# The ecological roles of golf courses in urban landscapes

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# Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted to a degree or diploma at any tertiary education institution.

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# Abstract

The proliferation of urban golf courses accounts for a growing proportion of the urban land area in Australia and other countries. While many suggest that golf courses have an environmentally negative impact, others believe they are important nodes in the network of urban green space and can provide refugial habitat for wildlife. However, research on golf course ecology is in its infancy and this limits development of explicit guidelines for ecologically sound development. Therefore, this PhD research used remote sensing technology to investigate the ecological roles of golf courses in maintenance of vegetation at the urban landscape scale. The thesis explores temporal and spatial landscape data as well as the possible cooling effects golf course can provide in the Perth Metropolitan Region.

The multifunctional aspects of green spaces in golf courses are highlighted in this study. Firstly, by using moderate resolution satellite imagery (Landsat) time series data for three decades from 1988 to 2018 to assess temporal changes in vegetation cover, the study found that vegetation clearance was significant and vegetation cover has become increasingly fragmented. It was concluded that golf courses contribute to urban conservation through the maintenance of vegetation cover and by increasing habitat connectivity during the long period of urbanisation. Secondly, high resolution satellite imagery (PlanetScope (PS) Level 3B) was then used to compare spatially the characteristics of vegetation within golf courses with other urban land-use. It found that golf courses have less conservation values than conservation land, but their role in preservation of native vegetation, vegetation health and habitat connectivity is more significant than other highly intensive urban land-uses. Thirdly, analysis of multispectral high resolution airborne imagery for assessing the capacity of golf courses in mitigating the urban temperature revealed that urban golf courses can provide cooling effects in the urban environment through the provision of tree coverage and other green areas.

Despite limitations of the research being carried out at the landscape scale, the findings of the thesis can enhance the future integration of golf courses into urban biodiversity conservation and ecosystem service improvement.

# Acknowledgement

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# Chapter 1 Introduction

## 1.1 Background

Urban areas are unique places, which often have little room for nature. Urbanization clears natural vegetation and threatens biodiversity leading to  the localized decline and extinction of many native wildlife species (Oke et al, 2021). Furthermore, urbanization leading the changes of land cover is a threat of the wellbeing of city dwellers (Cyril et al, 2013). Therefore, utilizing all the opportunities to preserve the limited green resources in cities has become a high priority in urban planning.

In urban environments, the use of land is extremely intensive where ecological priorities must compete with social and commercial interests in the decision-making process (Dearborn & Kark, 2010; Hölting et al, 2020). Thus, conservation efforts to protect large reserves that retain areas of quality 'interior' habitat can meet many challenges (Dearborn & Kark, 2010; Donaldson et al, 2017). While traditional approaches to urban conservation have focussed primarily on the retention of large habitat reserves (Dearborn & Kark, 2010), the more recent urban ecological approach has advocated the maintenance and restoration of urban landscape integrity by creating networks of interconnected habitat, using a combination of large reserves and natural habitats on private land and in public 'open space' areas (Baldwin et al, 2012; Fischer & Lindenmayer, 2002; Lindenmayer & Franklin, 2002; Norton et al, 2016).

Small urban green spaces can be of limited value to wildlife conservation compared to large nature reserves. However, they are not without ecological value in the urban matrix (Baldwin et al, 2012; Fischer & Lindenmayer, 2002; Lindenmayer & Franklin, 2002; Norton et al, 2016) by providing additional resources, softening *Edge*-effects, and increasing habitat connectivity (Fischer & Lindenmayer, 2002; Lindenmayer & Franklin, 2002). The contributions to ecosystem services help provide cumulative benefits at a regional level (Tratalos et al, 2007) such as counteracting the urban heat island effect, thereby reducing the energy costs of cooling buildings (Haq, 2011; Strohbach et al, 2012). Therefore, information on the ecological values of all urban land types is required to make ecologically responsible urban zoning decisions. Despite this, small habitat remnants outside the protected area network have still received relatively little research attention from ecologists

Recently, the rate of urban golf course proliferation has been increasingly globally, especially in the USA, UK and Australia (Petrosillo et al, 2019; The R&A, 2019). However, the ecological value of urban golf courses have become the subject of argument in recent decades (Hurdzan, 2020). This interest has been generated by concerns for their potentially adverse environmental impacts as well as by their capacity to contribute to urban conservation strategies (Petrosillo et al, 2019).

Because of the relatively large areas of green space (average 60 ha), there are reasons for urban foresters and ecologists to recognise the ecological values of urban golf courses (Hodgkison, 2006a). Furthermore, environmental standards for golf course design and management are improving. More natural course designs are being implemented that retain large areas of structurally complex native vegetation in out-of-play areas (Keith, 2016). In addition, golf courses can be considered as a type of urban land-use with strong community links that can facilitate restoration efforts to maintain the local environment. Therefore, golf courses represent an opportunity for small-scale, off-reserve conservation (Hodgkison et al, 2007b). Recently, a growing number of ecologists have investigated the capacity for golf courses to provide refugial habitats for regionally threatened wildlife. However, prior to the commencement of this study, few studies had assessed the ecological value of golf courses at an urban landscape scale. Moreover, there is a notable geographical bias in golf course studies investigating the conservation value of golf courses. The extent to which golf courses can provide ecological values in an urban matrix of green space network is uncertain.

Given their importance, studies have been undertaken that seek to understand the ecological values of golf courses through assessment and monitoring. Research in golf course ecology can help determine the extent and opportunity that urban golf courses can contribute to urban conservation and urban ecosystem services in more liveable cities. Most of the golf course ecology has focused on biodiversity (Petrosillo et al, 2019), and methods for golf course biodiversity traditionally have involved site-based (e.g. typically a quadrat, or a transect) assessments (Blair, 1996; Blair & Launer, 1997; Cristol, 2009). However, the demand for information at broader scales necessitates the application of spatial modelling as well as remote sensing technologies for mapping and assessment of ecological values of golf course at the landscape scale (Chu & Guo, 2012; Lawley et al, 2016; Soubry et al, 2021) for integration into urban planning and conservation strategies. Remote sensing is a very effective tool for urban forest monitoring and the topic has been comprehensively reviewed by Shojanoori & Shafri (2016). Therefore, to contribute to fill the indicated research gaps, this PhD research used remote sensing technology to assess the ecological properties of golf courses in an urban landscape. This study was conducted in Perth Metropolitan Region, Australia where over thirty golf courses have established along with urbanisation process in the last century.

## 1.2 Aims and objectives of the thesis

The overall aim of this thesis is to broaden the knowledge base for decision-making in golf course management and urban planning in the Perth Metropolitan Region. The specific objectives of the thesis are to:

- Identify research gaps in golf course ecology research (Chapter 2);
- Assess the roles of golf courses in the maintenance of vegetation cover and connectivity during a long urbanization period (Chapter 3);
- Identify the significance of vegetation attributes within golf courses compared to other land-use categories along an urban-rural gradient (Chapter 4);
- Assess the cooling effects of golf courses in an urban environment (Chapter 5);
- Assess contributions of the thesis research as implications for urban planning and policy development and propose priorities for future research to enhance the ecological values of urban golf course through improved golf course design and management practices (Chapter 6).

Based on the research gaps found in the literature review (Chapter 2), the thesis will attempt to answer three key research questions:

*1) What is the role of golf courses in maintaining urban vegetation during a long period of urbanization?*

Chapter 3 used the satellite Landsat images (30m x 30m resolution) for a time-series analysis to investigate the role of golf course in maintaining vegetation cover and connectivity during a long urbanization period (1988-2018).

*2) How significant are golf courses in maintaining vegetation in comparison with other land-use categories?*

Chapter 4 used the new generation of satellite imagery (PlanetScop, 3m x 3m resolution) to examine the significance of golf course in maintaining vegetation characteristics by comparing spatially their vegetation cover, native vegetation cover, and other land-use categories and among golf courses.

3) *What is the the role of golf courses in reducing urban temperature in comparison with other land-use categories?*

Chapter 5 used airborne multispectral high-resolution (0.3 x 0.3m) images to assess how golf courses in urban landscapes can play roles in reducing urban heat in comparison with other land-use categories and explore vegetation characteristics and golf course location that may shape the cooling effects of golf courses and other land-use in an urban landscape.

The roadmap of thesis chapters and interrelationships of research topics are described in Figure 1.1

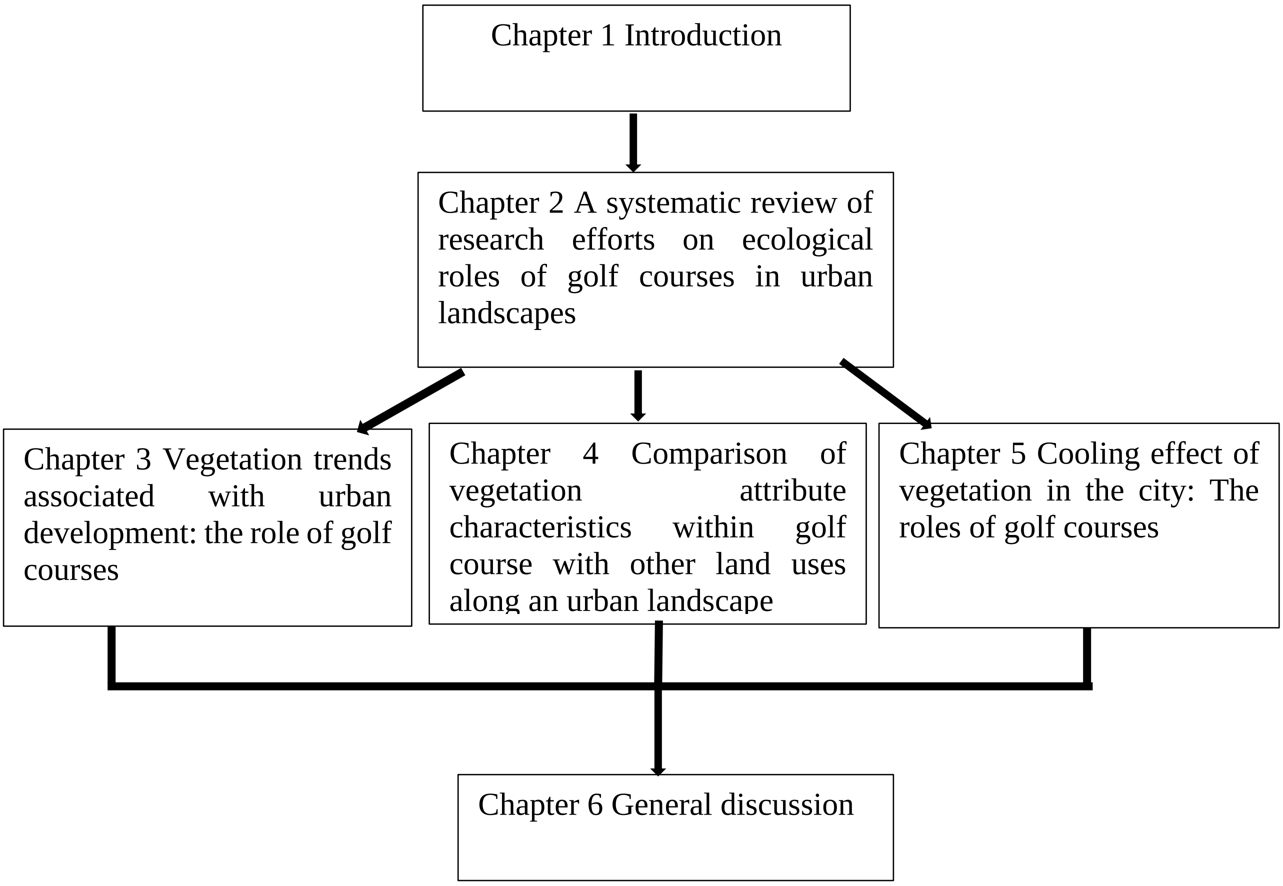


**Figure 1. 1 Roadmap of thesis chapters and interrelationships of research topics**

## 1.3 Significance of the thesis

- This study enhances understanding and recognition of the ecological roles of golf courses in urban landscapes and contributes to the gap in knowledge of ecological roles of golf courses.
- It provides information to support efforts to improve ecological values of golf courses with realistic goals.

- The findings will increase recognition of the roles of golf courses in urban conservation, and they highlight the need for involving golf courses and other green spaces in urban planning and conservation strategies in the future.
- Although the research was undertaken in Perth it is relevant to golf courses and urban vegetation more widely world-wide, particularly the value of trees – their conservation, planting and maintenance in a landscape context.

# Chapter 2 A systematic review of research efforts on ecological roles of golf courses in urban landscapes


## Abstract

Golf courses are a fast growing yet controversial land use in urban landscapes. Their controversy lies in the negative impacts on the environment during their construction and operation. However, their ecological values are increasingly recognized by ecologists. Due to social and commercial demands, the golf industry is still developing widely, even though its environmental concerns as well as ecological benefits are still not well understood. This review of golf courses aims to: (1) synthesize outstanding environmental problems of golf courses and management recommendations for minimizing those impacts; (2) synthesize key ecological values of golf courses and management recommendations for enhancing those values; (3) compare ecological values of golf courses to those of other land uses along an urban gradient; (4) and identify research gaps and suggest future research.

This chapter was conducted by using systematic review approach based on searching multiple databases. I found that golf courses are subject of debate because of environmental problems related to their construction and operation. However, the negative impacts of golf course are mixed. Some studies identified problems of overuse of water for irrigation, soil and water pollution, impacts on soil properties and altering natural habitats, whereas other studies concluded that the impacts are less significant and depend on golf course management practices. It is evidenced that golf courses provide some ecological values in preserving biodiversity and ecosystem services. Compared to other land uses across urban gradient, golf courses can provide ecological values that are lower than natural areas or protected areas but higher than agricultural land uses and highly urbanized areas. However, the ecological values of golf courses at landscape scales are not fully understood in the literature, and those in the Perth Metropolitan Region have been little studied, leading to the conduction of this PhD thesis to fill in the gaps.


## 2.1 Introduction

Healthy urban forests are critically important because they provide goods and services, and full ecosystem functions that benefit humans and the environment (Chapter 1). Benefits include promoting natural vegetation in cities, strengthening resistance to natural disasters, enabling biological processes such as pollination (Zitcovic, 2008), ameliorating heat islands (McPherson, 1994), reducing surface erosion from stormwater runoff, providing shelter from extreme weather events (Abdollahi et al, 2000), and providing habitats for wildlife (Dearborn & Kark, 2010). In addition, urban forests deliver a wide range of human well-being benefits including reducing stress (Van Den Berg & Custers, 2011), lowering the risk of poor mental health (Mitchell, 2013), decreasing mortality from cardiovascular disease (Donovan et al, 2013), improving self-esteem and empowerment (Maller, 2009) and cognitive ability (Lee et al, 2015a). Consequently, there is global interest from city governments to manage urban green spaces so that they support people and the environment (Threlfall et al, 2016b).

Nevertheless, under pressure of urban development, urban forest ecosystems have declined worldwide. The number of mega-cities has nearly tripled since 1990, and over half of the world's population is settled in urban areas with a further 2.5 billion people likely to be added to the urban population by 2050 (United Nation, 2018). As a consequence of increasing urbanization, more city residents face the prospect of living in built environments with fewer green spaces (Maas et al, 2006). Urbanization requiring vegetation clearing is globally recognized as a threat to urban forest ecosystems, responsible for habitat loss, fragmentation and biodiversity loss (Adams, 2005).

