), previous (subtraction-based) green space mask (middle), and new (directly measured) green space mask, coloured by green space class.

Figure 20. Papatoetoe West aerial image (left), previous (middle) and new (right) green space masks.

Private green space reduction is greatest in high-density areas, where the proportion of paved to unpaved residential space is largest. Figure 20 shows an area of Papatoetoe West, a residential area, which had one of the highest reductions in measured private green space (14% of the total area). This is a high-density residential area with over 6,500 residents per square kilometre.

5.2.3 Vegetation type

We generated a woody vegetation mask by computing a normalised vegetation index and applying a threshold selected using logistic regression (0.36). The resulting green mask suggested a total tree canopy cover of around 24%. However, this measure contains significant uncertainty owing to the relatively poor quality of the infrared imagery, with the three threshold selection methods (visual/histogram, entropy, logistic regression) giving values of 15–37%. The reported figure of 24% is consistent with 18% tree canopy measured by Auckland City Council for a similar area using LiDAR. The larger percentage reflects the fact that we have attempted to measure all woody (non-grass) vegetation rather than just tree canopy. However, visual inspection reveals some significant anomalies in the area classified as woody vegetation:

- dropout (false negatives): shadows, dead trees
- over-detection (false positives) long grass, very lush grass.

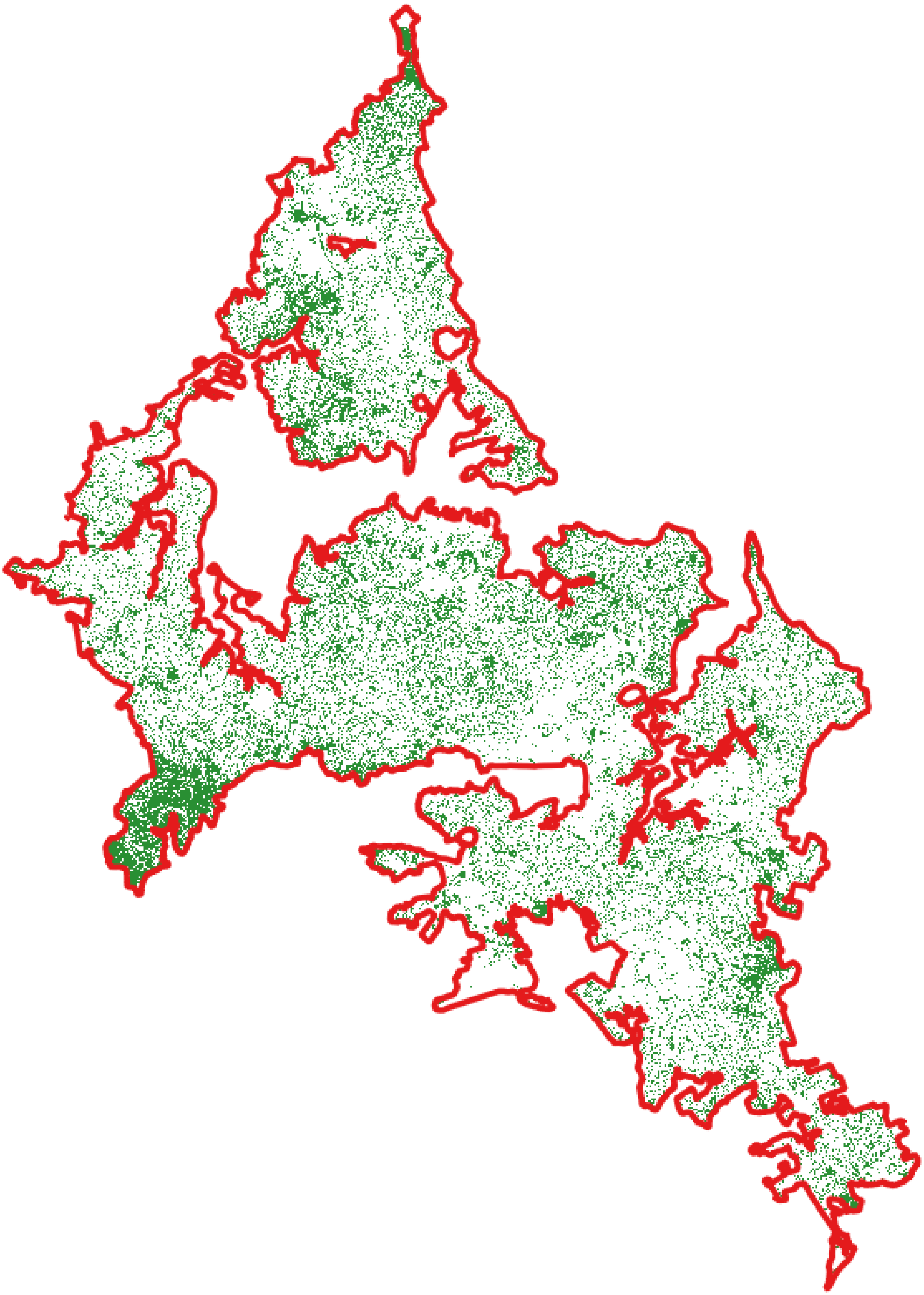


Figure 21. Auckland woody vegetation map.

