Between Grey and Green: Ecological Resilience in Urban Landscapes

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This paper analyses the city of Christchurch, New Zealand, which has been through dramatic changes since it was struck by a series of earthquakes of different intensities between 2010 and 2011. The objective is to develop a deeper understanding of resilience by looking at changes in green and grey infrastructures. The study can be helpful to reveal a way of doing comparative analysis using resilience as a theoretical framework. In this way, it might be possible to assess the blueprint of future master plans by considering how important the interplay between green and grey infrastructure is for the resilience capacity of cities.

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Brenda and Robert Vale (2009) wisely affirmed that land sets the ultimate resource limit. We use land resources to build our habitat, to provide ecosystem services, to produce food and to sustain our lifestyles, usually forgetting that land is a finite resource. Population growth and changes to more sophisticated lifestyles have produced the need for more services and more complex infrastructures that demand more space and consume more land resources (Millennium Ecosystem Assessment, 2005). The infrastructure design of the built environment, what might be considered the grey areas, impacts on the availability of other land surfaces, like green areas (for growing) and brown areas (open areas with permeable surfaces that could be easily converted to green areas), that are necessary for the sustainability and persistence of our species.

Despite or perhaps because of the many approaches to defining green and grey infrastructure, it is hard to find consensus among scholars (Mell, 2013). The terms sometimes refer to technologies and sometimes exclusively to land surfaces. In any case, what is clear is that cities need both. According to the Natural Economy Northwest Programme (2009), green infrastructure refers to all the natural assets that occupy land – for example, parks, sports facilities, agricultural land and private gardens – and that are important for regulating microclimates, absorbing carbon dioxide emissions and reducing the risk of flooding. Brown areas are not brownfields. In the United Kingdom and the United States of America, brownfields are usually related to industrial sites or contaminated areas (Alker et al, 2000). In this paper, brown areas have a broader meaning related to the reversibility of land cover infrastructure into green areas. For this reason they are included as a subcategory of the green infrastructure. Brown areas could be decks, permeable surfaces like synthetic grass or abandoned areas in between buildings with no grass or pavement.

Grey infrastructure refers to all the constructed assets that occupy land: namely, transport infrastructure (motorways, roads, car parks), commercial infrastructure (factories, offices, retail), services and social infrastructure (schools, housing

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and buildings in general). Grey areas are essential to keep the city functioning. However, the uncontrolled proliferation of grey infrastructure through sprawling, bigger buildings, more car parks and plot infilling occurs to the detriment of green areas, helping to intensify the heat island effect (IPCC [Intergovernmental Panel on Climate Change], 2014). This situation is critical in cities, where urban growth tends to increase the competition for space by reducing the quantity of green areas. The problem is that the benefits provided by these green areas are less tangible than the perceived economic benefits from the development of new motorways, buildings and businesses. The issue is highlighted when it comes to developing new master plans for cities that have suffered natural disasters. On the one hand, the city needs businesses to keep on running and therefore attracting new investments seems the way to put the city back on track, particularly through the development of a compact built environment with mixed-use buildings. On the other hand, the enthusiasm for attracting new businesses could result in the depletion of green areas and standardisation of the urban landscape, which could in turn impact on the city's resilience capacity to adapt to future natural hazards.

Because the organisation and distribution of green and grey infrastructures are evidence of human behaviour in terms of the historical choices made regarding land use, the study of changes in the use of land cover might help to better understand how to create conditions for the persistence of urban life in a context of change. This paper, therefore, analyses the city of Christchurch, New Zealand, which has been through dramatic changes after it was struck by a series of earthquakes of different intensities between September 2010 and December 2011. In this context, a resilience approach will involve observing changes in green and grey infrastructures. The challenge is to develop a deeper understanding of resilience (Vale and Garcia, 2016) that helps to narrow down how change can be usefully analysed. The study can be helpful to reveal a way of doing comparative analysis using resilience. In this way it might be possible to assess the blueprint of future master plans by considering how important the interplay between green and grey infrastructure is for the resilience capacity of cities. Therefore, the question that this paper investigates is: how can designers assess the impact of master plans on the resilience capacity of urban landscapes?

Theoretical background – green infrastructure, grey infrastructure and resilience

Early research about green and grey infrastructure (Norton et al, 2015) focused on the management of stormwater systems for the purpose of reducing the impact on aquifers, erosion and water pollution. Currently, the green and grey debate is closely related to the resilience of cities (McPhearson et al, 2015). Green and grey infrastructure approaches have also been used to forecast alternative ways of designing urban infrastructure that would mitigate the impact of natural hazards in a more natural and less costly manner (Sutton-Grier et al, 2015). The green infrastructure approach has also been used to understand the role that common gardens could play in periods of food shortage (Barthel and Isendahl, 2013) and in the development of cultural diversity (Colding and Barthel, 2013). In landscape architecture, green and grey infrastructures have been related to the resilience of cities by highlighting the role that open green areas play in providing shelter during and after earthquakes (Allan and Bryant, 2010). Moreover, research has shown that vacant areas are an important part of generating a 'temporary city' (urban spaces where activities happen while the city is reorganising) so that a community can keep on functioning while experiencing stressful situations (Wesener, 2015).