With intense demand for urban land, priorities in urban green space conservation have to compete with social and economic interests in urban planning (Freeman, 1999). Efforts to maintain and restore urban forests to create networks of interconnected habitat need to combine all opportunities to retain green spaces within cities (Catterall et al, 1998). Besides using formal reserves, urban planning should set targets in off-reserve conservation on public and private land (Baldwin et al, 2012; Linehan et al, 1995). Therefore, the capacity for all open-space areas, such as recreational parks, street trees and residential gardens to perform ecological, social and commercial functions, had to be considered in urban planning even though these open spaces may not be involved in conservation strategies (Linehan et al, 1995; Pirnat & Hladnik, 2018). Golf courses are one kind of recreational land use that account for a significant proportion of green space in many cities. Since the 1970$^{s}$, there has been proliferation of urban golf courses requiring large areas of land, with an average 18-hole golf course covering about 60 ha (Salgot et al, 2012). Australia is among the world's leading countries with 1,616 golf courses, and ranks No. 5 worldwide (The R&A, 2019).

There has been much negative criticism of this form of land use. For example, golf courses alter natural habitats and are considered to be environmental polluters through pesticide and fertilizer use (Guzmán et al, 2014). However, improved environmental outcomes are possible with the recent trend in golf course design with the rough out-of-playing-area occupying a significant proportion of a golf course and being less intensely managed than the greens, tees, fairways and practice areas (Baris et al, 2010). With this design strategy, over half of a golf course area can be green space comprising natural or planted forests. Hence, golf courses in urban settings constitute green-area habitats which sometimes surpass small sized nature reserves (Colding & Folke, 2009).

From an ecological perspective, golf courses in urban landscapes may present an opportunistic approach to biodiversity conservation and habitat management despite substantial concerns about this land use (Hodgkison, 2006b). This literature review examines the ecological roles of golf courses globally through different lenses. The main topics discussed in this review are: (1) the key environmental problems of golf courses identified in the literature, which need addressing for golf courses to attain their potential; (2) the outstanding ecological benefits of golf courses and the potential management practices for enhancing their environmental value; (3) the significant values of golf courses compared to other land uses across urban gradients based on existing control-case studies; and. (4) research gaps and suggestions for the conduction of this PhD thesis and other future research.

## 2.2 Methodology

The conceptual framework of this article is presented in Figure 2.1. The literature review was based on the “ISI Web of Science” core collection (ISI WOS; http://webofknowledge.com/), SCOPUS (https://www.scopus.com/), and CAB Direct (https://www.cabdirect.org/) databases (from 1970 to mid-2021) to target fields related to environmental impacts and ecological values of golf courses. I searched for “golf course" in hierarchical combination with “environmental impact", “social impact”, “economic impact”, “soil", “water”, “habitat", “biodiversity", “land use”, “ecology”, “ecological service", ‘‘conservation’’, ‘‘ecosystems’’, ‘‘fauna’’, ‘‘flora’’, ‘‘mammals’’, ‘‘insects’’, ‘‘birds’’, ‘‘plants’’, ‘‘species’’, ‘‘conservation’’, “urban matrix”, “???” “management”, “urban landscape", “urbanization", “urban heat island”, “human well-being” to reflect the research hypothesis that golf courses are multifunctional and can meet social, commercial and ecological interests.

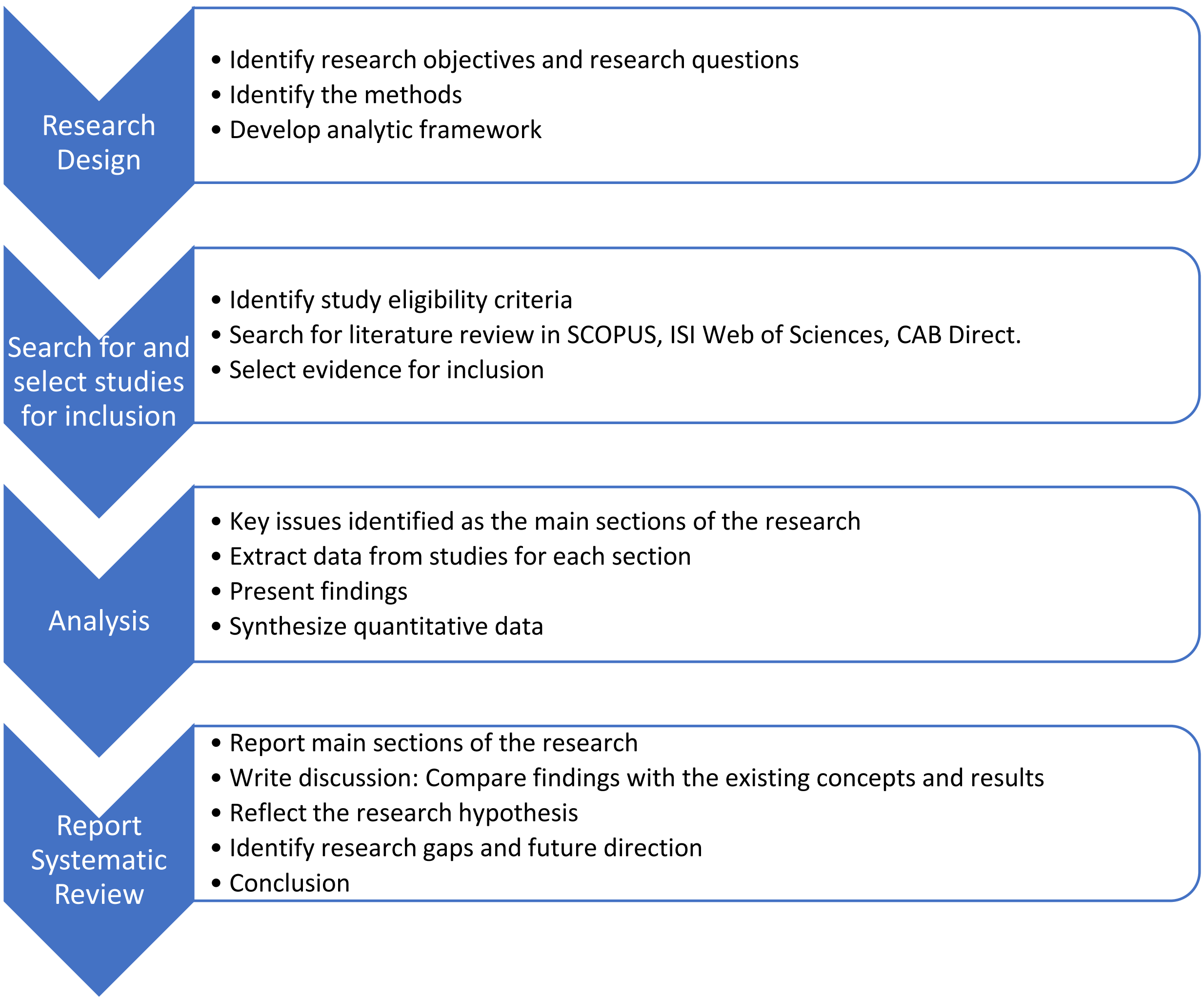


**Figure 2. 1 Conceptual framework of this chapter**

The document type was limited to peer-reviewed primary research (journal articles) and publications in the English language for the period 1971 – mid-2021. Documents identified by the search criteria were manually assessed for relevance based on reading the title, keywords, abstract and full text of each document. Relevant studies were identified as those having research objectives and results related to the ecological roles of golf courses at landscape scale. Duplicate articles across the three databases were removed, resulting in 417 articles for systematic review (Table 2.1).

**Table 2. 1 The process of record collection steps taken in the selection of papers for the systematic review**

| Steps | Scopus | WoS | CAB direct |
|---|---|---|---|
| Step 1: First records of key words | 2810 | 1687 | 731 |
| Step 2: Refine [Journal articles, time (1971-2021), language (English)] | 603 | 1320 | 611 |
| Step 3: Exclude papers unrelated to topic/area | 301 | 296 | 39 |
| Step 4: Remove duplicated articles among databases | **417** | | |

The review collected and organized 417 articles representing a large sample of the most relevant literature on golf course at the landscape context. The results highlighted that interest in golf courses ecology has increased markedly over the last 40 years (from 1971 to mid-2021) and plateaued in 2010-2011 (Figure 2.2) at around 22-28 papers per year.

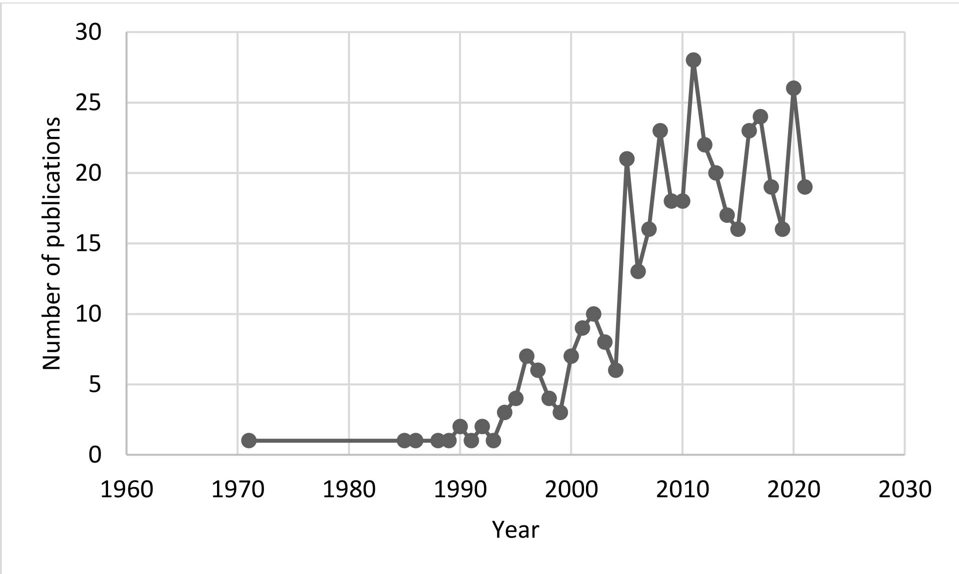


**Figure 2. 2 Number of articles dealing with the topic ‘‘golf courses’’ from 1971 to 2021**

The 417 articles were filtered and categorized into key environmental impacts (Table 2.2), and outstanding ecological benefits (Table 2.3). In order to compare ecological values of golf courses with other land uses (Table 2.4), I used 32 control-case studies and classified the groups of land uses that were compared to golf courses in those studies. The land use was categorized into 5 groups as follows: (1) General natural reference sites (described in control-case studies variously as predominant woodland *Edge*, natural land that golf courses replaced, surrounding natural areas, forested reference streams, nearby eucalypt fragments, adjacent habitats, natural water bodies, natural woodland, natural grass sites, naturalized forest areas, or remnant vegetation) which were not clearly described by the authors as belonging to protected areas or not; (2) Protected areas (biological preserve, nature preserve, lakes in protected areas, botanical garden); (3) Agriculture related land uses (old fields, pastures, cultivated farmland, farmland, coffee farm, seasonal farm, long grass sites, rural ponds); (4) Urban parks and recreational areas; and (5) Highly urbanized land uses (cemeteries; residential neighbourhood, monasteries). I quantified the research comparing each land use category with golf courses for studies that determined the values of golf courses as being "higher", "lower", or "similar" to each targeted land use category. Where more than one type of land use was compared with golf courses in a study, I considered each comparison separately, referred to as a 'comparative case' for quantitative comparison. Therefore, the chapter ended up with 56 comparative cases in 32 control-case studies.

## 2.3 Results and Discussion

### 2.3.1 Golf courses are subject to environmental debate

The rapid expansion of golf courses raised a number of environmental concerns (141 articles). The review summarizes key negative impacts of golf courses on the environment (Table 2.2). The following expands upon each problem, making management recommendations.

*Irrigation and water shortage*

One of the main concerns of golf course development is water consumption for turf grass maintenance and other operations, and this has become a source of water conflict in a number of regions (Utrero-González & Callado-Muñoz, 2014; Wurl, 2019; Young et al, 2014). A typical 60 to 80 ha golf course has a global consumption of 9.5 million $m^3$ water per day for irrigation (Lewis et al, 2001). Furthermore, in order to meet the water supply for irrigation, many golf courses rely on underground aquifers and their excessive extraction can lead to the invasion of saline water causing the problem of salinity for the hydrological system (Schwecke et al, 2007).

Water consumption is biggest in the dry season causing the water crisis during this time (Scott et al, 2018). For example, in Canada, average water use of 18-hole golf courses was 0.98 million litres per hectare (L/ha), but it doubled during the dry season (Scott et al, 2018). This should be a major concern for the golf industry in the future as climate change lowers precipitation and soil moisture, and increases temperature and pan evaporation (Scott et al, 2018), and there is an increasing water consumption demand with rapid urbanization and population growth (United Nation, 2018).

However, a golf course can consume less water if it is well managed. Water consumption by a golf course depends on its dimensions, the water requirements of turf, water retention properties of substrates, and local weather (Tapias & Salgot, 2006). Water demand varies across golf courses and depends on their management regimes (Ortuño et al, 2015; Scott et al, 2018). Best management practices can reduce water consumption such as using silt soils which could save 76% of water use (Ortuño et al, 2015; Scott et al, 2018), the incorporation of drought-tolerant turf grasses (Tapias & Salgot, 2006), deficit irrigation practices (e.g., under-irrigation of grass to below its maximum potential water demand) can save a further 20–60% (DaCosta & Huang, 2006), the incorporation of soil moisture sensors (to reduce over-irrigation) and adding wetting agents (to retain soil moisture) (Diaz et al, 2007), using wastewater and rainwater for irrigation (Klein et al, 2015), and adopting technological innovations that enhance irrigation efficiency (Robert & Carrow, 2007). By establishing "best in class" water use efficiency among common types of courses, potential water extraction savings of 35% have been identified (Scott et al., 2018).

Because of differences in policies and regulations facing management regimes of golf courses, water consumption of the golf industry varies among countries. For example, the annual water use of the golf industry in Canada is much lower than the average annual water use at courses in warmer and dryer regions of southern France, south-western The United States of America (USA), and the Mediterranean (Scott et al, 2018). The potential for increasing water use efficiency has been demonstrated in the USA where golf courses have reduced their water use by 21.8% in almost a decade by implementing different measures, including voluntary reductions in irrigation, reductions in the number of golf facilities, and water conservation practices (Gelernter et al, 2015). To effect change, there is a need for an ecological and social strategy for the golf industry to mitigate water consumption (Scott et al, 2018; Tapias & Salgot, 2006).