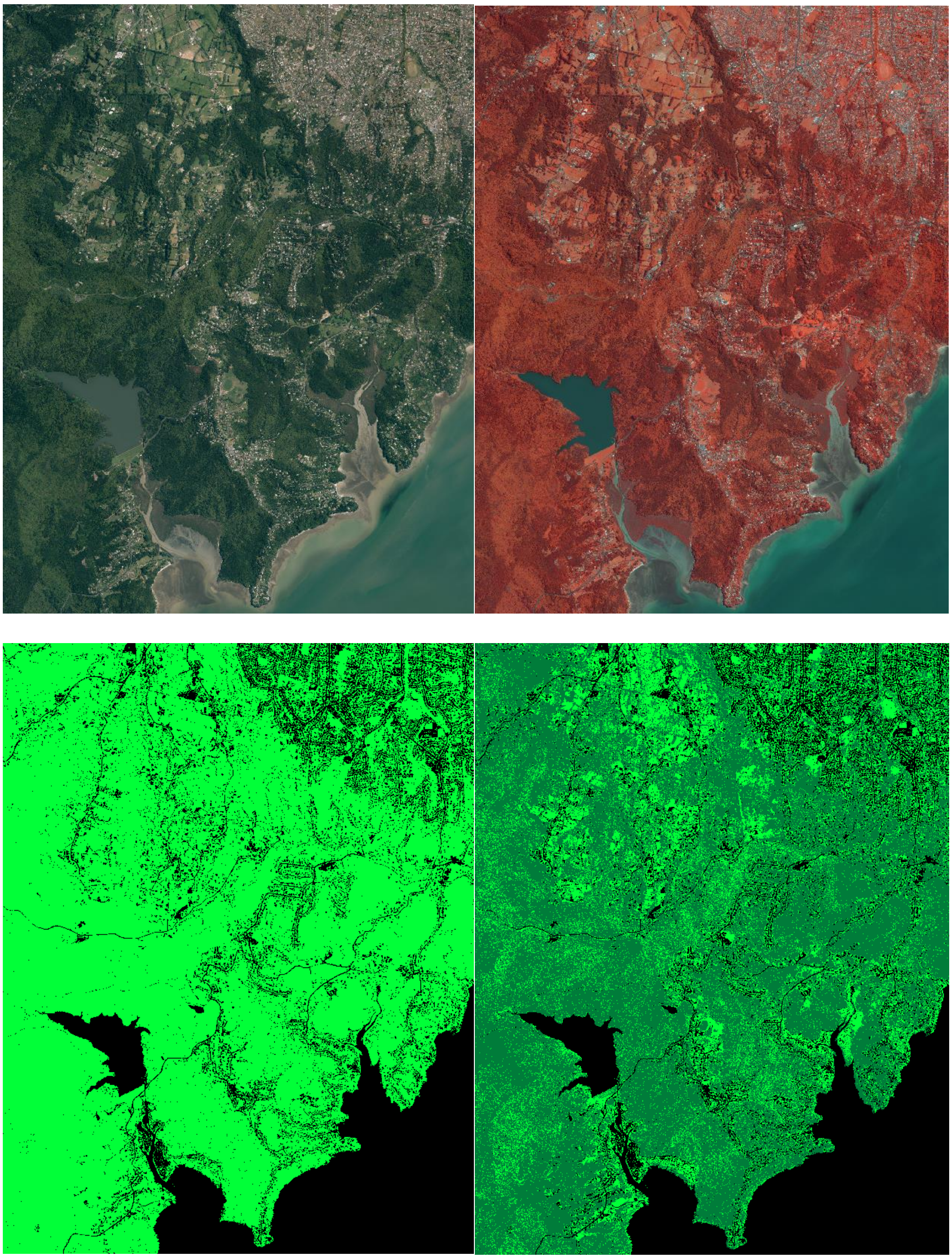


Figure 22. Waitakere RGB image (top, left), NIR+GB image (top, right), green space mask (bottom left), and green space by vegetation type (bottom right).