Another urban approach to the use of green infrastructure has been developed by Garcia (2013). This approach analyses the role of open green areas in the resilience of urban landscapes when a city undergoes changes that are produced by its own developmental processes rather than by extraordinary events like earthquakes or flooding. Recently, Garcia and Vale (2017) have questioned how much compact built environments really contribute to the sustainability and resilience of cities. According to the authors, compact cities are not necessarily more sustainable because the ecological footprint largely depends on the behavioural choices of the people living there rather than on the population density. Moreover, they argue that where built environments have been made more compact by replacing small domestic buildings with bigger and fewer mixed-use buildings, they become more rigid and standardised, making future changes potentially more expensive and less frequent. This is a factor that limits the capacity of the built environment to change. Furthermore, referring to Christchurch specifically, Richardson (2013) has challenged the future of the city's current urban interventions, alleging that rather than creating a more inclusive city, it could increase gentrification processes.

The idea that the compaction of a built environment will create better cities is thus in question. In the case of Christchurch, the urban landscape generated by the earthquakes can be understood as an opportunity for evaluating the resilience of loose landscapes through looking at the relationship between grey and green areas.

Understanding resilience

If cities are to survive any transition towards a more sustainable future, they need to harness the idea of designing cities to adapt to unpredictable changes produced by stressed ecosystems and the human societies within them (IPCC, 2014). Enhancing urban resilience is a helpful way of understanding how cities can use change to adapt and persist (Garcia and Vale, 2016). The first tests of applying resilience to urban landscapes came in studies of vulnerability, risk, mitigation, robustness and adaptation of cities in relation to climate change and natural hazards. Originally, resilience appeared as a concept in engineering and was later developed in psychology and ecology simultaneously but with different implications. In engineering, resilience refers to the elasticity of materials and was used to measure the quantity of energy that materials can stand without breaking or deforming permanently (Tredgold, 1818). The key point in the engineering definition is that resilience is about coming back or recovering from undesirable changes to a previous state of stability. In contrast, in ecology Holling (1973) refers to resilience as 'the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist'. He notes that keeping systems stable is of little use if they do not survive. Therefore, the management of ecosystems should focus on creating the appropriate environment for survival instead of only on avoiding disturbance.

Holling further shows that change is inherent in complex systems and that some disturbances, like fires in the savannah, are part of the life cycle of an ecosystem and a key element of its persistence. On this basis, resilience is not a state; it is a property of a system that is relative and temporal. Resilience depends on the capital that is measured and on the moment of its assessment. Moreover, resilience is not a status that can be held forever; therefore, a continuous assessment of the system is needed. In this paper, the understanding of resilience emphasises the relationship between persistence and change and, in addition, is about how to create stability by acknowledging change.

In relation to Christchurch, the concept of resilience discussed is linked with the persistence of the diversity of the urban landscape and, more specifically, with the diversity generated by the interrelationship between green and grey infrastructures and their role in making the city resilient to future natural hazards. The assumption is that the diversity of the urban landscape, in this case provided by the green and grey infrastructure, contributes to the heterogeneity and resilience of the city.

Heterogeneity, diversity and relative resilience

In landscape ecology, the analysis of the heterogeneity of landscapes has helped to create a better understanding of change. Forman and Godron (1986) propose that the heterogeneity of a landscape depends on three factors: function, structure and change. Structure is linked with the relationship between species and resources in the landscape. The structure of an ecosystem describes how resources and materials are distributed by number, geometry and kind of species. Function refers to the interrelationship between elements through the flow of energy and materials. Change is an alteration in the structure of the landscape – namely in its configuration, composition and distribution. For example, if a tree changes, it does not necessarily mean that the forest has changed; however, if all the trees belonging to one species are removed from the landscape, there will be a change in the composition and diversity of the forest, and in this way a change in its structure. Therefore, the heterogeneity of a landscape forms a useful concept for understanding changes that are not easy to predict and that are happening at multiple scales.

The concept of heterogeneity has also been used to understand resilience in ecosystems. The textural discontinuities hypothesis (Holling, 1992) uses the concept of heterogeneity to understand the link between different textures in a landscape and different resilience capacities. Gunderson and Holling (2002) argue the heterogeneity of a landscape is linked with its complexity and resilience. More complex, diverse and heterogeneous landscapes will have higher resilience capacities. Gunderson and Holling also affirm that the link between heterogeneity and resilience could be applied to the study of other complex adaptive systems, such as cities. This is very important for designers because the analysis of the texture of a landscape is closely related to our field of study and can be used to develop new hypotheses and advance the research into how cities cope with change.

Relative resilience (Allen et al, 2005) is a method used in ecology to assess and compare the distribution of species and resources in a landscape. The method Allen and colleagues developed uses a diversity index to assess the variety of species, as well as their number and distribution in a landscape. The relative resilience can be used to measure how much a system has changed after a disturbance by comparing changes in the diversity of the structure of two or more landscapes. According to Allen et al, a system will show resilience when changes in the population and in the distribution of elements and functions in a landscape fail to affect the structure of the system critically.

For example, if a system like the built environment of a city suffers an earthquake and many buildings are destroyed, the relative resilience of the system could be seen in its response to the quantity of change produced by the loss of buildings. If all the people leave because the city has nowhere to house them, the population structure of the city has changed; conversely if the remaining buildings have enough redundancy to house those displaced in the population, the structure has not changed. If the built environment has become less diverse after an earthquake (due to loss of people and their skills), it will mean that the resilience was at some point surpassed and the system could not maintain the same functions, structure and feedback while undergoing a disturbance. In contrast, if the diversity of a built environment has persisted after the earthquake, the system in question has buffered the changes produced by the disturbance and the buildings lost have not affected its structure. Relative resilience has previously been used in urban studies in a comparative analysis between the urban landscapes of Auckland in New Zealand and Nezu in Japan, as well as to understand the contribution of green and brown areas to the development of the urban landscape of Auckland (Garcia, 2013).