**Table 2. 2 Summary of the main environmental problems of golf courses and recommendations for minimizing negative impacts**

| Environmental problem | Description | Recommendation | Relevant research |
|---|---|---|---|
| Irrigation and Water shortage | Turf grass maintenance and other operations requiring irrigation can lead to water crisis. | 1. Using silt soils<br>2. Incorporation of drought-tolerant turf grasses<br>3. Deficit irrigation practices<br>4. Incorporation of soil moisture sensors and adding wetting agents<br>5. Use of recycled water for irrigating<br>6. Technological innovations | DaCosta & Huang (2006), Diaz et al (2007), Gelernter et al (2015), Klein et al (2015), Lewis et al (2001), Ortuño et al (2015), Robert & Carrow (2007), Scott et al (2018), Sendrós et al (2021), Tapias & Salgot (2006), Utrero-González & Callado-Muñoz (2014), Wurl (2019), Young et al (2014). |
| Soil and water pollution | Use of chemicals such as pesticides and fertilizers to maintain healthy grass can cause water and soil pollution | 7. Suitable timing and rate of application, and type of fertilizers and pesticides<br>8. Maintaining and improving natural areas, designing naturalistic golf courses to reduce chemical leaching<br>9. Developing technical measures to reduce the risks associated with reclaimed water reuse<br>10. Selecting appropriate turf species to reduce the amount of chemical usage<br>11. Following international and local regulations when using pesticides and fertilizers | Bachman et al (2016), Baris et al (2010), Bekken et al (2021), Bock & Easton (2020), Carey et al (2012), Haith & Rossi (2003), Haith & Duffany (2007), Lewis et al (2001), Lin & Qian (2019), Obear et al (2014), Semerjian et al (2018), Stacey et al (2019), Streeter & Schilling (2018), Tapias & Salgot (2006), Udeigwe et al (2015), Winter & Dillon (2005), Yang et al (2013). |
| Impacts on physical and biological properties of soils | Use of chemicals and physical practices can impact on microbial communities and physical characteristics of soils | 12. Improved selection of grass species to reduce chemical usage<br>13. Adequate selection of soils and substrates<br>14. Proper application of fertilizers and pesticides to reduce impacts on microbes and soil structure<br>15. Using lighter machines for construction of fairways to minimize soil compaction<br>16. Using machines under dry soil conditions | Alaoui & Diserens (2011), Allan-Perkins et al (2019), Tapias & Salgot (2006), Tu et al (2011). |
| Altering natural habitats | Construction and operation of golf courses cause loss and deterioration of natural habitats | 17. Selection of the best design, adapted to the existing landscape, respecting the possibilities that the land offers and taking advantage of native vegetation<br>18. Improving habitat quality through management practices during operation of the golf courses | Bingham et al (2017), Colding & Folke (2009), Dripps (2012), Hodgkison (2006a), Tapias & Salgot (2006). |

*Chemical usage causing soil and water pollution*

In order to maintain healthy grass on golf courses, intensive management practices such as usage of pesticides, fertilizers, and surfactants are applied (Bachman et al, 2016; Baris et al, 2010). The use of chemicals can cause soil and water pollution, and impact ecosystems within and surrounding golf courses through runoff, volatilization, photolysis, adsorption, absorption, and dilution/leaching (Bachman et al, 2016; Bock & Easton, 2020; Carey et al, 2012; Lewis et al, 2001). This can result in decreasing surface and groundwater quality, eutrophic downstream waters and soil contamination (Stacey et al, 2019; Streeter & Schilling, 2018; Udeigwe et al, 2015; Yang et al, 2013), with impacts on soil health, aquatic life, food chains, and reduced potential for use of soil and water resources (Haith & Duffany, 2007; Obear et al, 2014). In addition, due to shortage of water supply, many golf courses are using reclaimed water for irrigation, which has potential risks related to microbial pollution and inputs of salts and other chemicals (Lin & Qian, 2019; Semerjian et al, 2018).

However, the extent to which golf courses contribute to soil and water pollution is arguable due to conflicting results in the literature. In contrast to the negative impacts on water and soil quality referred to earlier, other studies indicate that well-maintained turf reduces nutrient runoff and leaching losses relative to other land uses (Haith & Rossi, 2003). A systematic review of 44 studies involving 80 golf courses over a 20-year period undertaken by Baris et al. (2010) found that widespread and/or repeated water quality impacts by golf courses had not occurred. The conclusion that golf courses pose minimal soil and water risk has been confirmed in a number of more recent studies (Bachman et al, 2016; Bock & Easton, 2020; Udeigwe et al, 2015), depending on the local circumstances, golf course design and management (Bachman et al, 2016; Baris et al, 2010; Bock & Easton, 2020; Petrosillo et al, 2019; Tapias & Salgot, 2006). Therefore, options exist for reducing negative impacts of chemical use on golf courses. Management options that have been suggested for reducing the risk of pollution include: optimum timing, rate and type of fertilizers and pesticides (Bachman et al, 2016; Tapias & Salgot, 2006); maintaining natural areas and designing more naturistic golf courses (e.g., vegetation buffers along streams which can reduce chemical leaching from golf courses) (Winter & Dillon, 2005); developing technical studies and sanitary risk assessments for reclaimed water reuse (Salgot et al, 2012); selecting appropriate turf species to reduce the amount of chemical usage (Tapias & Salgot, 2006); and adhering to international and local chemical regulations (Arcury-Quandt et al, 2011).

*Impacts on physical and biological properties of soil*

In addition to the potential risk of pollution, application of pesticides and fertilizers to maintain turf may have deleterious effects on soil biota and soil structure. Past studies have measured some impacts on soil microbial communities on golf courses (Allan-Perkins et al, 2019; Bartlett et al, 2007; Gan & Wickings, 2017; Tu et al, 2011). In addition, the construction and maintenance of specific areas of a golf course, such as top dressing with sandy materials in order to improve drainage and soil aeration, has been shown to influence the phenotypic expression of the soil microbial community (Alaoui & Diserens, 2011). As soil microbial communities provide many ecosystem functions, consideration should be given to leveraging them in order to improve N fertility, nutrient cycling and biocontrol of pest and disease organisms (Bartlett et al, 2007; Gan & Wickings, 2017).

Furthermore, traffic from golfers, the use of heavy machinery and the common practice of "top dressing" in course maintenance can alter soil structure (Alaoui & Diserens, 2011; Bandaranayake et al, 2003; Bauters et al, 2000). Soil compaction can also occur when heavy machinery is used during golf course construction, leading to an increase in soil bulk density, penetration resistance, and to a decrease in pore size distribution (Alaoui & Diserens, 2011). Therefore, the fairway and the tee with a higher proportion of player traffic and common practice activities have been consolidated to increase bulk density (Alaoui & Diserens, 2011). However, these negative impacts can be minimized by the best management practices used to maintain golf courses (Petrosillo et al, 2019). The above impacts on soil properties can be minimized through the adoption of  suitable management practices, including improved selection of grass species to reduce chemical usage,  fertilizer and pesticide practices to reduce impacts on microbes and soil structure (Tapias & Salgot, 2006), using lighter machines during construction to minimize compaction and using machines under dry soil conditions (Alaoui & Diserens, 2011).

*Altering natural ecosystems*

During the construction and operation of a golf course, the consumption of water, reconfiguration and canalization of water streams, the erosion processes and the removal of vegetation have significant impacts on ecosystems of existing landscapes (Dripps, 2012; Tapias & Salgot, 2006). The construction of golf courses can convert native vegetation areas into turf and exotic vegetation, altering the existing natural habitat and causing impacts on the local native flora and fauna (Colding & Folke, 2009; Tapias & Salgot, 2006).

In the past, designers and constructors of golf courses tended to use exotic tree species, but recent policies on golf course establishment has greatly changed with more respect of the indigenous fauna and flora as well as of other environmental impacts (Tapias & Salgot, 2006). The recent trend in golf course construction is to have four playing-area types (greens and tees, fairways, practice areas, and roughs). The rough area is out-of-play area which occupies a significant proportion of a golf course's area, normally covered by natural bushland and are far less intensely managed. Therefore, the recent trend golf courses are more eco-friendly than the former, three playing-area types which are more intensively used with no rough area (Baris et al, 2010). With sustainable design and management, many golf courses offer suitable habitat conditions for insects, earthworms, amphibians, reptiles, and birds (Tapias & Salgot, 2006). Moreover, the ecological consequences of any golf course construction will depend on the type of land that is lost to development (Hodgkison et al, 2007b). To minimize impacts on natural habitats, Terman (1997) recommended that golf courses be designed that respect nature and can support wildlife, reduce water runoff, irrigation, and chemical inputs. Moreover, improving the habitat quality within a golf course's boundaries to provide suitable habitats for a variety of species can improve biodiversity of the region (Terman, 1997; Threlfall et al, 2015; Zwartjes & Delong, 2005).

### 2.3.2 Ecological values of golf courses

*Golf courses contain significant well-treed areas*

Golf course design often seeks to retain remnant vegetation in the rough areas. Most of these remnants comprise native vegetation which, because of urbanization, have greatly declined in many parts of the world (Colding, 2007; Yasuda & Koike, 2006). They maybe important habitats such as grasslands, heathlands, and natural woodlands which may contain native, valuable, rare and endangered species (Doll & Duinker, 2020; Jim & Chen, 2016; Threlfall et al, 2016b). The well-treed areas in golf courses, together with other green spaces in cities may be the source of degraded remnant vegetation that could be potential sites for offsetting biodiversity (Burgin & Wotherspoon, 2009). It has been suggested that golf courses can become potential hotspots for biodiversity conservation within urban ecosystems (Hunter et al, 2010; Jim & Chen, 2016).

In many golf courses, the vegetation is healthy and has complex structure and healthy. Golf courses often have big trees with a diameter over 50 cm and high concentrations of dead wood, which is a critical component to forest ecosystem dynamics (Doll & Duinker, 2020; Quinton & Duinker, 2018). Big trees with hollows provide important habitats for wildlife (Davis et al, 2014). The structural complexity of understory vegetation is high in golf courses in comparison to other green spaces (Threlfall et al, 2016a). In the irrigated sites, the tree canopy on golf courses is often in better condition than in other urban green spaces (Doll & Duinker, 2020).

However, in some golf courses, vegetation is dominated by exotic plant species (Threlfall et al, 2016a), or it is neglected and invaded by weeds (Burgin & Wotherspoon, 2009). In these cases, the vegetation in rough areas has little conservation values. In some situation, golf course land is covered mostly by turf. Courses comprising non-native species can be viewed as a ‘‘green’’ deserts (Larson & Perrings, 2013). Moreover, dieback of tree canopy within golf courses presents challenges to maintaining ecological integrity in golf courses (Doll & Duinker, 2020). In fact, golf courses are unlikely to be as ecologically valuable as undisturbed natural habitats because they have heavily humanized footprints (Doll & Duinker, 2020). Similarly, golf course managers may put their priority on maintaining vistas rather than preserving a healthy tree canopy (Doll & Duinker, 2020). Therefore, maintaining and improving patches of vegetation within golf courses are always a challenge.

Despite these assertions, the value of well-treed courses as ecologically significant spaces has been well documented over the past two decades (Hodgkison et al, 2007b; Jim & Chen, 2016; Tanner & Gange, 2005; Threlfall et al, 2016a). Therefore, in the pursuit of long-term ecological integrity, improved golf course management is of the utmost importance. Designing naturalistic golf courses with large areas of vegetation and respecting the remnant patches will be important to maintain ecological functions (Tapias & Salgot, 2006; Terman, 1997). Furthermore, there is a need to have regulations for golf courses managers to take actions together with government authorities to maintain remnant vegetation within their golf courses boundaries.

**Table 2. 3 A summary of the outstanding ecological values of golf courses, with recommendations for enhancing benefits**

| Environmental asset | Description | Recommendation | Relevant research |
|---|---|---|---|
| Golf courses contain valuable well-treed area | Golf course design may involve rough areas which comprise remnant vegetation or well-treed areas | 1. Designing naturalistic golf courses with large areas of vegetation that retain remnant patches of local ecosystems<br>2. Establishing regulations for golf course managers to maintain remnant vegetation | Doll & Duinker (2020), Jim & Chen (2016), Ossola et al (2019), Threlfall et al (2016b), Yasuda & Koike (2006) |
| Golf courses provide refugial habitats for wildlife | Golf courses contain a variety of habitats including remnant patches, planted trees, grass, and wetland habitats such as ponds that support a wide range of wildlife | 3. Golf course design should respect natural habits of the existing landscape<br>4. Management practice to enhance habitat quality: e.g. proportion of native vegetation, habitat complexity or diversity<br>5. Regulations for golf course managers to preserve habitats for wildlife | Colding et al (2009), Dair & Schofield (1990), Dale et al (2020), Hodgkison et al (2007b), Tanner & Gange (2005), Threlfall et al (2016a), Wurth et al (2020)<br>And a range of control-case studies listed Table 3. |
| Biodiversity connectivity | Golf courses can contribute to enhancing ecological networks in fragmented urban landscapes | 6. Golf courses should be integrated into urban planning and conservation strategy for better outcomes of conservation in cities | Colding (2007), Dobbs & Potter (2015), Saarikivi et al (2013), Saornil et al (2019), Volenec & Smith (2021) |
| Ecosystem service bundles | Golf courses in urban environment can provide bundles of ecosystem services | 7. Designing golf courses with maximized non-playing areas<br>8. Selecting appropriate grass species for fairways and greens<br>9. Using recycled water for irrigation | Adams (2005), Barnett (2019), Bolund & Hunhammar (1999), Dai et al (2016), Fung & Jim (2017), Rice & Horgan (2011) |

*Golf courses provide refugial habitat for wildlife*

Golf courses contain a variety of habitats including remnant patches of vegetation, planted trees, grass, and wetland habitats such as ponds and these support a wide range of wildlife taxa groups in resource-poor environments of cities (Dair & Schofield, 1990; Hodgkison et al, 2007a; Tanner & Gange, 2005; Wurl, 2019; Wurth et al, 2020). Golf courses even contain a higher diversity relative to adjacent farmland (Tanner & Gange, 2005). However, the refuge value of golf courses is also likely to vary among taxonomic groups with a higher proportion of migrating population such as birds (Terman, 1997) than species having limited mobility such as amphibians and reptiles (Hodgkison et al, 2007c).

Golf courses not only provide a habit for common species, but they sometimes have threatened species (Hodgkison, 2006a; Threlfall et al, 2015). Threatened species include a range of wetland birds, small forest-dependent birds, insects and mammals in American golf courses (Blair, 1996; Blair & Launer, 1997); and marsupials, forest-dependent reptiles and amphibians within Australian golf courses (Colding & Folke, 2009; Colding et al, 2009; Hodgkison et al, 2007c). Some of wildlife species found within Australian golf courses (for example, in Queensland) even may not occur outside golf courses (Colding & Folke, 2009; Colding et al, 2009; Hodgkison et al, 2007b). Golf courses if well managed can increase the species richness over time, and can be potential sites for biodiversity banking offsets (for example in Sydney, New South Wales, Australia) (Burgin & Wotherspoon, 2009).

The refuge value of golf courses is related to the habitat's characteristics including understory and overstorey canopy vegetation, leaf litter, logs and long grass, which benefit bird assemblages (Threlfall et al, 2016a). Scientists recommend that urban landscape managers can improve bird habitats by retaining large hollow trees (Davis et al, 2014), increasing the proportion of native vegetation, and improving habitat complexity or diversity (Dale et al, 2020). Thus, improved golf course design and management practices can aspire to enhancing habitats for biodiversity retention.

*Biodiversity connectivity*

In fragmented urban landscapes, ecological networks are critically important because linkages between patches or stepping stones can support wildlife movement between built-up areas (Dramstad et al, 1996). The Australian, Hong Kong, Canadian and USA golf courses contain significant areas of healthy trees (Doll & Duinker, 2020; Petrosillo et al, 2019; Quinton & Duinker, 2018). However, the question of how vegetation in golf courses are linked to the urban green matrix are not yet formalized. This is a kind of ecological land-use complementation which is not established for conservation purposes but collectively interacting with other green spaces to support biodiversity in a fragmented urban matrix (Colding, 2007). Golf courses contribute significantly to improved gene flow in wildlife populations, especially migratory species, by providing suitable habitats for reproduction and green corridors for dispersal, thus preventing or reducing isolation and loss of genetic variability (Burgin & Wotherspoon, 2009; Dobbs & Potter, 2015; Saarikivi et al, 2013).