Figure 21 shows the overall woody vegetation map. Unlike Hamilton, Auckland has significant woody vegetation throughout the city, reflected in the higher overall coverage (24% for Auckland versus 17% for Hamilton). Figure 22 shows green space and woody vegetation for an area in Waitakere; the mask by vegetation type (lower right) is generally a good match to the visual and NIR imagery.

5.3 Wellington

5.3.1 Revised green space totals

Wellington's total green space was measured using a 2021 RGB+NIR mosaic. Image quality was significantly higher than for Auckland, but inferior to that for Hamilton. Some NIR bleed was still apparent, but much less than for the Auckland imagery.

The green mask (NDVIb) threshold for Wellington was originally selected manually at 0.15. This was then refined using a machine learning algorithm (logistic regression) to select the threshold that best separated green and grey space based on a set of sample areas. This gave a revised threshold of 0.1. Using this threshold, the total green space was 72.1%. This is very close to the originally reported green space estimate of 71.8%.

The city-wide green space was then filtered by open space classification to compute the amount of green space of each type. The resulting coverages are listed in Table 11.

Table 11. Wellington green space, by usage type

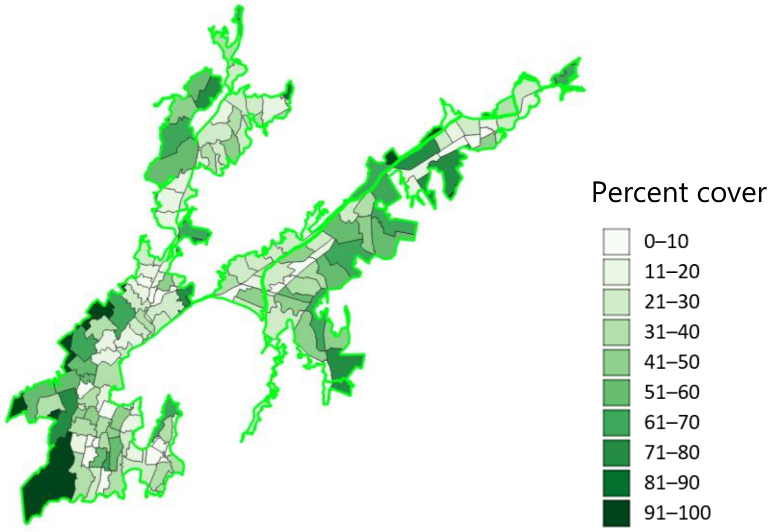
Classification	2021 analysis (direct detection) %	2016 analysis (subtraction-based) %	Inferred (extra) grey space (% of reported open space)
Public open spaces	41.2	43.0	1.8 (4.2%)
Private/residential	24.8	28.9	4.1 (14.2%)
Commercial/industrial	0.8	0	–0.8
Transport corridor	5.4	0	–5.4
Total	**72.1**	**71.8**	**–0.3**

The largest difference observed was, again, a loss of private/residential green space of 4.1 percentage points, suggesting that around 14% of private/residential unbuilt space is paved, much lower than for Auckland (21%) or Hamilton (36%). Balancing this loss is the green space that exists in the commercial areas, although for Wellington this is low, adding just 0.8%. Note that unlike the original study, which attempted to map green space on the ground, the green space directly measured using NIR includes tree canopies; for Wellington this is significant owing to the high level of tree cover, including over streets. The lower proportion of paved private space is also expected given Wellington's steep topography, with significantly more private land too steep for development, including a significant number of private dwellings that have no driveway or off-street parking.

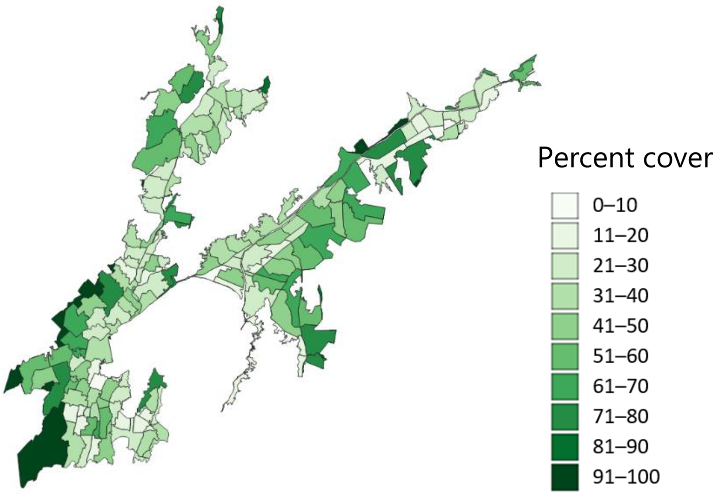
Similarly, there is some loss of green space in the public open space areas (2 percentage points, or around 4% of the reported public open space areas). However, again, some of this is likely to be dropout from shadows. In contrast, the transport corridor adds 5.4% more green space; this also includes tree canopies. Overall, the green space measured using the new mask is within the margin of error of the originally reported figure.