The importance of change and diversity to the urban landscape is known to designers. In cities, new buildings are constructed and old ones destroyed every year while others remain in place. Morphologists have devoted their studies to observing change in urban landscapes and its importance in developing cities and the communities living in them. Conzen (1960) suggests that the urban landscape is a palimpsest on which the history and culture of a city have been imprinted. For her part, Jacobs (1961) has discussed the importance of diversity by analysing the impact of modernism on the loss of street life. Jacobs was meticulous in observing that the size of plot and buildings affects the quantity and diversity of the street life. Another to discuss the importance of diversity to the built environment and its identity is Relph (1976), in analysing the negative effects of fast and big changes on the sense of belonging to a place. The analysis of the changes happening in the built coverage of plots, as well as in the number and size of buildings, and the related street systems, could be used to explore and understand the texture of the landscape and its contribution to the understanding of change in cities.

What the resilience framework offers to urban studies is the possibility of understanding diversity as a variable that is linked with a system's opportunities to adapt and persist. Moreover, the analysis of the heterogeneity of an urban landscape produced by the diverse distribution of its elements, like the distribution of green and grey areas in Christchurch, could provide some insight into the complexity and potential resilience of its urban landscape.

Methodology

The paper analyses how the diversity of grey and green infrastructures in the central business district (CBD) of Christchurch could contribute to the resilience of the built environment. To measure changes in the diversity of the urban landscape, a comparative analysis is made between three hypothetical scenarios after the earthquakes. The scenarios chosen are: 1) the urban landscape after the earthquakes; 2) the Blueprint for the CBD produced by the Canterbury Earthquake Recovery Authority (CERA); and 3) a hypothetical landscape where all the buildings targeted for demolition are replaced by open green space. By using different scenarios, it becomes possible to observe different stages in the equilibrium of the CBD of Christchurch. The objective is to try to understand what different plans mean for the diversity and future resilience of the city.

The methodology has three steps: data collection; analysis of the relative resilience; and finally a comparative analysis of the three scenarios proposed using a diversity index. The following sections explain each step of the methodology.

Data collection

The materials used for this research were mainly maps and satellite pictures of the urban landscape of Christchurch after the earthquake. Complete digitised maps (in shapefiles or other digital formats suitable for opening in geographic information software like ArcMap or QGIS) containing plots, building footprints, streets and green areas were not found in a single source. Therefore, when information was not available it was inserted using satellite pictures as a reference. The key data sources available for producing the maps were: a satellite picture of the CBD of Christchurch; a digitised version of the cadastral map of the CBD containing the plot system (extracted from Koordinates website); and digitised information containing all the building footprints along with CERA's projected demolition work. The impervious and permeable surfaces were mapped using satellite pictures provided by Google Maps, Google Earth, OpenStreetMap and Land Information New Zealand.

Relative resilience

To calculate the relative resilience of each scenario, a cluster analysis was performed to find the size classes contained in the green and grey infrastructures and also to produce a diversity index based on the range of sizes found in each group. The cluster analysis is used to find the number of groups of variables in a data set. It is useful for managing and comparing large data sets. The analysis grouped the different sizes of each feature into clusters. A feature is every single building footprint or green, grey or brown area mapped. A layer contains all the features of one category. Each cluster represents a class size. The quantity of clusters differs from layer to layer according to the quantity (number) and size (square metres) of the features in each category (building footprints, brown areas, green areas and grey areas).

The cluster analysis was performed separately for each category, using WEKA, free software developed by the University of Waikato. WEKA produces a 'model' that describes the number of clusters and features contained in each group. The results of the cluster analysis WEKA produces can also be attached as a third column to the initial data set imported from QGIS. In this way it is possible to identify what elements belong to which cluster. If needed, the new data set can be exported to QGIS and the information used to map the results.

Diversity index

The diversity index was created using the Shannon-Wiener diversity formula. The index was used to measure the distribution of features across the group sizes found in the cluster analysis. According to the ecological theory of resilience (Allen et al, 2005), elements with more clusters will tend to have a richer structure and probably a higher resilience. The number of clusters represents the size classes that can be found in one category (building footprints, brown areas, green areas and grey areas). The number of clusters can be used to measure the richness and complexity of each layer analysed. More clusters mean greater richness and therefore, more complexity.

The relative distribution refers to the relationship between the number of features in one class against all the features distributed in all the clusters. It thus represents the proportion of elements in a class compared with the whole, and can be expressed as a percentage.

The pi value is the natural logarithm and explains how evenly features are distributed across classes. It is measured from 0 to 1, where 0 represents all the features being equally distributed and 1 represents all the features belonging to one group. Therefore the closer to 1 the pi value is, the more uneven the distribution.

The diversity value refers to the possibilities that two elements of a group belong to the same class. It is measured from 0 to 1. The closer a result is to 1, the higher the possibility for two randomly picked elements to be different. The closer the diversity value is to 0, the less diverse the cluster.

The final or total diversity in one category is defined by the sum of the diversities found in every cluster (see the total in table 1). The diversity is always a negative number, and for that reason is multiplied by –1 to make it positive.

The area of study: Christchurch CBD

In February 2011, Christchurch suffered an earthquake of magnitude 6.3 on the Richter scale, costing the lives of 185 people, as well as causing severe injuries to 6,600 people and the destruction of more than 1,500 buildings. It followed on from a previous quake in September 2010 and was part of a sequence of earthquakes and aftershocks that formed the most dramatic event in the contemporary history of New Zealand. The sequence has had an impact on the country's economy. Significantly too the natural hazards that have disrupted the everyday life of the people of Christchurch remain as threats to the stability of the city (Christchurch Central Development Unit, 2012). Therefore it is important to rethink the rebuilding of the city to deal with this uncertainty.