*Ecosystem service bundles associated with human well-being*

Urban green spaces have multiple benefits such as storing carbon, serving as habitats for biodiversity, generating shade, increasing humidity through evapotranspiration for alleviating heat and reducing air and noise pollutions that benefits city dwellers health (Declet-Barreto et al, 2013; Scott et al, 2017). Similarly, golf courses in urban environments can provide bundles of ecosystem services, including both ecosystem services and ecosystem dis-services (Dai et al, 2016; Petrosillo et al, 2019). The vegetation in golf courses provides the capacity to reduce soil loss through erosion (Rice & Horgan, 2011), while lakes within golf course have the capacity of flood storage for surrounding areas (Bolund & Hunhammar, 1999; Colding et al, 2009). Besides, golf courses can provide ecosystem goods, with the most important being recreation value as it accounts for over 95% of the total value of ecosystem services in golf courses (Dai et al, 2016).

With a warming climate, "Urban Heat Islands" (UHI) will occur when natural land cover in cities is replaced with dense concentrations of buildings, pavement, and other surfaces that absorb and retain heat (Aram et al, 2020). The UHI effect is a phenomenon in which a significant difference in temperature can be observed between different parts of a city or between a city and its surrounding rural areas, or (O'Malley et al, 2014). UHI is of great concerns because it can cause heat-related illness and mortality and can lead to increased energy costs (e.g., for air conditioning) (Aram et al, 2020). Under the situation of massive urbanization in cities world-wide (Chapter 1), cities increasingly have limited green resources. Therefore, golf courses are expected will play an increasing role as "cool islands" and "natural havens" in cities dominated by building structures and heat-absorbing concrete cover. The cooling effects of golf courses are strongest with woodlands comprising complex multiple-tiered structures which can mitigate UHI effect and climate change impacts (Fung & Jim, 2017; 2019). In addition, large areas of well managed turf are able to absorb and fix carbon (Bartlett & James, 2011). A newly constructed golf course has a technical carbon sequestration capacity of 0.44 Mg C/ha/year (Adams, 2005), some of which accumulates as soil C reserves (Jarzebski & Gasparatos, 2019). However, maintenance practices such as designing golf courses with maximized non-playing areas or selecting appropriate grass species for fairways and greens can render courses from sinks to sources generating the large C emissions (Selhorst, 2011). To maximize the potential environmental benefits of turfgrass systems while increasing the economic efficiency of each site, management practices with low C-intensity should be utilized (Selhorst, 2011).

Furthermore, the management measures for golf course also generate ecosystem dis-services such as water consumption and soil and water pollution, indicated in section 2.3.1 about negatively environmental impacts of golf courses (Bachman et al, 2016; Baris et al, 2010; Bock & Easton, 2020; Carey et al, 2012). However compared to the positive values of ecosystem services, these negative values aree much smaller (Dai et al, 2016). In order to keep the ecosystem services of golf course sustainable, recommendations for golf course design and management include increasing non-playing areas to maximize ecosystem services of golf courses, selecting appropriate grass species and irrigation with recycled water. In addition, improving management efficiency and operation quality are also important (Dai et al, 2016).

### 2.3.3 How significant are golf course ecological values in comparison with other land-use categories?

Although the ecological values of golf courses are widely recognized, consensus regarding these values has not been reached due to conflicting results when comparing golf courses with other land uses. For example, some studies indicate that rough areas covered by natural woodlands within golf course have the biodiversity level equal or even higher than surrounding natural areas (Jim & Chen, 2016; Tanner & Gange, 2005; Threlfall et al, 2016b), but many other showed that golf courses have lower levels of biodiversity than adjacent area (Blair, 1996; Colding & Folke, 2009). This is because the researchers have made conclusions based on individual case studies in specific geographical locations. Thus, findings may not be representative for overall assessment of the role of golf courses with other land uses across different regions. For this reason, a quantitative comparison synthesized from different studies may be particularly useful because it may foster a broadened understanding of golf courses in ecosystem management. Therefore, I reviewed 17 case studies found in the literature from 1996 and 2007 to compare biota on golf courses with other land types and found that golf courses had higher ecological value in 64% of comparative cases (Table 2.4).

**Table 2. 4 Quantitative assessment of ecological values of golf courses in relation to other types of land-use**

| Land use categories to compare with golf courses | Number (%) of comparative studies | | | | Aspects of comparison | Relevant references |
|---|---|---|---|---|---|---|
| | Higher | Lower | Similar/ No difference | Total cases | | |
| Protected areas | | 86% | 14% | 7 | • Flora and fauna diversity<br>• Carbon stocks | Blair (1996); Blair & Launer (1997); Colding et al (2009); Flügel & Rademacher (2020); Jarzebski & Gasparatos (2019); Robert (2008) |
| General natural reference sites | 42% | 16% | 42% | 19 | • Habitat quality and suitability<br>• Flora and fauna diversity<br>• Number of species of conservation concern<br>• Plant health, stage of regeneration | Cristol (2009); Davis et al (2014); Doll & Duinker (2020); Gallo et al (2017); Hodgkison et al (2007b); Jim & Chen (2016); LeClerc et al (2005); Saarikivi et al (2013); Saarikivi et al (2015); Smith et al (2005); Sorace & Visentin (2007); Terman (1997); Threlfall et al (2016a); Winter et al (2002); Yasuda & Koike (2006); Zwartjes & Delong (2005) |
| Agriculture related land uses | 67% | 22% | 11% | 9 | • Habitat quality and suitability<br>• Flora and fauna diversity<br>• Carbon stocks | Ambardar et al (2018); Foley et al (2012); Jarzebski & Gasparatos (2019); LeClerc et al (2005); Saarikivi et al (2015); Stanback & Seifert (2005); Tanner & Gange (2005); Yasuda & Koike (2006) |
| Recreational areas, urban parks, | 45.5% | 45.5% | 9% | 11 | • Habitat quality and suitability<br>• Flora and fauna diversity<br>• Vegetation structure | Blair (1996); (Blair & Launer, 1997; Gallo et al, 2017); Hudson & Bird (2009); Mata et al (2017); Robert (2008); Threlfall et al (2016a); Threlfall et al (2015); Threlfall et al (2016b); Yasuda & Koike (2006) |
| Highly urbanized land uses | 70% | 20% | 10% | 10 | • Habitat quality and suitability<br>• Flora and fauna diversity<br>• Vegetation structure<br>• Carbon stocks | Blair (1996); Blair & Launer (1997); Gallo et al (2017); Jarzebski & Gasparatos (2019); Mata et al (2017); Robert (2008); Threlfall et al (2016a); Threlfall et al (2015); Threlfall et al (2016b) |
| **Total** | **46.4%** | **32.2%** | **21.4%** | **56** | | |

Overall, the ecological values of golf courses are significant with about 46% of the comparative studies indicating that golf courses have higher values, 32.2% cases showing the values of golf courses being similar, and some 20% cases determining ecological values of golf courses being lower than other land uses. However, when it comes to different groups of land uses, the results varied. Golf courses showed lower values compared to protected areas in most of the comparative studies (86%); but were higher or similar to general natural reference sites in most cases; results were mixed when comparing to urban parks with similar proportion of the lower and higher cases; and higher values than the highly urbanized land-use category in most cases (70%). This finding further illustrates the significance of ecological values of golf courses and their roles in biodiversity conservation and ecosystem management.

This variation of ecological values along five land-use groups representing urban gradients indicates that urban expansion requiring the conversion of natural habitats (e.g., forested areas, vegetation remnants, and even agricultural land) into built environments or highly urbanized green spaces can cause a massive depletion of ecological values. Golf courses themselves, whether causing a degradation or making improvement of ecological values once they are constructed, will depend on what types of original habitats they replaced. If golf courses are formed on land of low ecological and biodiversity value, they can enhance the biodiversity through time (Burgin & Wotherspoon, 2009).

The analysis in this chapter also indicated that most of the comparative cases using the measurable indicators that reflects a comparative assessment of ecological values such as flora and fauna diversity, quality of habitats or carbon stock, but may not reflect a comprehensive assessment. For example, when it comes to biodiversity assessment, Gallo et al (2017) found a similar a-diversity, but remarkably dissimilar communities in different urban green spaces, which indicate that different land uses contribute differently, but are collectively important for maintaining and conserving biodiversity in cities. The 70% and 67% values indicate the potential ecological contribution of golf courses that needs to be addressed by both golf courses managers and local authorities in taking conservation actions. This is critical in fragmented environments of cities where protected areas are limited with high costs to maintain them. Hence, golf courses and other green spaces within urban boundaries are willing stewards having potential role in the conservation of biodiversity and ecosystem management (Colding, 2007).

### 2.3.4 Research gaps and recommendations for future research

First, there is a notable geographical bias in golf course studies. I found that the environmental research interest in golf courses lies mainly in the developed world with the USA accounting for more than half of the publications. Two other single countries with significant research in golf courses are Australia (35 articles) and Canada (22 articles). There are 85 publications in European countries and 26 in Asian countries (Figure 2.3).

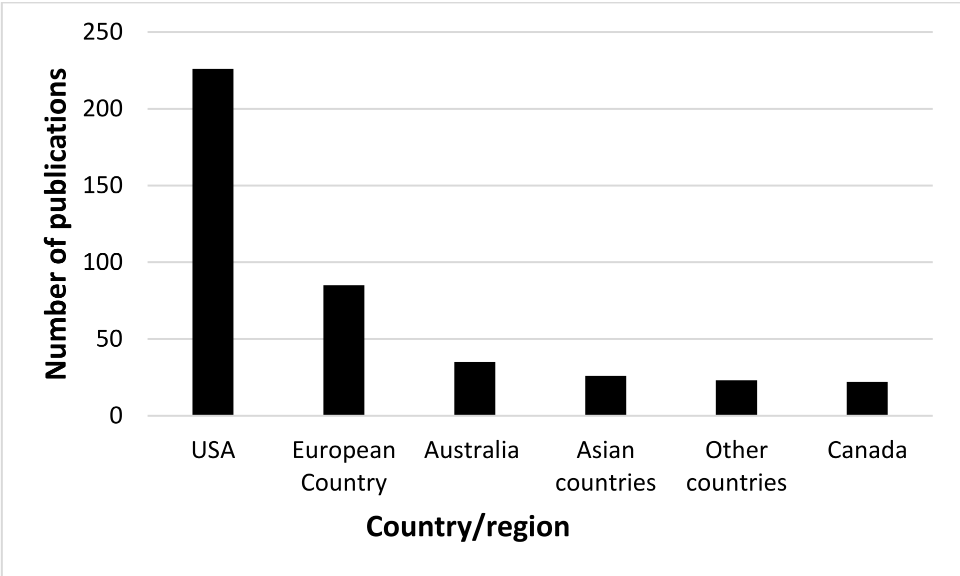


**Figure 2. 3 Number of articles dealing with the topic ''golf courses'' by geographical location**

Even within a country, the research interest of golf course is often localized to specific state or region. For example, in Australia, most golf course studies are in Victoria, New South Wales and Queensland, and there are no studies in Western Australia which accounts for 14% of the country's golf (The R&A, 2019). This limitation may lead to a bias in assessing the ecological roles of golf courses. Additional research needs to be carried in different regions including the developing world where the management practices golf courses may be different to the developed world.

Second, the review found that most of the research interests focused on two sides of the golf course's ecology, including the negatively environmental impacts of golf courses as well as the ecological benefits of golf courses (similar numbers of approximately 140 publications). Also, the number of publications about the policy and management practices and the human well-being aspects are smaller (Figure 2.4A**)**. Therefore, in the changing climate time when cities become the hottest places in the world, more studies on the ecological role of golf courses in providing ecosystem services such as reducing urban heat should be carried out to provide lenses for better urban planning. Regarding the ecological values research, most of them focus on biodiversity conservation value (120 publications). Very little research (less than 20 publications) analyzes the ecosystems services that golf course can provide such as the role of golf courses in cooling and improving the microclimate in cities (Table 2.4B).

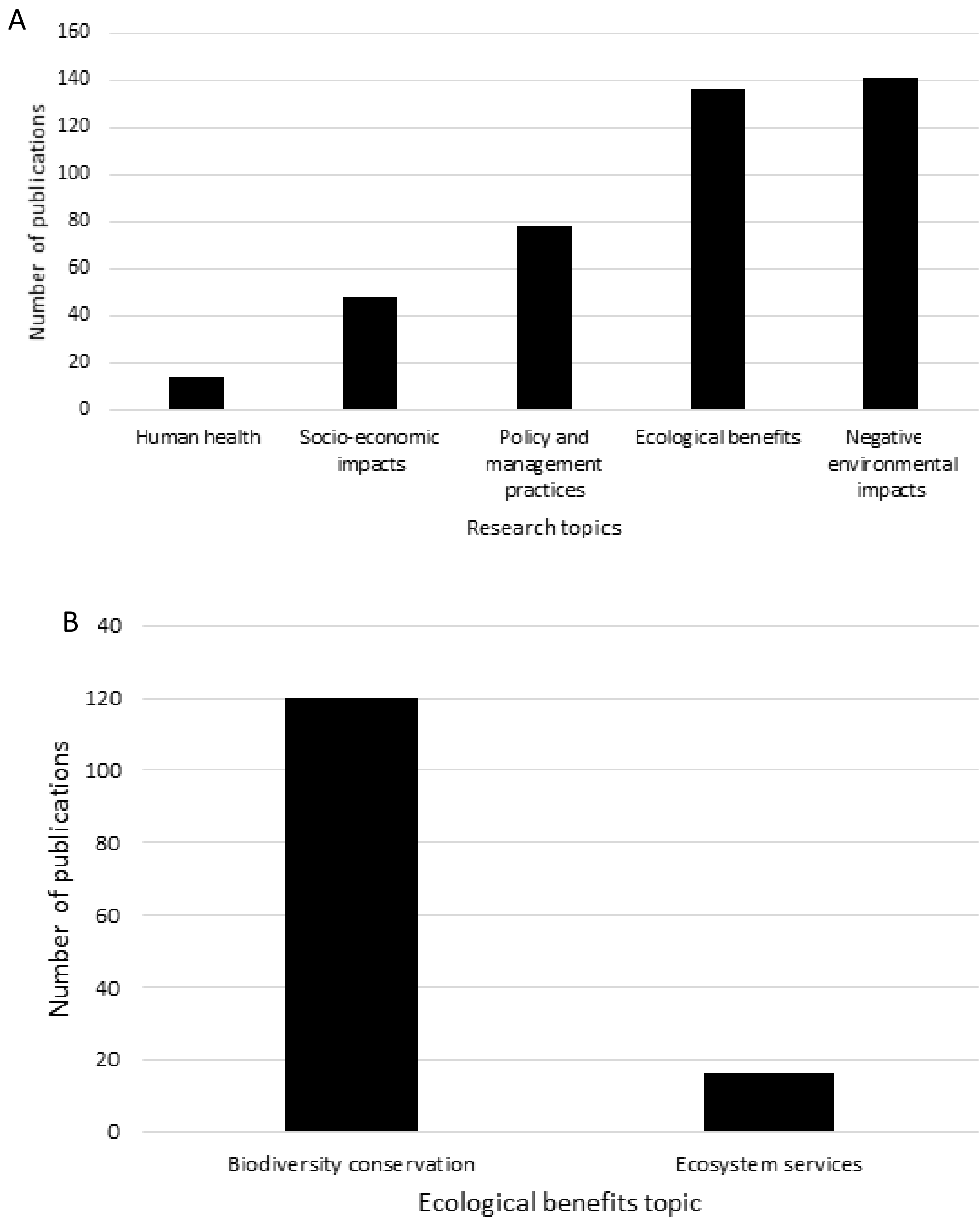


**Figure 2. 4 A – Number of publications across the main search topics; B – Number of publications in sub-topics of the theme ecological benefits of golf courses**

Third, the current literature underscores the limited knowledge of ecological values of golf courses at the landscape scale. Most studies have been carried out at fine scales, investigating the conservation values of some specific golf courses at specific locations. Therefore, understanding of the broader ecological values of golf courses across urban matrix and urban gradients should be improved. This should include vegetation condition, biodiversity connectivity, spatial configuration.