5.3.2 Revised green space distribution

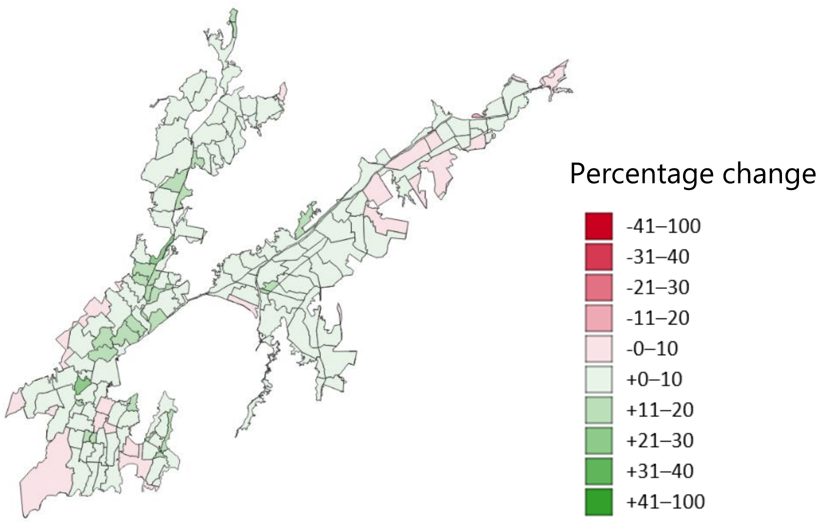
Figure 23–25 compare public, private and total green space distributions between the original subtraction-based approach and the new, directly measured method. As anticipated from the small magnitude of change in the total green space proportions, there is very little difference between the original green space distributions and those based on the new mask, with only the private space distribution showing a significant reduction in greenness, particularly in areas of higher green space proportion.