The city of Christchurch, located in the South Island of New Zealand, has historically been the island's most important economic and population node. The city was built on a plain terrain that is bordered to the east by the Pacific Ocean and the estuary formed by the Avon and Heathcote rivers. The city was officially recognised in the 1850s and its centre was designed using a grid, which has helped to define the identity of the city.

The central area of the city has been chosen for this study because it has become a focus of attention for planners and designers and also because it is a meaningful place for the community (Pickles, 2016). The area of analysis was red-zoned after the earthquake – meaning all members of the public, including residents were excluded from it – for safety reasons. Since then, it has become one of the referents for the reorganisation of Christchurch and the place where an important part of the demolition work is concentrated. Even though this central area is no longer red-zoned, it continues to go through massive changes that are further defining the future of the city. For this reason, it is timely to start developing methods that can help policy makers, developers, designers and the community to assess the outcomes and implications of each proposed change and, in this way, to compare alternative futures for Christchurch. Moreover, what needs to be assessed is the capacity of the proposals to create a city that will cope with future uncertainties. But how is it possible to assess the changes and plans happening in the city? The next section addresses this question.

Analysis

Object of study

In each of three scenarios (figures 1–3), the green infrastructure was divided into two groups: green areas and brown areas. Green areas were defined as open spaces with permeable surfaces that are sometimes classified as natural reserves (parks, gardens, rivers and so on). Brown areas refer to open spaces with permeable surfaces that are not necessarily green but could easily be turned into green areas (like decks or unpaved areas in backyards). Most of these areas were in spaces remaining between buildings, but some were in front yards, backyards and vacant plots.

The grey infrastructure was represented by impervious surfaces. To facilitate the mapping of the grey infrastructure, it was separated into two groups: roofs of buildings and paved surfaces. The building roofs were mapped using the building footprints in each plot as a reference. Building footprints refer to the built area of buildings at ground-floor level. All other impervious surfaces that were not related to the building roofs were assumed to be grey areas. Grey areas are thus the car parks, paved courtyards and other paved surfaces. Streets, roads and motorways, which should be included in this group, were not considered in the mapping because the information available was insufficient to provide accurate measurements.

Description of the scenarios

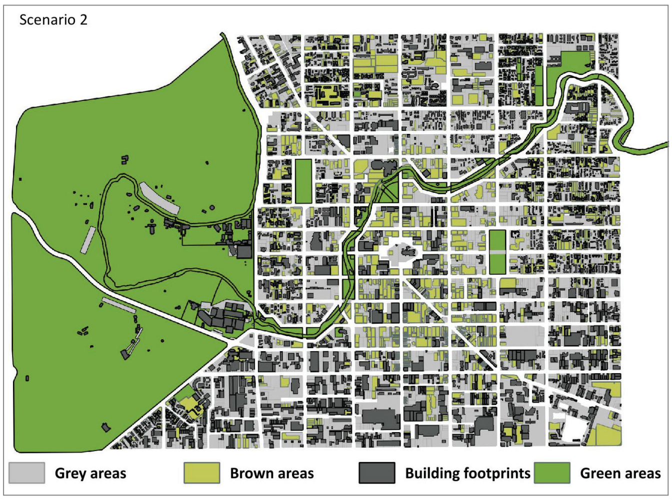
Scenario 1 refers to the urban landscape of the study area immediately after the 22 February earthquake (as at 24 February 2011). The main characteristic of this landscape is the incompleteness produced by plots with no buildings. The dominant surface in the built environment is a mixture of building footprints (dark grey in figure 1) and grey areas in between these (light grey in figure 1). The building footprints clustered around the ChristChurch Cathedral tend to be bigger than the residential building footprints found in the north and east blocks of the CBD. Building footprints and grey areas get even bigger in the blocks located in the south of the CBD, which is the area populated by warehouses. The green areas

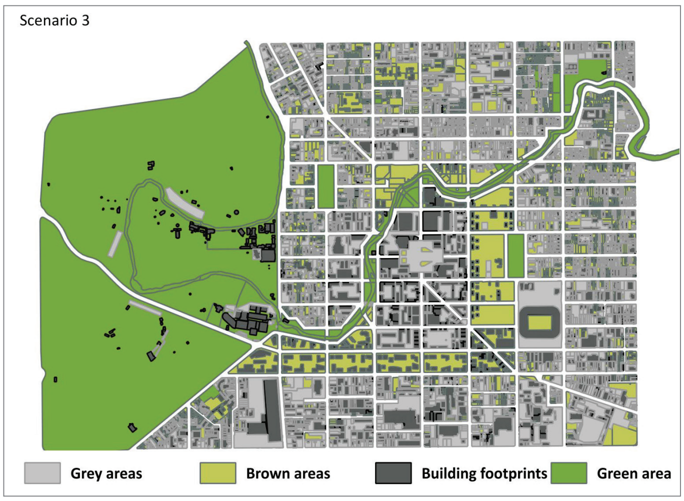
Figure 1: Scenario 1 – urban landscape post-earthquake

(light green in figure 2), as defined by the river and parks, have a strong presence in the landscape. Hagley Park occupies a third of the CBD. The rest of the green infrastructure is fragmented and dispersed within residential blocks in the north and east of the CBD. This scenario will be the reference with which to compare the alternative futures proposed in scenarios 2 and 3.