Fourth, we lack information about the effects of golf courses on the ecological processes resulting from land conversion and golf course management practices. Understanding of changing in ecological values of long-time operation of golf courses compared to the original land-uses that they replaced across different management regimes will provide lessons for management to improve the ecological contribution of golf courses. Research is also required to determine if improved golf course design and management practices can enhance golf course values

## 2.4 Conclusions

This review highlights the different environmental impacts and ecological values associated with golf course. Although golf courses are established for commercial and social purposes, they have raised environmental concerns but undoubtedly played important roles in maintaining biodiversity and other ecosystem services in urban landscape. Though they are not point of protected area networks, they can complement other green spaces and collectively contribute to enhancing the urban forests. The degrees to which golf courses can damage or benefit the environment depends on management regimes. Potentially, golf courses in cities could become more purposefully managed for conservation of biodiversity conservation and the improvement of ecosystem services. Therefore, the government authorities should collaborate with golf course managers to propose best management practices to enhance the ecological values of golf courses. Further research can help define the parameter for golf course in future green cities. This will entail different parts of the world, at the landscape scale, exploring ecosystem services and the ecological processes as the result of land conversion and golf course management practices.

# Chapter 3 Vegetation trends associated with urban development: the role of golf courses[1]


## Abstract

Globally, cities are growing rapidly in size and density, and this has caused profound impacts on urban forest ecosystems. Urbanization requiring deforestation reduces ecosystem services that benefit both city dwellers and biodiversity. Understanding spatial and temporal patterns of vegetation changes associated with urbanization is thus a vital component of future sustainable urban development. We used Landsat time series data for three decades from 1988 to 2018 to characterize changes in vegetation cover and habitat connectivity in the Perth Metropolitan Region, in a rapidly urbanizing Australian biodiversity hotspot, as a case study to understand the impacts of urbanization on urban forests. Moreover, as golf courses are a major component in urban areas, we assessed the role of golf courses in maintaining vegetation cover and creating habitat connectivity. To do this we employed (1) land use classification with post-classification change detection, and (2) Morphological Spatial Pattern Analysis (MSPA). Over 17,000 ha of vegetation were cleared and the area of vegetation contributing to biodiversity connectivity was reduced significantly over the three decades. The spatial patterns of vegetation loss and gain were different in each of the three decades (1988-2018) reflecting the implementation of urban planning. Furthermore, MSPA analysis showed that the reduction in vegetation cover led to habitat fragmentation with a significant decrease in the *Core* and *Bridge* classes and an increase in isolated patches in the urban landscape. Golf courses played a useful role in maintaining vegetation cover and contributing to connectivity in a regional biodiversity hotspot. Our findings suggest that for future urban expansion, urban planning needs to more carefully consider the impacts of deforestation on connectivity in the landscape. Moreover, there is a need to take into consideration opportunities for off-reserve conservation in smaller habitat fragments such as in golf courses in sustainable urban management.


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## 3.1 Introduction

Globally, cities have grown rapidly in number and size over recent decades (Bagan & Yamagata, 2014; Tabea & Eva, 2015). This trend is predicted to continue as urban areas are expected to absorb most global population growth (United Nations Department of Economic and Social Affairs UNDESA, 2012). While the process of urbanization presents key implications for changes in physical landscapes and demographic characteristics, it can cause profound impacts on environmental components, especially on urban forest ecosystems (Gaston et al, 2013; McGrane, 2016).

Vegetation in urban landscapes is critically important because it provides goods and services, and full ecosystem functions that benefit city dwellers and the environment. On the one hand, a remarkable range of human well-being benefits are derived from urban green spaces including mitigating the urban heat island (UHI) effect (Declet-Barreto et al, 2013; Scott et al, 2017), reducing stress (Van Den Berg & Custers, 2011), improving healing times (Ulrich, 1984), increasing self-esteem and empowerment (Jane, 2009), and improving cognitive ability (Lee et al, 2015b). On the other hand, urban green spaces provide various ecosystem services such as strengthening resistance to some kinds of natural disasters for example, floods (Kim, 2016), promoting biological processes such as pollination (Zitkovic, 2008), and reducing surface erosion from stormwater runoff (Seitz & Escobedo, 2014). The amount of vegetation in cities strongly influences biodiversity, especially where vegetation is set aside during the process of urbanization (Bailey et al, 2010). However, if species dispersal and exchange among these patches is insufficient to allow gene flow and diversity, loss of regional biodiversity is inevitable (Yu et al, 2015). Therefore, urban development that requires deforestation, with habitat loss and fragmentation is a threat to biodiversity (Bailey et al, 2010; Bierwagen, 2007).

Urban conservation strategies must therefore consider not only the size and quality of habitat reserves, but the connectivity in the intervening urban vegetation matrix (Bierwagen, 2007). While the need to protect large habitat reserves is obvious, opportunities for off-reserve conservation of smaller habitat fragments should not be overlooked (Lindenmayer & Franklin, 2002). Understanding spatial and temporal patterns of vegetation change associated with urbanization, as well as opportunities for the preservation of green spaces outside natural reserves, is vital for future sustainable urban development especially in areas of global ecological importance (Chapter 2).

As the number of golf courses is rapidly increasing in many urban areas worldwide (Napton & Laingen, 2008), there have been many environmental arguments about this green space category in urban landscapes. Golf courses are sometime considered to be major polluters of the environment through pesticide and fertilizer use (Carlos & Duvan, 2014). In fact, golf courses have been established for recreational purposes, which are a mix of bushland, fairways and infrastructure. Though they are not fully ecologically functional as natural parks, previous studies investigating the condition of vegetation inside golf courses indicated that the bushland in non-playing areas of golf courses is important to biodiversity conservation and the provision of ecosystem services in cities (Hodgkison et al, 2007b), such as providing refuge habitats for urban-avoiding wildlife (Colding & Folke, 2009; Puglis & Boone, 2012; Terman, 1997). Therefore, potentially, together with natural reserves, golf courses can play some roles as off-reserve sites for purposeful biodiversity conservation in urban landscapes. Nevertheless, little research has been undertaken to comprehensively assess the role of golf courses in maintaining vegetation patches as interconnected nodes in urban landscapes during a long period of urban development where deforestation is significant (Chapter 2).

Deforestation for urban expansion can occur gradually over multiple years. Satellite-based remote sensing holds certain advantages in the characterization of these changes in urban landscapes because of the large spatial coverage, high time resolution, and wide availability of data (Theobald, 2014). Many methods have been used to detect, monitor and quantify vegetation changes, but differences in vegetation index and land use classification are the most widely used methods for vegetation changes over a long period of time (Hu et al, 2016).

A great number of vegetation indices have been proposed, ranging from very simple to very complex band combinations (Li et al, 2015). The most widely-used vegetation index is the Normalized Difference Vegetation Index (NDVI), which is an efficient and simple metric to identify vegetated areas and their condition (Tucker, 1979). This separates green vegetation from other surfaces based on the differential absorption of red light by chlorophyll and reflection of NIR by green vegetation (Myneni et al, 1995). Furthermore, information on vegetation cover dynamics can be combined with Morphological Spatial Pattern Analysis (MSPA) to describe the spatial configuration of the ecosystem at the pixel level, making it possible to detect temporal changes in the structural connectivity of habitats in urban settings (Vogt et al, 2007).

Therefore, to enhance the understanding of vegetation dynamics associated with urbanization and the role of golf courses in maintaining urban vegetation, we used Landsat imagery to map vegetation cover and to assess its spatial and temporal distribution over three decades from 1988 to 2018. Maps of vegetation cover were used for MSPA analysis to detect changes in habitat connectivity. We chose the Perth Metropolitan Region for the study as it lies within a rapidly urbanizing biodiversity hotspot in Australia. The three primary research objectives were to: (1) determine the spatial and temporal patterns of deforestation in urbanization; (2) evaluate the spatial and temporal patterns of green landscape connectivity; and (3) assess the role of golf courses in preserving green spaces and biodiversity in an urban landscape. This analysis will provide a useful perspective on the land-use pressure facing vegetation remnants in this region which is recognized as one of 35 international biodiversity hotspots with over 1,500 plant species with a high degree of endemism (Myers et al, 2000).

## 3.2 Methods

### 3.2.1 Study area

The study area belongs to the Perth Metropolitan Region covering four sub-regions (Northwest, Middle Central, Inner Central and Southwest). Perth has a Mediterranean-type temperate climate with a hot and dry summer (December to March), and a cold and rainy season occurring between May and October (Kottek et al, 2006). Under future climate-change scenarios, this area is projected to experience a lower annual rainfall (Hope et al, 2006).

Perth belongs to Australia's southwest corner, which is recognized as a global biodiversity "hotspot" with outstanding natural environments. Our study area occurs on the Swan Coastal Plain which is part of the southwest of Australia which in turn has the highest concentration of rare and endangered species on the entire continent (at least 1,500 endemic species). More than 6,000 species of native plants and 100 native mammals, birds, frogs and reptiles occur in this region, making it a biodiversity "hotspot" (Mittermeier et al, 2004; Myers et al, 2000).

Perth has retained a significant area of natural vegetation, which has conservation significance thanks to the introduction of legislation and policies aimed primarily at protecting biophysical environmental values. This includes the Western Australian Environmental Protection Act 1986 (Government of Western Australia, 1986); the Federal Government’s Environment Protection and Biodiversity Conservation Act 1999 (The Australian Government, 1999); and more recently, Bush Forever (Government of Western Australia, 2000a; 2000b), a policy which took a whole-of-government approach to identify and protect biologically significant bushland and wetlands within the Perth Metropolitan Region . However, Perth has experienced extensive urban development since the 1980s (Subas, 2014). The expansive growth of the Perth

Metropolitan footprint has contributed to the loss of biodiversity, together with the ecosystem services provided by natural areas. Together with urbanization, the golf industry has expanded contributing to a growing proportion of Perth's urban green space with 34 golf courses in the study area (Figure 3.1).

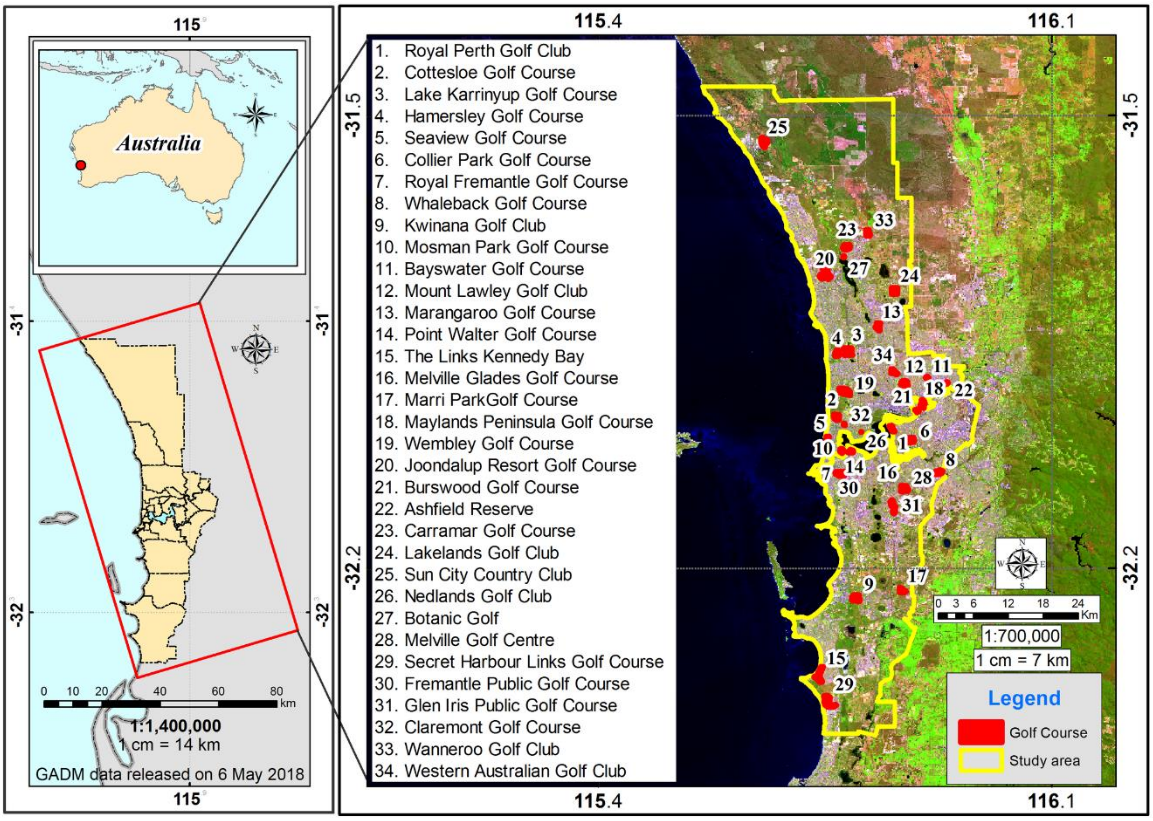


**Figure 3. 1 Location of the study area in Perth, south-western Australia (note that the land-use map is detailed in Figure 4.1). The satellite image was obtained from Landsat 8 on 30 September 2018 from the public domain: http://eros.usgs.gov of the Earth Resources Observatory and Science (EROS) Center. Location of golf courses are shown.**

### 3.2.2 Approaches

We conducted two types of analyses in this study: (1) assessment of vegetation cover change in golf courses since 1988 relative to surrounding areas to provide a broad overall context of the urban vegetation changes that have taken place throughout the region and the role of golf courses; and (2) assessment of MSPA. In these analyses, we used four data sets (1988, 1998, 2008, 2018) covering thirty years of urban development. The steps taken in this study are summarized in a flow chart (Figure 3.2).

*Landsat data and pre-processing*

Three Landsat 5 Thematic Mapper images (WRS path 113 row 82) were acquired from 1988 to 2008 and one Landsat OLI 8 (WRS path 113 row 82) was acquired in 2018 at four time steps, including year 1988 ($11^{th}$ December), year 1998 ($7^{th}$ December), year 2008 ($18^{th}$ December), and year 2018 ($14^{th}$ December). The Landsat imagery were obtained from the US Geological Survey (USGS) of the Earth Resources Observation and Science Center (EROS). Image dates were selected acquired during December (summer, dry season) to reduce the seasonal difference effects. All images selected are cloud-free scenes or low cloud cover (0.05% and 0.4%) scenes where the whole study area is cloud-free; therefore, there was no requirement for removing cloud cover. Georeferencing was performed at the USGS prior to downloading the data (L1T level of systematic geometric accuracy) and no further refinement was undertaken. Atmospheric and topographic corrections were performed on the Landsat data sets. The atmospheric correction was carried out to adjust the multitemporal dataset to a common radiometric scale (Song et al, 2001).