Public green space inferred from open space, as previously reported

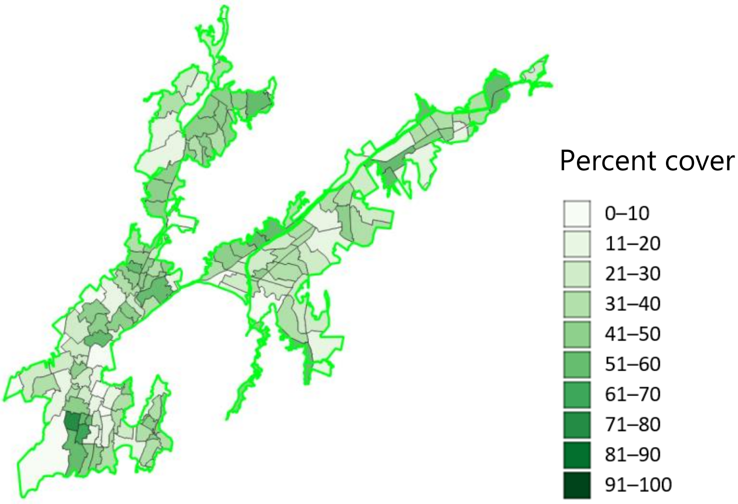


Public green space measured directly from infrared imagery

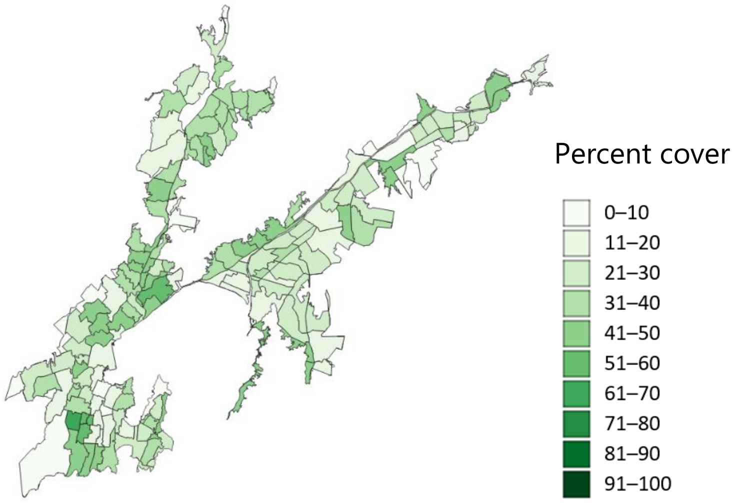


Difference between inferred and measured public green space

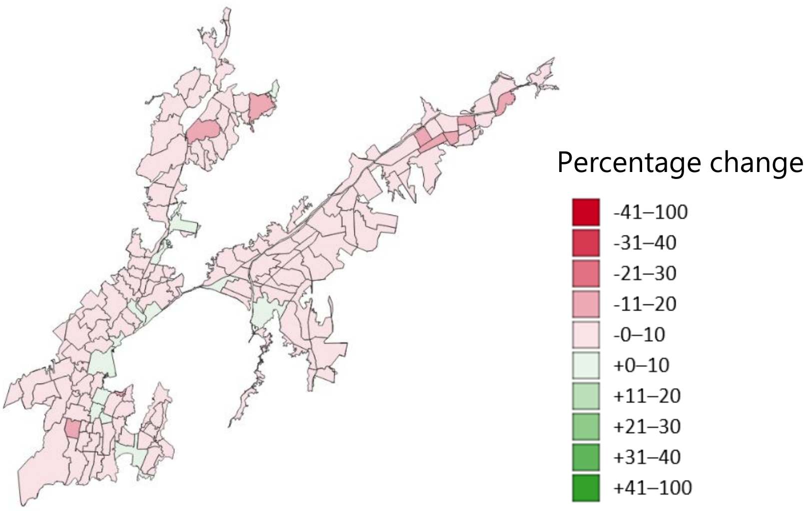
Figure 23. Wellington public green space distribution.