Scenario 2 presents a hypothetical landscape where demolished buildings have been turned into permeable surfaces. Behind this is the idea that the complexity of the green infrastructure of the city, and consequently its resilience, can be increased by adding new permeable open spaces to the landscape. Therefore, in this scenario, much of the core of the central area is open space (light green in figure 2). These open spaces use the plot system inherited from past landscapes to guide the layout. This provides a set of vacant spaces that look fragmented but could be linked to produce a network of green areas that would allow for temporary activities to happen. The intention behind this scenario is to increase

Figures 2 and 3: Scenario 2 – urban landscape with vacant plots now green space and scenario 3 – CERA's Blueprint for the Christchurch CBD





the complexity of the landscape without building more impervious surfaces – in other words, without adding new buildings to the city.

Scenario 3 (figure 3) is based on the Christchurch Central Recovery Plan, particularly the Blueprint for the CBD that CERA produced in partnership with public and private sector institutions. The most important element introduced in this plan is an inner green belt that embraces the surroundings of Cathedral Square and serves as a framework for the location of new buildings and amenities (figure 3). This 'green frame' divides the CBD into two sectors: the first is enclosed by the green frame and characterised by a compact arrangement of mixed-use buildings; the second is outside the green frame and is characterised by a dispersed residential periphery with neighbourhood centres. Even though the plan has an uncertain future, it is useful to evaluate it critically to see what alternative scenarios might have to offer for increasing the resilience of Christchurch. In this particular case it is important to determine whether more open green spaces will increase the complexity of the green and grey infrastructures of the landscape.

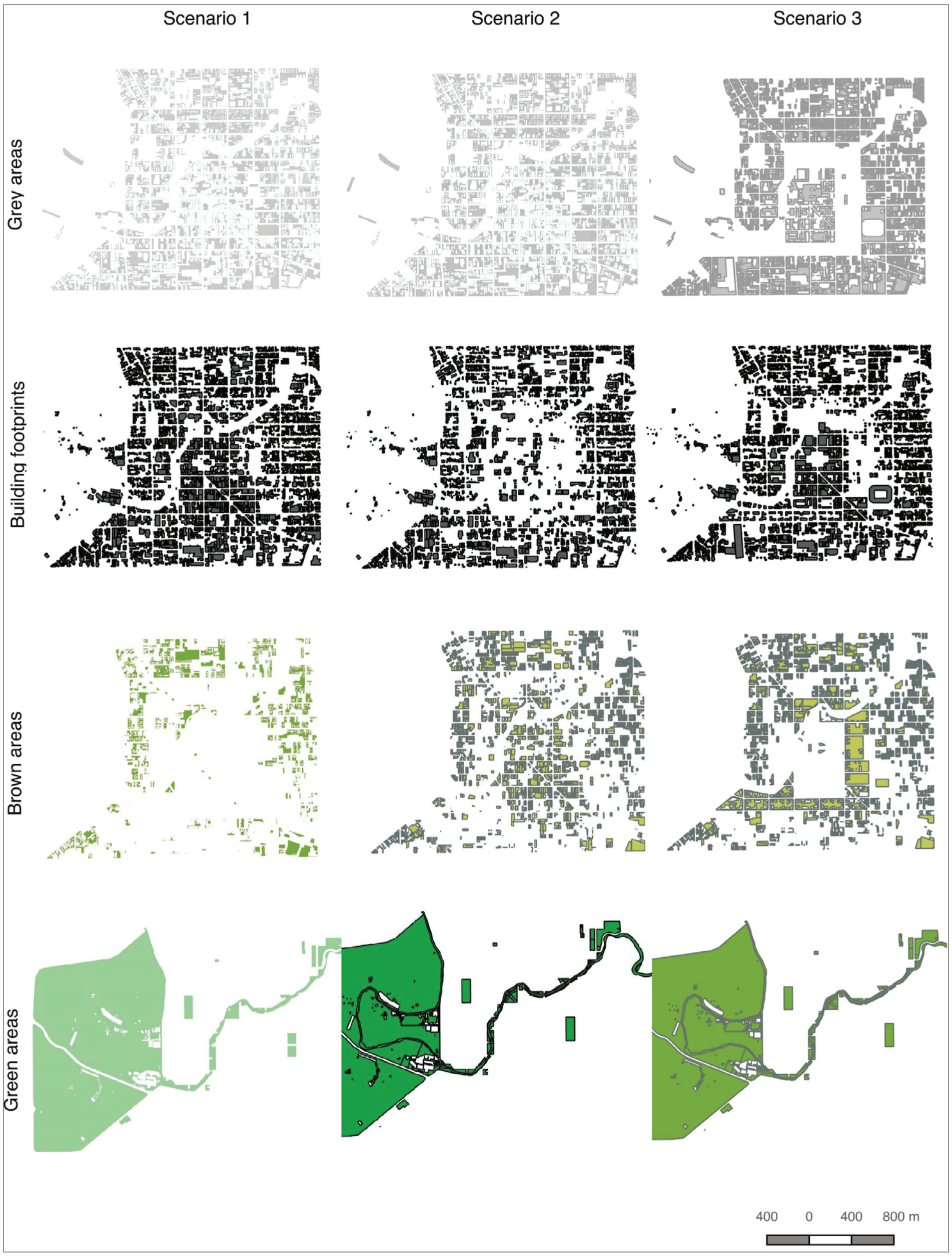


Figure 4: Visualisation of green and grey infrastructures for each scenario. Grey infrastructure is represented by grey areas and building footprints (first and second rows). Green infrastructure is represented by brown and green areas (third and fourth rows)

Organisation of the information

To produce a cluster analysis, all information was first digitised (redrawn from maps) or exported to ARCHGIS, where maps were already in a digital format. When all the information was assembled in this way, it was organised into different layers corresponding to the different elements (green and grey infrastructures). Once the information was classified and organised (figure 4), it was possible to know the area (in square metres) of every element in the map, whether it was a building footprint, or a green, grey or brown area. This information is needed for the cluster analysis.