The first process of atmospheric correction was conversion of the digital number (DN) remote sensing data values to at-sensor radiance based on the image header file. After that we employed the image-based models - dark object subtraction (DOS) to correct atmospheric scattering scene-by-scene. This method is a widely used and effective method in atmospheric correction (Cui et al, 2014; Dewi & Trisakti, 2017; Gilmore et al, 2015; Lu et al, 2002; Mohajane et al, 2018; Nazeer & Nichol, 2014; Yusuf et al, 2018). Topographic correction was conducted to remove topographic effects. We used a sun-canopy-sensor (SCS) correction based on the 30 m digital elevation model (DEM) because topographic shading is not only due to slope but also to shadowing of one tree crown over another and this is one of the most widely and effective used methods of topographic correction (Gu & Gillespie, 1998).

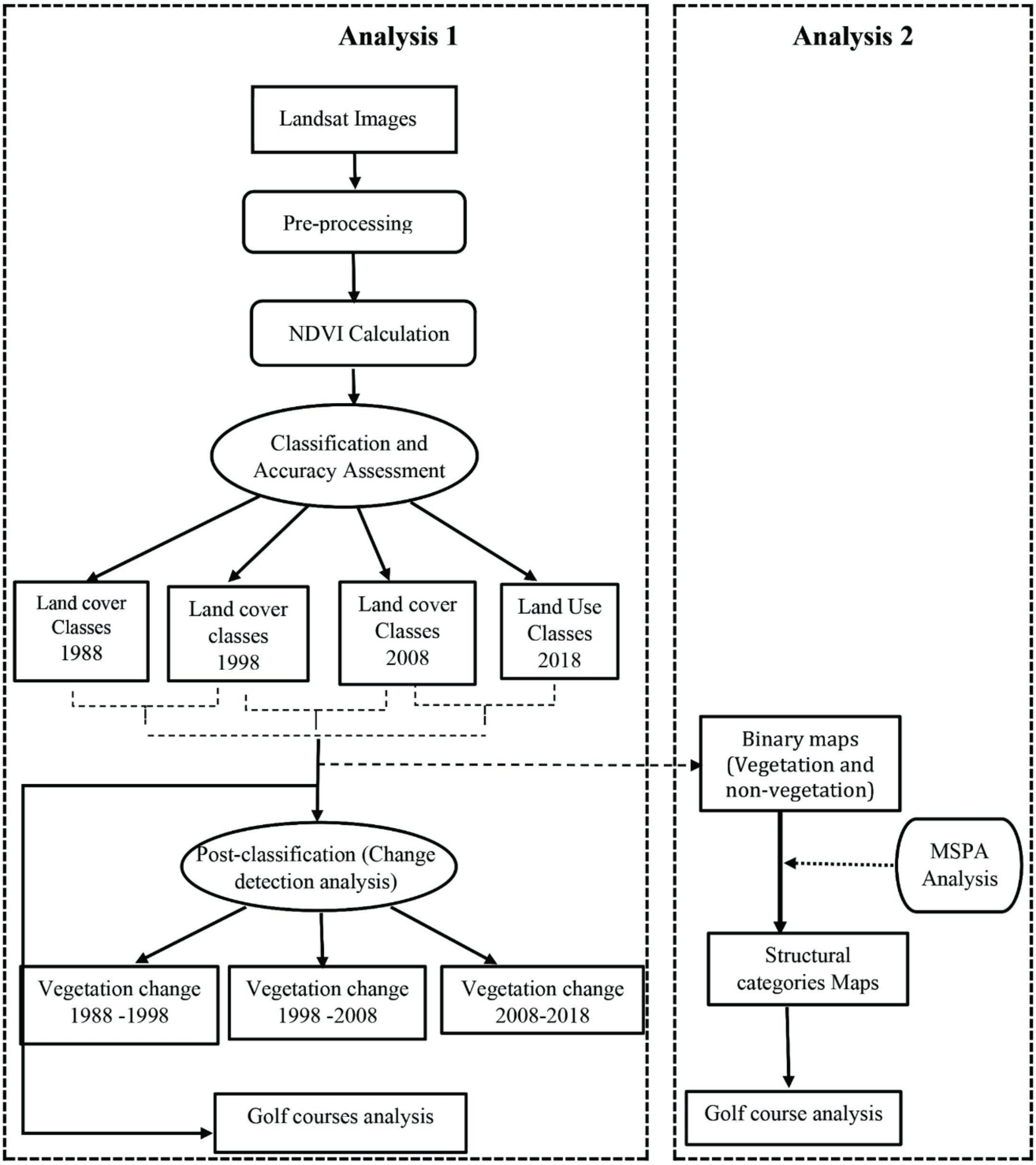


**Figure 3. 2 Flow chart summarizing the major steps taken during the investigation**

*Classification*

In a preliminary step, we used a decorrelation stretch to enhance the image for more effective visualization. Prior to image classification, NDVI images were generated. A classification technique was then applied to the NDVI images of 1988, 1998, 2008 and 2018 using Arc-GIS 10.3 software. NDVI images were obtained by calculating the ratio between the red (R) and near infrared (NIR) values of the satellite image using Equation 1:

$$\text{NDVI} = \frac{(\text{NIR}-\text{R})}{(\text{NIR}+\text{R})} \qquad (1)$$

In Landsat 4-7, NDVI = (Band 4 – Band 3) / (Band 4 + Band 3).

In Landsat 8, NDVI = (Band 5 – Band 4) / (Band 5 + Band 4).

Landsat TM data from different dates were independently classified based on the NDVI values. Water bodies have negative NDVI values, whereas bare soil and built-up areas have an NDVI value of around zero. Chlorophyll in green vegetation, on the other hand, absorbs RED to drive photosynthesis thereby providing moderate and high NDVI values close to +1 (John & David, 2000). Based on this understanding, the four NDVI images were classified into three classes (Vegetation, Built-up + bare soil, Water bodies) using the NDVI threshold ranges technique in Arc-GIS 10.3 software.

The classification based on NDVI threshold was evaluated using accuracy assessment. An error matrix compared information from a classified image or land cover map to known reference (truth) sites for a number of sample points assessed in 2018. We obtained photographs of representative land use categories with GPS locations to assist in our image interpretations. Also, we used Google Earth images, true and false color combination images and knowledge-based information including expert knowledge, land use maps and reports. For historical images, Google Earth was used to substitute the traditional reference data collection on each of the sites (Cha & Park, 2007). Based on data of accuracy assessment, we reclassified the preliminary land use classification maps to improve the accuracy of classification.

*Vegetation change detection*

In order to detect the vegetation cover change, we created binary maps of vegetation and non-vegetation from the classified maps in the previous analysis, one for each adjacent pair of time steps, which depict where degradation occurred within a decade of urbanization. This post-classification analysis uses two images from different dates and classifies them independently. We then calculated changes in vegetation cover type using Equation 2:

$$\text{Change area} = D_2 - D_1 \qquad (2)$$

where D1 and D2 are the area of the target vegetation cover at the beginning and the end of the study period, respectively. This analysis allows the calculation of vegetation loss and gain in each period.

*Golf courses Analysis 1*

We compared the vegetation cover, and the change (vegetation loss and gain) taking place within all golf courses in the study area, and in their surrounding regions. After creating the GIS boundaries of the golf courses, we extracted the vegetation cover and the vegetation change within these boundaries at four-time steps in 1988, 1998, 2008 and 2018 to compare vegetation dynamics within the golf courses and the whole study area over time.

*Morphological Spatial Pattern Analysis (MSPA) for the structural connectivity of habitats*

MSPA was employed to describe the structural connectivity of habitats in Perth for four-time steps in 1988, 1998, 2008 and 2018. This method describes the spatial and temporal configuration of the ecosystem at the pixel level (Vogt et al, 2007), which was based on the concept of "habitat availability" and "graphic theory" (Pascual-Hortal & Saura, 2006; Saornil et al, 2019) in which the landscape is considered as a collection of nodes, and links with a node is a place where connectivity exists and will depend on the width of itself. The output of the MSPA analysis includes the seven structural categories into which habitats are divided, including *Core*, *Edge*, *Perforation*, *Bridge*, *Loop*, *Branch* and *Islet* (Wickham et al, 2010) and (Shi & Qin, 2018) and is summarized in Table 3.1.

**Table 3. 1 Definition of Morphological Spatial Pattern Analysis (MSPA) classes**

| Class | Description | Ecological meaning |
|---|---|---|
| *Core* | A collection of foreground pixels which are interconnected and greater than the user-specified *Edge* width from background | Large-scale natural patches with high connectivity |
| *Edge* | Transition pixels between the foreground and background that form the outer *Edge* | The transition zone between vegetation and non-vegetation areas. |
| *Perforation* | The transition pixels between foreground and background inside *Core* areas that form the inner *Edge* | Unnatural patch inside the *Core* area. |
| *Bridge* | A set of linear foreground pixels between two *Cores* that connect two or more *Core* areas. | The striped ecological land that connects two *Cores*, which is equivalent to the connecting corridor of the green space network. |
| *Loop* | Linearly oriented foreground pixels extended from *Core* that connects *Core* area to itself. | Connecting corridor inside a large natural patch. |
| *Branch* | Linearly oriented foreground pixels extended from *Core* that do not connect to any other *Core* area | Striped ecological land with low connectivity. |

| Class | Description | Ecological meaning |
|---|---|---|
| *Islet* | A collection of foreground pixels which is smaller than the *Core* zone and do not connect to any other foreground cells. | Small natural patches that are isolated and do not connect to each other. |

In order to undertake the MSPA analysis, we defined the input data (foreground class). For this study, we used the classified maps for 1988, 1998, 2008, 2018 in Analysis 1 to create the binary maps which contained vegetation and non-vegetation classes. Hence, the high and full covered vegetation pixels were defined as the foreground pixels (green landscape) in the MSPA approach. The results of MSPA analysis for the four-time steps allowed us to assess the changes in habitat connectivity through time associated with urbanization.

*Golf course analysis 2*

To assess the role of golf courses in maintaining biodiversity connectivity over 30 years, we compared the habitat connectivity within all golf courses in the study area and in their surrounding green spaces. Using the GIS boundaries of the golf courses, we extracted the habitat connectivity within the golf course boundaries for four time steps (1988, 1998, 2008 and 2018).

## 3.3 Results

### 3.3.1 Land use classification in Perth

Data sets representing four time periods (1988, 1998, 2008 and 2018) are shown in Figure 3.3, Figure 3.4 and Table 3.3, which provide an overview of the land cover changes (vegetation, built up and bare land, water bodies) over recent decades. From the 1988 and 1998 data sets, it is evident that over half of the region was vegetated. However, the urban footprint of built up and bare land area had increased 10% from 1998 to 2018. As a consequence, there was a significant decrease in vegetation cover, which comprised 56% of the land surface in 1988 and declined by 10.1% over the next 30 years (Table 3.2).

**Table 3. 2 Land cover classification within the Perth Metropolitan Region**

| | | Land cover category | | | | | |
|---|---|---|---|---|---|---|---|
| | | Whole area | | | Golf course | | |
| | | Vegetation | Built up and bare soil | Water bodies | Vegetation | Built up and bare soil | Water bodies |
| 1988 | Area (ha) | 98,446 | 74,376 | 2,667 | 929 | 210 | 0.1 |
| | Proportion (%) | 56.1 | 42.4 | 1.5 | 81.5 | 18.5 | 0.0 |
| 1998 | Area (ha) | 91,754 | 81,464 | 2,271 | 1,042 | 97 | 0.7 |
| | Proportion (%) | 52.3 | 46.4 | 1.3 | 91.4 | 8.5 | 0.1 |
| 2008 | Area (ha) | 88,341 | 84,971 | 2,176 | 1,084 | 55 | 0.2 |
| | Proportion (%) | 50.3 | 48.4 | 1.2 | 95.1 | 4.9 | 0.0 |
| 2018 | Area (ha) | 80,755 | 92,243 | 2,491 | 1,093 | 46 | 0.7 |
| | Proportion (%) | 46.0 | 52.6 | 1.4 | 95.9 | 4 | 0.1 |

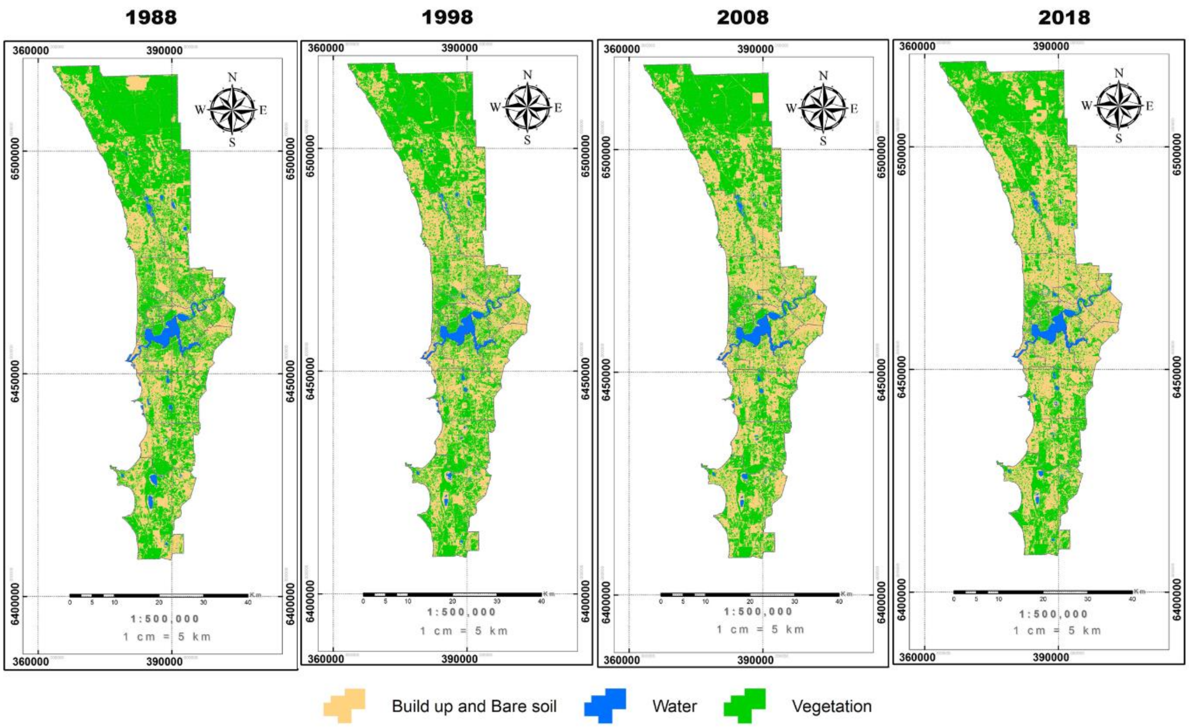


**Figure 3. 3 Map of land cover classification for Perth in four-time steps between 1988 and 2018. The three classes of land cover shown are vegetation, water, and build up and bare soil**

The analysis had the overall accuracy (OA) of classification from 87% and the kappa coefficient from 91% for the three classes (Table 3.3).