Private green space inferred from open space, as previously reported

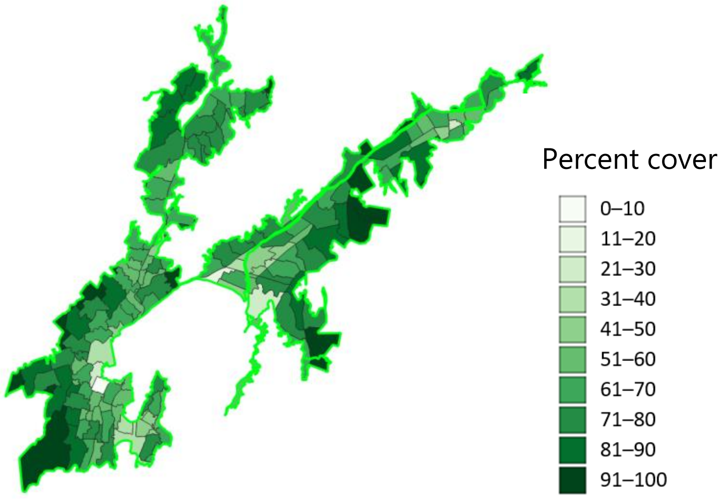


Private green space measured directly from infrared imagery

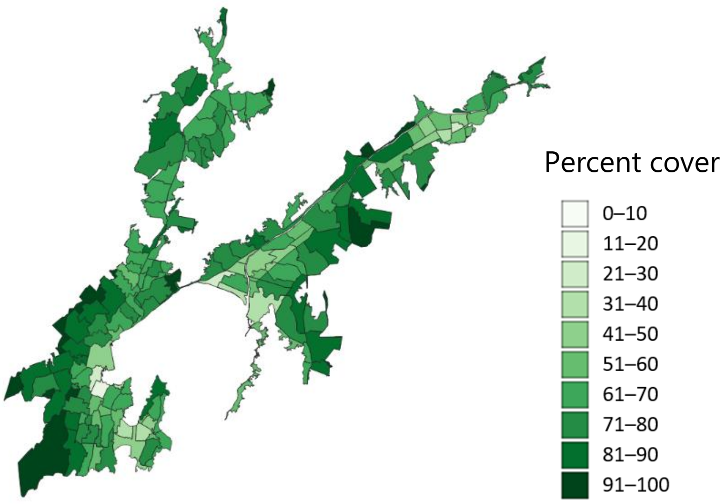


Difference between inferred and measured private green space

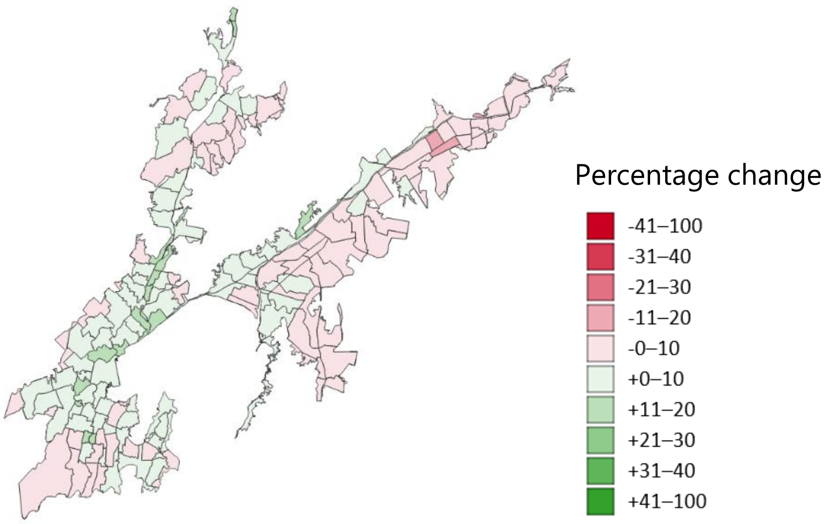
Figure 24. Wellington private green space distribution.



Total green space inferred from open space, as previously reported



Total green space measured directly from infrared imagery



Difference between inferred and measured total green space

Figure 25. Wellington total green space distribution.

Wellington shows more pronounced differences between the subtraction-based and directly measured public green space distributions. This is because the public space in Wellington's hill areas is dominated by road corridors and these were excluded from the previous analysis; these road corridors are mostly vegetated, with much of the road itself overtopped by tree canopy. The area with the highest increase in public space coverage, Northland suburb, illustrates this (Figure 26). In contrast, most losses in public green space are small differences caused by impervious surfaces and bare ground or rock (with some minor dropout from shadows), leading to an overall increase in total public green space.

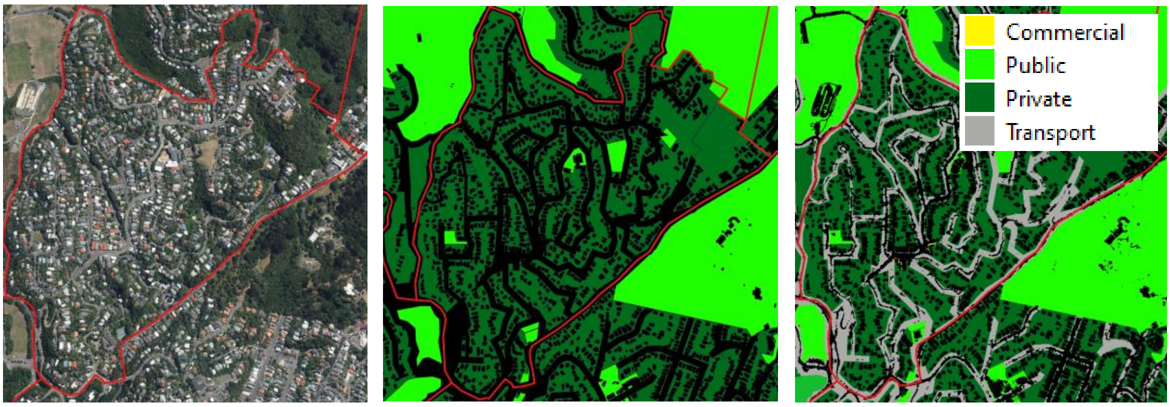


Figure 26. Northland aerial image (left), previous (subtraction-based) public green space mask (middle), and new (directly measured) green space mask (right).

Most areas show a reduction in private green space, with some experiencing losses of more than 10% of the total area. These large losses are a combination of new development since the 2016 imagery was taken and an increase in residential density in other areas. The primary impact was caused by the increase in paved areas on residential sections; these two factors generally affect the same areas (e.g. Papakōwhai South in Porirua) (Figure 27).

Figure 27. Papakōwhai South aerial image (left), previous (subtraction-based) private green space mask (middle), and new (directly measured) green space mask (right).

A small number of areas saw an increase in private green space, with four areas experiencing an increase of 5% or more (Lyall Bay/airport, Gracefield, Takapu, Petone Central). All of these contain large commercial areas, where small green spaces (including tree cover) add up to a significant amount of overall commercial green space. These commercial areas were all excluded in the previous study on the basis of inaccessibility.

5.3.3 Woody vegetation cover

We inferred a vegetation cover layer using NDVIr, thresholded to 0.34 (selected using logistic regression), which appears to give good coverage and separation. This map indicates that 45% of the city area is covered in woody vegetation (63% of the total green space).

The resulting map was compared to an existing study of *tree cover* (Morgenroth 2021). This study concluded that Wellington had a lower figure for tree canopy cover of 30.61%. However, it cannot be directly compared, for two reasons.

- The study area is different (Wellington City only, versus Wellington City, Porirua, and Hutt Valley), and a slightly different boundary.
- The Morgenroth study measured *trees* (defined as over 3.5 m tall and at least 1.5 m in diameter) rather than *woody vegetation*, and therefore excludes low bush and small plants.