Cluster analysis

The areas of features in each layer were imported from QGIS to WEKA as CSV format (Comma Separated Value). The data were clustered in WEKA using the 'Expected Maximization' mode. This mode was chosen because it gives the possibility of discovering the number of clusters in each category without predefining them. It is important to set the K value (number of clusters) to –1 so the algorithm finds the number of clusters. Figures 5–7 are the charts used to visualise the results of the cluster analysis for each scenario. In each chart, vertical bars represent clusters, while the colour in each bar refers to a different category – namely, building footprints, brown areas, green areas and grey areas.

In scenario 1 (figure 5), building footprint (the number of buildings in the landscape) is the most populous element with more than 2,000 counts. Grey areas are the richest element of the urban landscape with 10 clusters (light-grey bars in figure 5), while the green areas have only one cluster. This means that the various areas that constitute the total amount of green space do not differ dramatically in size. The richness of building footprints and brown areas is quite balanced with five and six clusters respectively. This is probably the result of having different land occupation ratios for building footprint and plot sizes.

In scenario 2 (figure 6), the group of brown areas is the richest element with 11 clusters. Even after the demolition process has been completed, the group of building footprints has not lost any clusters (six) but instead the structure shows a greater richness with the addition of another cluster. With 24 clusters across the different categories, this scenario is the richest urban landscape of the three proposed.

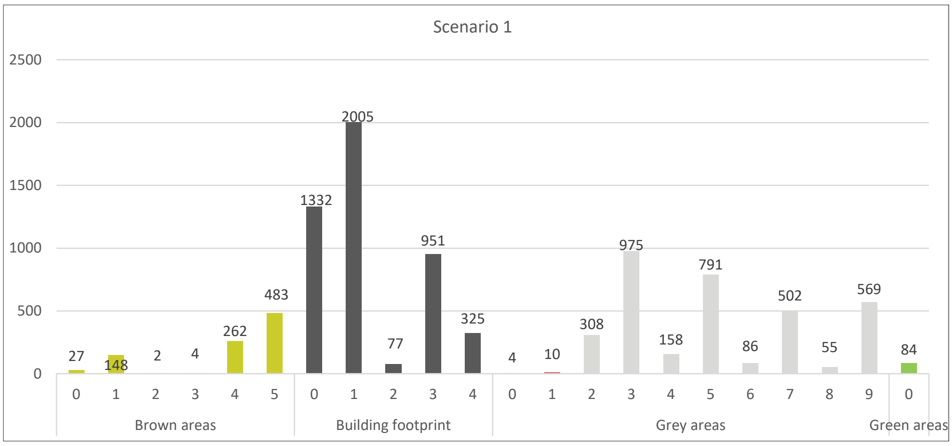


Figure 5: Clusters in scenario 1. The x-axis gives the number of clusters divided into categories. From left to right: brown areas (light green), building footprints (dark grey), grey areas (light grey) and green areas (green). The y-axis refers to the number of features contained in each cluster.

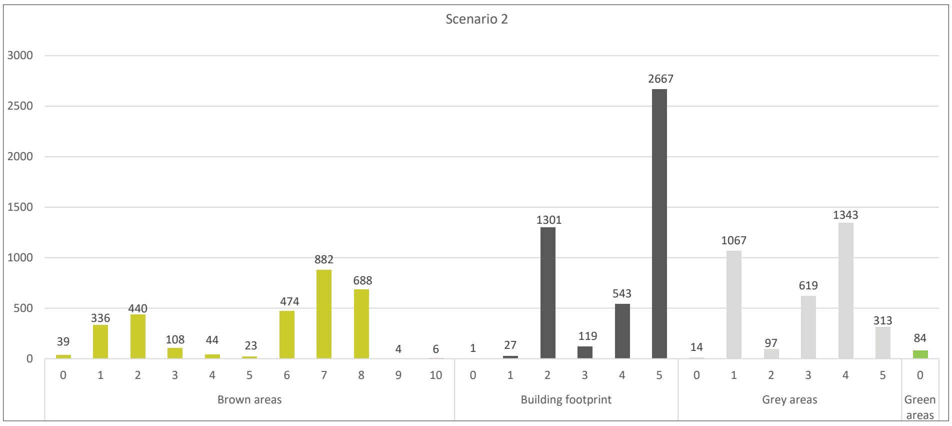


Figure 6: Clusters for scenario 2. The x-axis gives the number of clusters divided into categories. From left to right: brown areas (light green), building footprints (dark grey), grey areas (light grey) and green areas (green). The y-axis refers to the number of features contained in each cluster.

In scenario 3 (figure 7), the group of building footprints is the richest element of the urban landscape with eight clusters. This suggests building footprints are more diverse. However, because the structure of grey areas has been reduced to only two clusters, it seems that the arrangement of the new buildings in the landscape has produced standardised sizes for open spaces between buildings. These spaces are much bigger than in the other scenarios but are also more homogeneous in their sizes and shapes. Even though the green framework could introduce new green spaces to the CBD (it is the scenario with the most brown areas), it is still the landscape with the fewest clusters (16).

Results: diversity index

The diversity index was calculated in Excel by creating a table with the number of clusters analysed per layer, the quantity of features in each cluster, the relative distribution of the features across clusters, the pi value (ln pi) of the features (each area) and the diversity value of each element. Table 1 shows an example of the diversity index for brown areas in scenario 1. The same analysis was performed for all categories in each scenario.