**Table 3. 3 Accuracy assessment of land cover maps generated**

| Year 1988 | | | | |
|---|---|---|---|---|
| LULC Class | Vegetation | Build Up and Bare Soil | Water Bodies | Total |
| Vegetation | 14 | 1 | 0 | 15 |
| Build Up and Bare Soil | 1 | 12 | 2 | 15 |
| Water Bodies | 0 | 0 | 15 | 15 |
| Total | 15 | 13 | 17 | 45 |
| | | Overall Accuracy | 87% | |
| | | Overall Kappa | 0.91 | |
| **Year 1998** | | | | |
| LULC Class | Vegetation | Build Up and Bare Soil | Water Bodies | Total |
| Vegetation | 15 | 0 | 0 | 15 |
| Build Up and Bare Soil | 0 | 13 | 2 | 15 |
| Water Bodies | 1 | 0 | 14 | 15 |
| Total | 16 | 13 | 16 | 45 |
| | | Overall Accuracy | 90% | |
| | | Overall Kappa | 0.93 | |
| **Year 2008** | | | | |
| LULC Class | Vegetation | Build Up and Bare Soil | Water Bodies | Total |
| Vegetation | 14 | 1 | 0 | 15 |
| Build Up and Bare Soil | 1 | 14 | 0 | 15 |
| Water Bodies | 0 | 0 | 15 | 15 |
| Total | 15 | 15 | 15 | 45 |
| | | Overall Accuracy | 93% | |
| | | Overall Kappa | 0.96 | |
| **Year 2018** | | | | |
| LULC Class | Vegetation | Build Up and Bare Soil | Water Bodies | Total |
| Vegetation | 15 | 0 | 0 | 15 |
| Build Up and Bare Soil | 0 | 13 | 2 | 15 |
| Water Bodies | 1 | 1 | 13 | 15 |
| Total | 16 | 14 | 15 | 45 |
| | | Overall Accuracy | 87% | |
| | | Overall Kappa | 0.91 | |

Using the GIS layer of land use categories, we also extracted the data for three classes within the golf courses in comparison with the whole area (Table 3.2). Our analysis shows that while there was a significant decrease in vegetation cover throughout the region, the total area of golf courses remained unchanged at around 1,093 ha over the last 30 years.

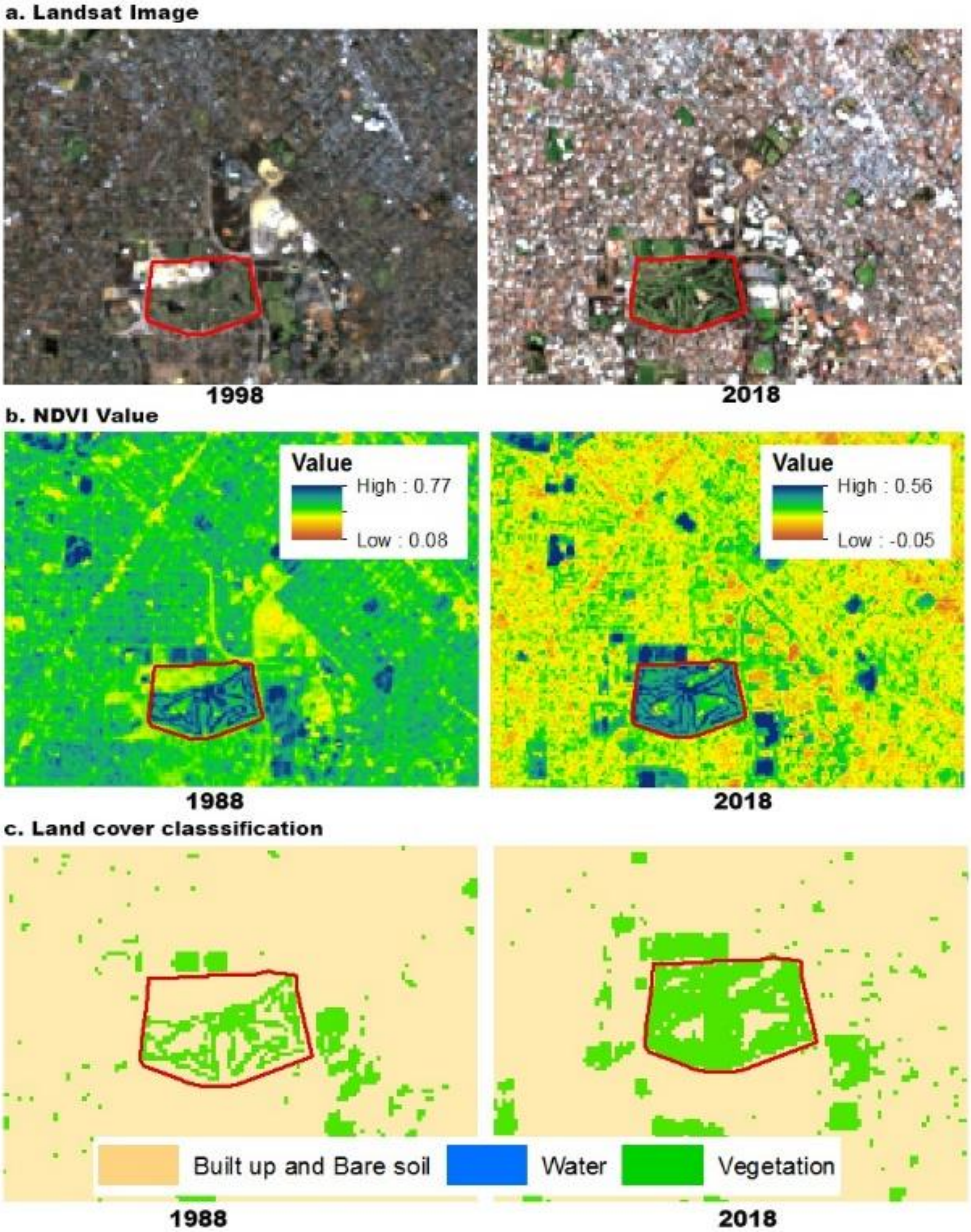


**Figure 3. 4 Land cover classification showing a detailed view of the Collier Park Golf Course for Landsat image (a), NDVI values (b), and Land cover classification (c)**

### 3.3.2 Spatial patterns of vegetation change

To characterize spatial patterns of vegetation dynamics, we detected the vegetation loss and gain for each of the three decades (Figure 3.5). In the period 1988 to 1998, deforestation occurred intensively in the central and north regions. From 1998 to 2008, vegetation loss expanded to the north and south of the city. However, in the last decade from 2008 to 2018, vegetation loss accelerated in the distal regions with urbanization. However, there was also some vegetation gain over the three decades (Figure 3.5, Table 3.4) predominantly in the northern part of the city.

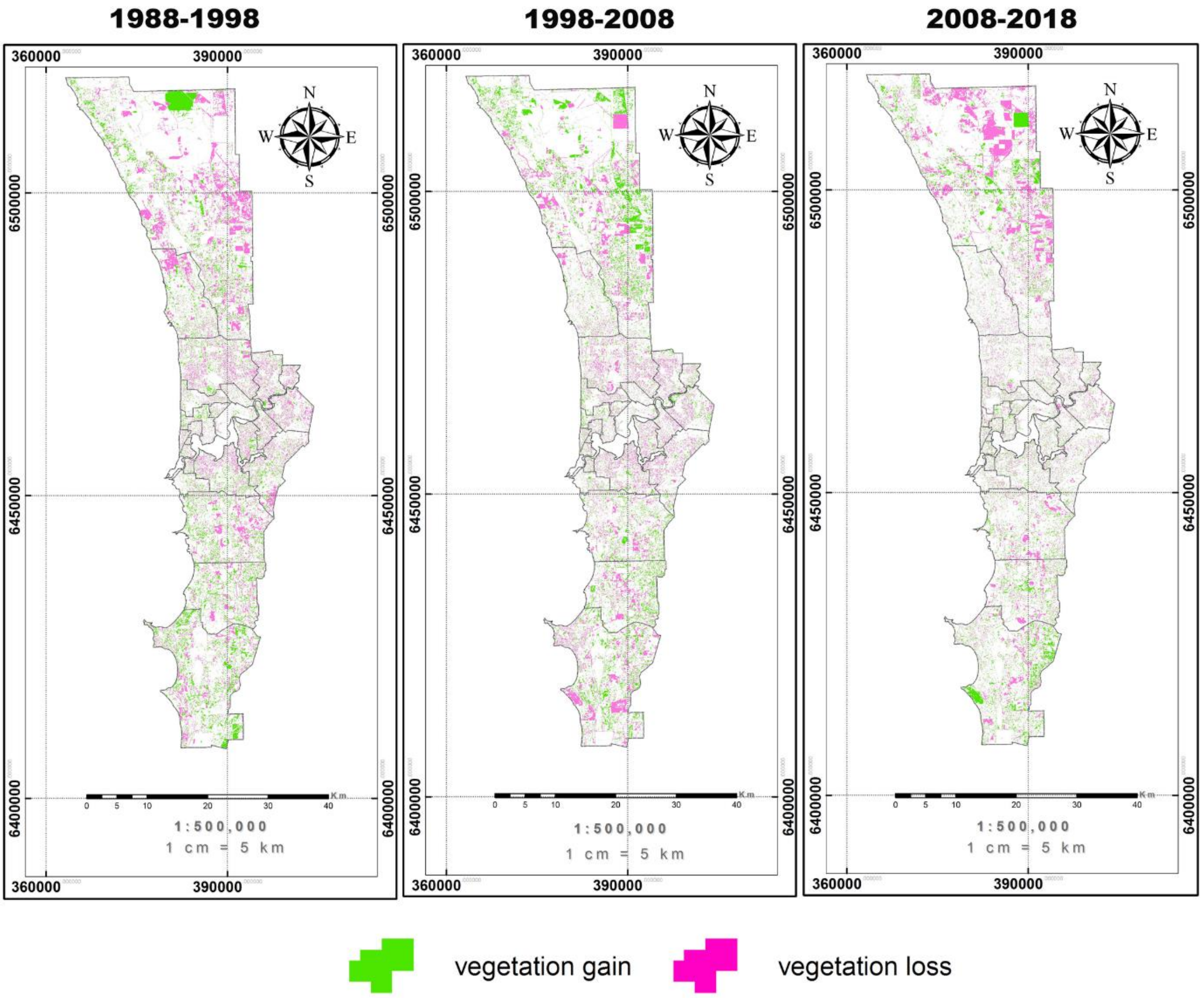


**Figure 3. 5 Change in vegetation cover over the period 1988 to 2018 for the Perth region. Vegetation gain and vegetation loss are indicated**

**Table 3. 4 Vegetation loss and gain (ha) between 1988 and 2018**

| | | **Period** | | |
|---|---|---|---|---|
| | | **1988-1998** | **1998-2008** | **2008-2018** |
| Whole Area | Vegetation loss | 22,231 | 19,250 | 20,178 |
| | Vegetation gain | 15,538 | 15,838 | 12,591 |
| | Net loss | 6,692 | 3,412 | 7,587 |
| Golf courses | Vegetation loss | 68 | 27 | 40 |
| | Vegetation gain | 219 | 92 | 43 |
| | Net gain | 152 | 64 | 4 |

Calculation of changes within the golf courses and in the whole area (Table 3.4) showed that the major urban area of Perth experienced a net loss in vegetation cover. Though vegetation compensation occurred together with deforestation over 30 years of urbanization, the vegetation loss was always much larger than vegetation gain with the largest net vegetation loss occurring in the last decade. However, the golf courses showed a different trend where the net gain of vegetation cover happened over three decades, and the largest gain was between 1988 and 1998.

### 3.3.3 Analysis of connectivity components of green space networks

Results of the MSPA analysis indicate that the reduction in vegetation cover over the last thirty years has led to a decline in connectivity (Table 3.5). Among the two MSPA classes that are important for connectivity (*Core* and *Bridge*), the total area of *Core* class decreased by about 10% over three decades while the *Bridge* class was maintained at around 37,000 ha, but the proportion of this class per total vegetation cover area (VCA) increased due to the reduction of vegetation cover over time (Table 3.5).This analysis also shows the fluctuation in the areas of the rest of the MSPA classes including *Islets*, *Loops*, *Edges*, *Perforations*, and *Branch*es which do not contribute to connectivity in the landscape. The proportion of these classes increased through time from 24% in 1988 to 30% in 2008 and 2018.

Figure 3.6 shows that the *Core* area was distributed mostly in the northern part of the city and their areas decreased significantly in later years. In 1988, the *Bridge* class covered a large area of the city's central region but this decreased over time. In recent years, most of the vegetation cover in the central region of the city belongs to the *Islet*, *Loop*, *Edge*, *Perforation* and *Branch* classes, illustrating that isolation became more serious in the central region of the city over the three decades.

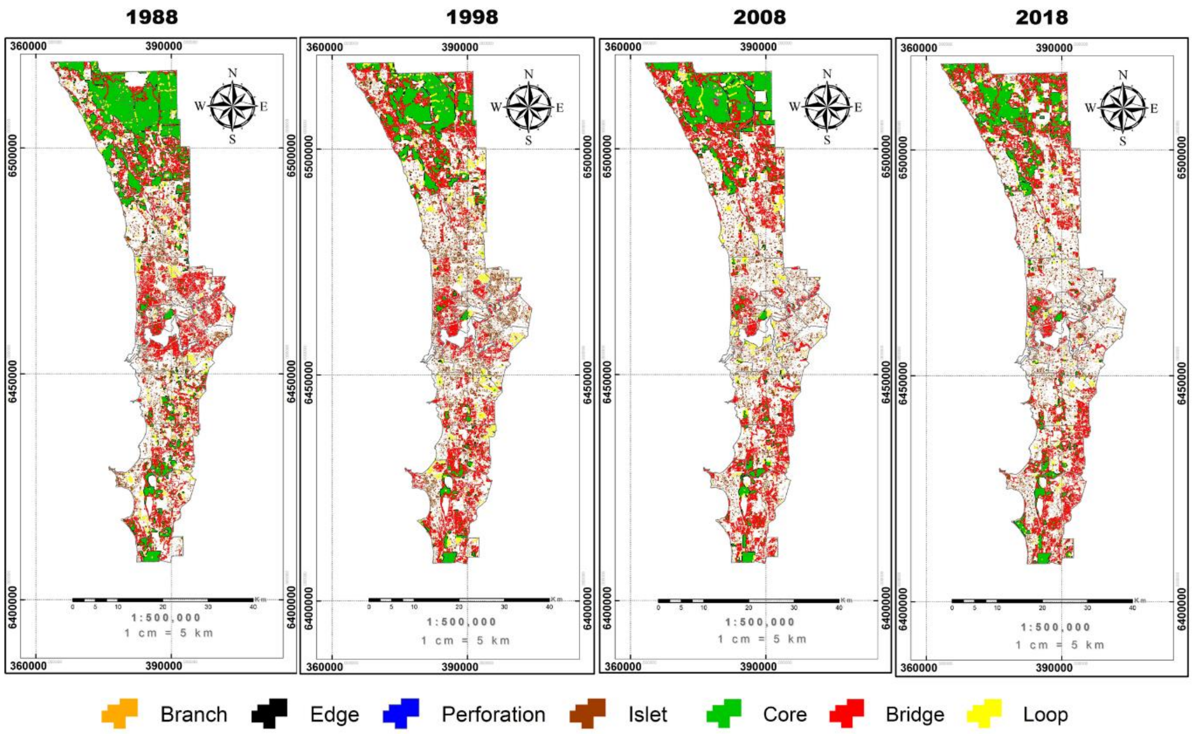


**Figure 3. 6 Results of the Morphological Spatial Pattern Analysis (MSPA) for the Perth region from 1988 to 2018 at for four-time steps**

The vegetation cover within golf courses also contributes to connectivity. The proportion of *Core* area within golf courses fluctuated between 12% and 27%. Moreover, the largest proportion of vegetation in golf courses was classified as *Bridge* but it experienced a downward trend from 52% to 41% in three decades. Of the remaining classes which do not contribute to connectivity, the *Edge* and *Loop* classes accounted for a higher proportion with each of them contributing 7% to 16% of total vegetation cover.