Figure 28 compares the tree cover (Morgenroth) and woody vegetation (this study) maps.

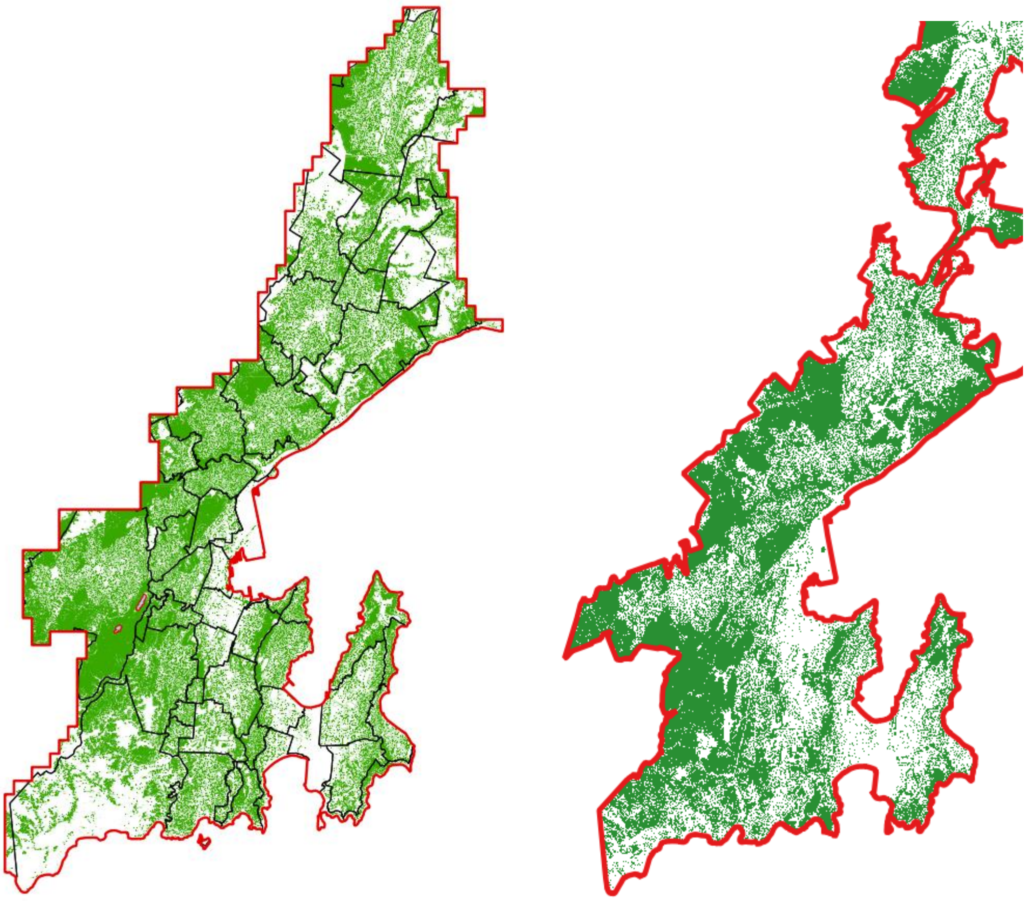
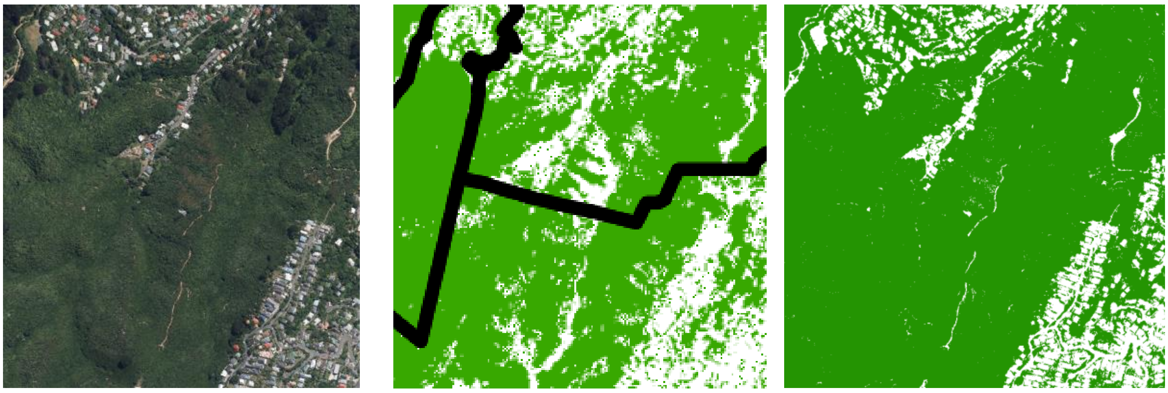


Figure 28. Wellington tree cover (Morgenroth 2021, left) versus vegetation cover (this study, right).