Figure 8 sets out the results of all the calculations done for the diversity index. The chart is useful for visualising and comparing the results for the diversity index of green and grey infrastructures in every scenario. It shows that in scenario 1 grey areas are the most diverse category. The diversity in the building footprints category is probably generated by the contrast between the big size of industrial buildings and the small size of residential houses. The residential

Table 1: Example of diversity index for brown areas in scenario 1

Scenario 1	Clusters	Features	Relative distribution (pi)	Ln pi	Diversity pi (ln pi)*(−1)
Brown areas	0	27	0.029157667	−3.535037369	0.103073444
	1	148	0.159827214	−1.833661961	0.293069082
	2	2	0.002159827	−6.137727054	0.01325643
	3	4	0.004319654	−5.444579874	0.023518704
	4	262	0.282937365	−1.262529731	0.357216835
	5	483	0.521598272	−0.650857581	0.33948619
	Total	926			**1.129620685**

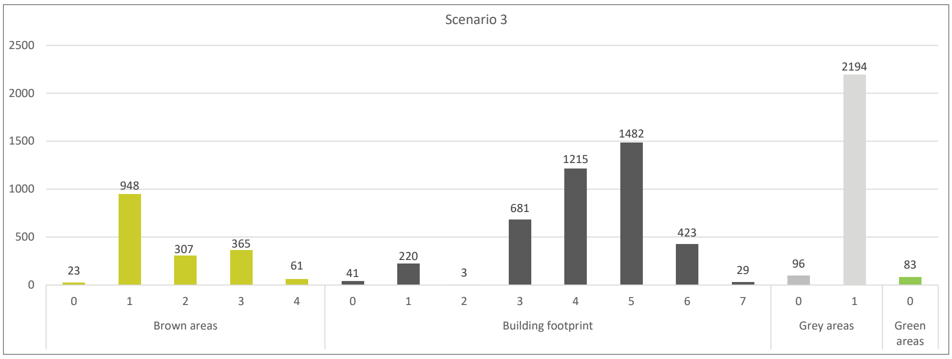


Figure 7: Clusters for scenario 3. The x-axis gives the number of clusters divided into categories. From left to right: brown areas (light green), building footprints (dark grey), grey areas (light grey) and green areas (green). The y-axis refers to the number of features contained in each cluster.

plots create a fine grain with small buildings and green backyards that contribute to the richness of building footprints, grey areas and brown areas. In scenario 2 the most diverse elements belong to brown areas (figure 8). This result supports the idea that the generation of a fragmented network of vacant spaces between buildings produces great diversity in brown areas without lessening the diversity of the built environment critically. The built environment that results from this scenario is a rich and diverse landscape that helps to maintain the complexity of scenario 1. In scenario 3 the most diverse category is building footprints (figure 8). This is probably due to the introduction of new buildings during the reorganisation process, and it is also linked with the richness found in the cluster analysis (figure 7). The results show that the diversity of each scenario has different characteristics, which in turn unravels the role that every element plays in the urban landscape.

Figure 9 compares the total diversity in each scenario (light-blue column), which is the sum of diversity values for green and grey infrastructures. The sub-total diversity of the green infrastructure (light green) is the sum of green and brown areas for each scenario, while that of the grey infrastructure is the sum of the diversities in grey and building footprint areas. Scenarios 1 and 2 are the more diverse while scenario 3 is the least diverse, particularly due to its lower values in the diversity of grey and green infrastructure areas. Based on the results illustrated in figure 9, scenarios 1 and 2 have a higher relative resilience because of their greater diversity.

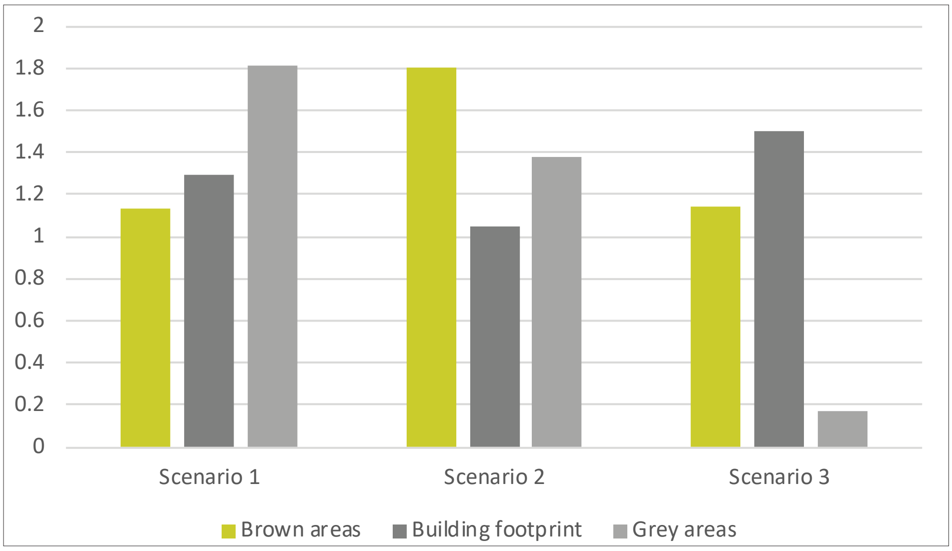


Figure 8: Diversity index for brown areas (light green), building footprints (dark grey) and grey areas (light grey) for scenarios 1–3. The value of green areas was 0, so these are omitted. The x-axis gives the categories analysed and grouped by scenario (1–3). The y-axis refers to the diversity index (total diversity) for each category.

Discussion

It is necessary to have an arrangement of elements of different sizes and shapes to produce the discontinuities that will make urban landscapes more diverse. Green and grey infrastructures are both important in defining the diversity and complexity of the urban landscape (see figure 9). The open spaces between buildings are key contributors to the richness and diversity of the urban landscape. When building footprints get richer and more diverse (scenario 3 in figure 8), brown and grey areas get more homogeneous and less rich. However, when the diversity of open spaces between buildings increases (grey areas in scenarios 1 and 2, figure 8), the diversity of the whole urban landscape increases (figure 9).

An important factor that has increased the diversity of brown and grey areas in scenarios 1 and 2 is that the grey and green areas are defined by the size and shape of the plot system. When the plot system is affected, the entire urban landscape is driven to change. In scenario 3 the plot system was more affected by the predominance of bigger buildings, some of them with a free perimeter, which were not found in the traditional plot system.

In the Christchurch CBD, the most compact scenario (scenario 3) was not the most diverse one. According to the results, the green belt around the compact centre proposed in scenario 3 will not be enough to increase the diversity of the urban landscape. The result of this research challenges the idea that a sudden compaction of the built environment will enhance the resilience of its urban landscape.

Conclusions

Cities are changing continuously and they will be under more pressure in years to come as their human populations grow. Christchurch will not be an exception. The city will also have to deal with the challenge of continuing to reorganise in the face of the possibility that further earthquakes may occur in the future. The first step in establishing a more resilient built environment is to make appropriate kinds of decisions about the use and occupation of the urban landscape. Focusing only on making buildings more resistant to earthquakes will not be enough to increase the

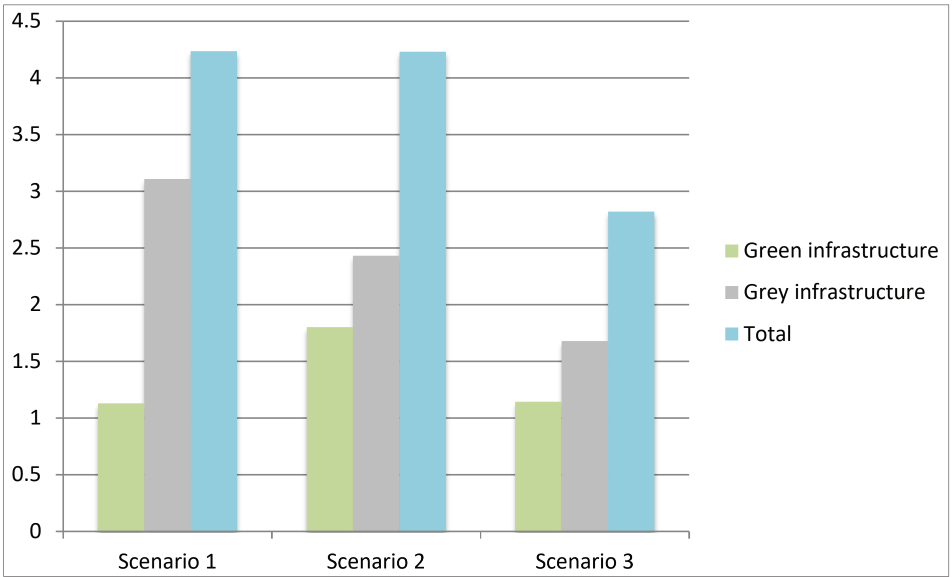


Figure 9: Total diversities per scenario (light blue) and sub-total diversities for green (light green) and grey infrastructures (light grey) in each scenario (1–3). The x-axis gives the categories per scenario. The y-axis refers to the diversity index value per category.

resilience of the built environment because it is the design of the non-built spaces in the landscape that largely defines its richness and diversity. Designing the green and grey infrastructures of urban landscapes to enhance the resilience of a city seems like a relevant consideration that deserves further research.

Some findings from this paper can be used to question the idea that having a heavily clustered and dense built environment is the best solution for the Christchurch CBD. From a resilience perspective, the challenge for the future of the urban landscape of the CBD is to create spaces that interact and catalyse more diversity. At the moment the landscape of the city has a degree of looseness that can be seen as an opportunity. Many of the vacant plots in the city, where construction is not permitted, have been occupied by car parks, an activity that allows the owners of the land to make some profit without having to rebuild. Tourists come to Christchurch to see the city but also to experience the inheritance that the earthquakes have imprinted on the city, from the destruction of buildings to the new works undertaken to reorganise the city. The walls of several buildings in the CBD are exhibiting amazing works of art that express the suffering, desires and hopes of the community. The diversity of these events is happening in between buildings, in vacant places and spaces that have emerged after the earthquake. This is an opportunity for designers to rethink a new type of CBD, where the central area could be characterised by a landscape of heterogeneous and diverse spaces. Perhaps a resilience approach to the future of Christchurch is less about what needs to be built and more about what spaces should not be built on, in order to create an urban landscape that can gradually introduce more complexity in the future. However, this is a challenging task for designers given the future of Christchurch is not only about design actions. The present study has focused solely on the morphology of the built environment yet cities are much more than buildings. Future research can use the methods explained while adding more variables that better describe the complexity and history of the city.

The analysis of the three scenarios presented in this paper has served to produce an alternative understanding of how the concepts of green and grey infrastructures can be used to compare the resilience of the urban landscape of the CBD of Christchurch. Rather than proposing a solution or silver bullet to the reshaping of the built environment in a 'resilient way', it offers an approach to acknowledging and measuring what is gained and what is lost when a particular design is imposed on the landscape; in other words, the cost of the opportunities profited from and lost.

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