The woody vegetation layer has substantially the same patterns as the Morgenroth tree cover map, but with more solid blocks where the vegetation does not all qualify as trees. Figure 29 shows an example of this. In the inferred vegetation layer, the entire bush area has been classified as vegetation, including gorse, while in the Morgenroth tree map significant areas are excluded. The woody vegetation layer also picks up significantly more vegetation on residential properties that fails to qualify as trees (lower right).



Aerial image **Tree cover (Morgenroth)** **Vegetation cover**

Figure 29. Wellington sample aerial image, vegetation mask, and tree-cover mask.

6 Conclusions

This study suggests that measuring green space directly using indices derived from visual and near-infrared imagery is feasible, but the level of accuracy is strongly dependent on the quality of the available infrared imagery. The total green space measured using this method was similar to that reached using the subtraction-based method for Auckland and Wellington, but produced a significantly lower result for Hamilton. The result for Hamilton is probably the most robust given the high quality of the infrared imagery, and this suggests the subtraction-based method significantly overestimated green space in Hamilton. This is because, whereas in Auckland and Wellington losses in (mostly private residential) green space from paving were largely balanced by the addition of green space in the transport corridor, Hamilton had a significantly larger proportion of residential paved area that was not completely offset by the green space in the transport corridor. Hamilton has also experienced significant new development in the period between the two studies, further eroding green space.

By separating green space, grey space, and building footprints we can obtain a more accurate picture of the physical makeup of our cities. Categorising and mapping green space by usage type also shows up the non-trivial contribution of green space from road corridors (particularly motorways) and, to a lesser degree, commercial and industrial areas.

We also showed that we can obtain an approximate map of woody vegetated versus grassed green space areas, although the accuracy is lower than for green versus grey space. Comparisons with published tree canopy figures (where available), as well as visual inspection of the imagery, support the conclusion that the masks are fairly accurate, noting that the definition of woody vegetation used in this study is broader than that generally used to measure tree canopy cover (including a minimum tree canopy size and minimum height) and so will return larger coverage statistics.

Finally, comparing the new masks to those from the previous study also showed up areas where development is taking place, suggesting these masks could be a useful tool for detecting change in total green space and its distribution over time.

7 Recommendations

7.1 Method enhancements

This study mapped and measured green space and vegetation cover to generate green space and vegetation masks based on indices derived from infrared and visual imagery. Although fairly accurate, several challenges were identified, including the near-infrared band bleeding into surrounding impervious areas, and the inability to accurately classify bare ground and shadows.

We recommend trying more advanced techniques, such as training a deep learning model (as was used to detect the building footprints) to perform the classification. Deep learning models learn to infer the class of each pixel in the mask raster based on surrounding spatial patterns as well as each image pixel's actual values, so this approach may be able to more accurately classify shadows based on whether they are surrounded by vegetation or impervious surfaces, for example. The masks generated by this study could be used as the training data for the model, which we anticipate would then predict the mask with greater accuracy than the NDVI-based indices alone.

This study relied on near-infrared imagery to generate the masks. While this is becoming more common it is by no means widespread, and the quality varies widely. For the most accurate results the acquisition of new, high-quality, near-infrared imagery should be funded. However, it may also be possible to use the masks generated in this study to train a deep learning model that relies on standard RGB colour imagery alone for subsequent mask generation. This would dramatically increase the potential scope of analysis.

Finally, for woody vegetation mapping, the masks generated in this study could be combined with LiDAR[7] analysis to more accurately map problematic areas such as those in shadow, although this would require additional image acquisition.

7.2 Extended scope

Generation of the green space and woody vegetation masks, and the subsequent analysis and aggregation, is largely algorithmic in nature. It would be feasible to automate most of the process and to then extend it to other cities, and to repeat the exercise at regular intervals. This would be very practical if a deep learning model could be trained to be sufficiently robust to infer the masks for any city without further training.

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[7] LiDAR (light detection and ranging) is a method for determining distance by targeting a surface with a laser and measuring the time for the reflected light to return to the receiver. It can be used to obtain a 3D representation of the ground surface, from which features such as tree cover can be inferred.

As stated above, it may be possible to train a model to accurately separate green space and woody vegetation using RGB imagery only, allowing all existing RGB imagery to be assessed. If not, this study may provide an incentive for councils to consider adding near-infrared to their aerial image capture programmes.

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9 References

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