**Table 3. 5 Results of Morphological Spatial Pattern Analysis (MSPA) analysis of connectivity of Perth's vegetation from 1988 to 2018**

| Landscape type | Year | Perth Metropolitan Region | | Within golf courses | |
|---|---|---|---|---|---|
| | | Area (ha) | Proportion of total VCA (%) | Area (ha) | Proportion of total VCA (%) |
| *Core* | 1988 | 32,012 | 32.6 | 325 | 23.2 |
| | 1998 | 20,607 | 22.5 | 171 | 12.7 |
| | 2008 | 22,251 | 25.3 | 230 | 16.7 |
| | 2018 | 18,101 | 22.5 | 383 | 27.3 |
| *Bridge* | 1988 | 37,127 | 37.9 | 738 | 52.6 |
| | 1998 | 39,412 | 43.0 | 814 | 60.2 |
| | 2008 | 37,902 | 43.1 | 732 | 53.1 |
| | 2018 | 37,503 | 46.7 | 588 | 42.0 |
| *Islet* | 1988 | 10,396 | 10.6 | 31 | 2.2 |
| | 1998 | 16,436 | 17.9 | 78 | 5.8 |

| Landscape type | Year | Perth Metropolitan Region | | Within golf courses | |
|---|---|---|---|---|---|
| | | Area (ha) | Proportion of total VCA (%) | Area (ha) | Proportion of total VCA (%) |
| | 2008 | 12,922 | 14.7 | 15 | 1.1 |
| | 2018 | 12,349 | 15.4 | 37 | 2.7 |
| *Perforation* | 1988 | 1,099 | 1.1 | 3 | 0.2 |
| | 1998 | 486 | 0.5 | - | - |
| | 2008 | 834 | 1.0 | - | - |
| | 2018 | 406 | 0.5 | 6 | 0.4 |
| *Edge* | 1988 | 7,430 | 7.6 | 162 | 11.5 |
| | 1998 | 4,814 | 5.3 | 95 | 7.0 |
| | 2008 | 4,986 | 5.7 | 147 | 10.7 |
| | 2018 | 5,218 | 6.5 | 230 | 16.4 |
| *Loop* | 1988 | 5,670 | 5.8 | 112 | 8.0 |
| | 1998 | 6,295 | 6.9 | 146 | 10.8 |
| | 2008 | 5,607 | 6.4 | 209 | 15.2 |
| | 2018 | 3,669 | 4.6 | 129 | 9.2 |
| *Branch* | 1988 | 4,361 | 4.5 | 32 | 2.3 |
| | 1998 | 3,619 | 4.0 | 47 | 3.5 |
| | 2008 | 3,491 | 4.0 | 43 | 3.2 |
| | 2018 | 3,117 | 3.9 | 29 | 2.1 |

## 3.4 Discussion

We used Landsat imagery to characterize the patterns of vegetation change, habitat connectivity and the role of golf courses in maintaining green spaces and connectivity in an urban landscape. We found that deforestation led to a reduction in habitat connectivity in the Perth Metropolitan Region. However, golf courses can play an important role in maintaining vegetation and supporting biodiversity connectivity in urban landscapes. Previous studies have documented the increase in the urban footprint of Perth using multi-temporal urban expansion statistics derived from Satellite imagery (MacLachlan et al, 2017); However, their work did not address the issues of vegetation dynamics, nor the biodiversity and structure of the vegetation and habitat connectivity in the Perth Metropolitan Region . Therefore, our study addresses this gap.

### 3.4.1 Deforestation and urbanization

The vegetation dynamics in the major urban areas of Perth reflect the pattern of urbanization over time. The reduction in green space found in this study can be explained as a close relation to the process of development in this city. Over the last three decades, urban development in Perth has taken place at a fast rate (Subas, 2014). In the early 1990s to 2006, Perth's population grew by around 1.8%, but the figure has nearly doubled since then (World Population Review, 2019). Also, this study indicated that, from 1988 to 2018, Perth’s urban footprint increased from 74,376 to 92,243 ha (Table 3.2) and is consistent with previous research in urban growth in this region (MacLachlan et al, 2017). In the last 20 years, on average, 740 ha/yr of urban and urban deferred zoned land was consumed by subdivision, and 830 ha/yr was consumed by construction in the Perth Metropolitan Region and nearby Peel region (Western Australian Planning Commission, 2019b). In addition to this expansion, the city has become denser with the construction of new residential dwellings in urbanized areas. Although vegetation gain occurred in some places as a result of natural increase in canopy cover as urban vegetation grows through the conservation efforts, vegetation offset from development projects (e.g. mining), the plantation programs of the government taking place in bare soils in some suburbs, and efforts to increase green spaces from private land owners, the vegetation loss associated with urbanization has been more significant.

The difference in spatial patterns of vegetation loss is also related to the urban plans of this city. Our results show that between 1988 and 1998, there was significant vegetation loss in the central region of the city which can be linked to The Corridor Plan (Metropolitan Region Planning Authority, 1970). Historically, Perth's development pattern from 1970s to 1990s was based on linear corridors stretching out from the city's *Core*, with large non-urban wedges between each of these corridors (Metropolitan Region Planning Authority, 1970). However, from 1998 to 2008 and from 2008 to 2018, deforestation was more significant in the outer subregions north-west and south-west of the city due to the adoption of Metroplan (Department of Planning and Urban Development, 1990). Perth recently has been divided into subregional areas, rather than corridors for planning purposes. The two coastal subregions (the North-West and South-West) included in our study have consistently achieved higher rates of population growth under Metroplan (Bureau of Infrastructure, 2010).

Originally the region was covered by woodlands dominated by eucalypts and banksias and coastal heath interspersed with chains of wetlands. Perth is home to a rich biodiversity, with more than 1,700 species of flowering plants and iconic species of threatened fauna in the region (Department of Biodiversity, 2017). Therefore, such deforestation for urbanization has resulted in the devastating loss of significant natural habitats in this biodiversity hotspot city, leading to the designation as an endangered ecological community by the Australian Government (Department of the Environment, 2016).

### 3.4.2 Connectivity of green space networks in urban landscapes

The MSPA analysis indicates that the loss of vegetation as a consequence of urban expansion has led to a marked reduction in connectivity of green space networks in the Perth urban landscape. As only *Cores* (the stepping stones between forest habitat patches) and *Bridges* (the structural corridors to link *Core* areas) can contribute to the connectivity between the habitat areas in the landscape (Saura et al, 2011), the reduction of these areas in Perth associated with urbanization throughout the time indicates the high impact of urban development on habitat connectivity. This analysis also shows the increase in proportion of *Islets*, which are totally isolated patches, and other classes (*Perforations*, *Loops*, *Branch*es, *Edges*) that cannot reach a new *Core* habitat area for originating the potential movement (Saura et al, 2011). Clearly, expansion of Perth city has fragmented the remaining blocks of natural habitat and increased isolation of natural habitats. Urbanization requiring clearing of vegetation caused the division of large, continuous habitats into smaller, more isolated habitat fragments. By affecting ecological processes, fragmentation affects biodiversity and ecosystem services such as microclimate characteristic, habitat provision, pollination, and the presence of pest species (Christine Estreguil, 2012). This may reduce population and gene flow among patches and may disrupt the connection between subpopulations and a large regional population (Morjan & Rieseberg, 2004) and thus threaten the long-term viability of relict populations.

Fragmentation was obvious in the central region of the city and in recent decades it has become more serious in the outer parts of the city. This is critical as Perth is within a globally recognized biodiversity hotspot, which is home to rich biodiversity found nowhere else in the world. The connectivity in the major urban area of Perth is not only critical for the linkage of habitats within the Swan Coastal Plain but also for the connection of these coastal habitats to a large regional biosphere in south-western Australia.

The results also illustrated that a ‘*Core*’ area and a network of ‘*Bridge*’ types exist in the central and outer subregions of Perth. This is the consequence of early conservation efforts of the government which created protected areas such as Kings Park, Bold Park and other significant areas. Very few cities in the world have such large areas of natural bushland in the center of a big city (The Green, 2018). However, future urban growth will continue to put pressure on the biodiversity. If current policies (Perth and Peel@3.5million) are fully implemented, existing stocks of urban and urban deferred land would be consumed by about 2075 (Western Australian Planning Commission, 2015). The challenge for urban planning to preserve urban forests and biodiversity is thus increasing, and it is clear that planning for future expansion should also include large protected areas.

Our MSPA output with spatial distribution of seven classes provides fundamental information for future urban planning. There is a need to maintain important green spaces which are classified as *Cores* and *Bridges* in the city, especially in the central region where most of the natural vegetation exists as islands. Also, the MSPA *Branch* classes can be used to identify candidate ecological restoration areas. The *Branch* class can be thought of (Wickham et al, 2017) as a foundation of a potential corridor that could, if revegetated, connect two spatially disjunct *Core* areas to improve connectivity in the larger region.

Although other analyses, such as functional connectivity, should be taken into account in landscape connectivity assessment (Vogt et al, 2007), the structural connectivity analysis in this study will be useful for determining the priority protection level and critical areas of the connecting corridor, informing conservation strategies at a variety of scales, especially when the biodiversity values of this region are suffering from various threats including deforestation, feral animals, weed incursions, more frequent fires through arson and tree disease (Department of Biodiversity, 2017).

### 3.4.3 The role of golf courses in maintaining urban forest

Our study indicates that golf courses account for a significant proportion of the urban area of Perth. This category of land use has been vital in maintaining green space in urban areas over the past thirty years. In contrast to the overall decline in urban green space, golf courses have preserved green spaces within urban settings and even created a net gain of vegetation cover over time. The highest net gain was seen in the period between 1988 to 1998 when some golf courses were established resulting in the planting of trees.

In the green 'matrix' of Perth, golf courses with their significant area of vegetation cover have contributed considerably to the connectivity in the urban landscape. A significant proportion of their green space was classified as *Core* or *Bridge* categories. The proportion of vegetation within golf courses classified as *Bridges* was higher than in the whole study area. Golf courses with large areas of native vegetation provide "links" to other large natural patches of urban vegetation.

Although there are concerns with the environmentally negative impacts of golf courses as a source of pollution through pesticide and fertilizer usage (Carlos & Duvan, 2014), habitat modification (Terman, 1997) and high water usage (Neylan, 2007), previous studies provide evidence about the biological values of golf courses, such as providing refugial habitat for urban-avoiding wildlife (Burgin & Wotherspoon, 2009; Chester & Robson, 2013; Colding et al, 2009; Deslauriers et al, 2017; Dobbs & Potter, 2016; Hodgkison et al, 2007b; Hudson & Bird, 2009; Saarikivi et al, 2010; Saarikivi et al, 2015; Tanner & Gange, 2005). Our study indicates that golf courses in urban settings have been maintaining large green space in urban settings and may play a role in biodiversity connectivity in the city.

### 3.4.4 Monitoring urban forest dynamics

In this study, we utilized medium-resolution satellite remote sensing data to identify land use classes, characterize vegetation dynamics and connectivity. The data maps the spatial and temporal patterns of land use types characterizing a consistent, detailed vegetation dynamic of the city (Angiuli & Trianni, 2014; MacLachlan et al, 2017). Clearly, the biophysical elements of urban landscapes are well-reflected through physical features (NDVI) derived from remote sensing data with an accuracy of up to 89%.

Despite these kinds of data, it is hard to describe the detailed information of ecosystems such as species composition and forest structure; to differentiate between the types of green space and habitat quality as the spatial resolution of the imagery is unable to differentiate between trees, shrubs, turf, groundcovers etc. However, medium-resolution satellite remote sensing data have an advantage in mapping land cover dynamics across large areas of big cities over time when high resolution imagery is not available. In our study area, Landsat is the only platform that provides the opportunity to retrospectively assess vegetation trends over the last three decades. For monitoring urban forests in big cities, the large scale and long temporal datasets are more advantageous compared with datasets that focus only on discerning a specific land use type in a relatively small area (Theobald, 2014; Toole et al, 2012; Wu et al, 2009). This is because it allows spatially detailed identification of changes associated with development over time. Therefore, the approach described in this paper provides baseline information for sustainable urban planning and development. In addition, the MSPA analysis can further evaluate the dynamic of vegetation cover by the describing the spatial configuration of ecosystems at the pixel level, detecting changes of habitat connectivity over time (Vogt et al, 2007).

## 3.5 Conclusions

With rapid urban expansion, the most meaningful question to address is how to balance urban development and urban forest preservation. Urbanization requiring deforestation is inevitable in many cities worldwide. Our study found a significant loss of vegetation cover in a biodiversity hotspot over three decades of urbanization, which led to a reduction in habitat connectivity in the urban landscape. A lesson learned from the experience of urbanization in Perth is that any future urban growth following the patterns observed over the past three decades will continue to put pressure on maintaining urban forest ecosystems and biodiversity conservation. As cities continue to grow in response to socio-economic development, considering all opportunities for urban biodiversity conservation is important. Urban conservation strategies must therefore consider not only the protected areas, but also the off-reserve sites.

The results, of this chapter indicate that golf courses in urban settings have been maintaining green-area habitats and have played an important role in biodiversity connectivity in the city. Potentially, urban golf courses could become more purposefully managed for biodiversity conservation and the improvement of critical ecosystem services in urban areas. In rapidly urbanizing biodiversity hotspots like Perth, where fragmentation is one the biggest threats to biodiversity, the way that golf courses contribute to increase the connectivity in the intervening urban matrix should not be underestimated. As with the majority of studies, the design of this chapter is limited to the temporal analysis of vegetation cover and vegetation connectivity of the golf courses in an urban landscape during the urbanization process. More details of spatial analysis of vegetation characteristics of golf course in comparison with other land-use categories need to be explored for thoughtful insights of ecological roles of golf courses in maintaining vegetation, and this will be explored in Chapter 4. However, with significant findings that golf courses can maintain urban vegetation, it is suggested that government authorities and golf courses owners to pay more attention to maintaining ecosystem health in urban golf courses.

# Chapter 4

# Comparison of vegetation attribute characteristics within golf course with other land uses


## Abstract

Networks of urban green space are important for conserving biodiversity, providing ecosystem services, and supporting the health and wellbeing of urban residents. Golf courses have been confirmed as one of the most important urban green spaces in urban wildlife conservation, but the significant roles of golf courses in maintaining vegetation cover and increasing vegetation connectivity compared to the functions of other urban land-use categories is often overlooked. This study was conducted at a landscape scale in Perth, Australia, using remote sensed data sets to (a) assess the vegetation characteristics within golf courses compared with other land uses, and (b) to identify the characteristics of golf courses that affect the vegetation cover and connectivity among golf courses.

This study found that golf courses have moderate levels of vegetation cover, but the proportion of native vegetation is small in golf courses (36%) compared to rural land (~70%) and conservation land (~92%). Vegetation in golf courses is quite fragmented with the majority classified as *Islets*, but vegetation health is good with the highest values of NDVI (median above 0.6) compared to that of vegetation in other land-uses. Vegetation attribute characteristics varied among golf courses depending on their size and location. Larger golf courses tended to have higher proportions of vegetation cover (both total and native) and higher connectivity. Golf courses that are adjacent to other vegetated areas have a higher proportion of total vegetation cover, native vegetation cover and more connectivity. The important role that golf courses have in sustaining vegetation connectivity in urban-rural situations offers both challenges and opportunities for urban planning and biodiversity conservation strategies. Therefore, a prioritization strategy in vegetation conservation and biodiversity connectivity is to integrate golf courses and other private land-uses for more effective management and sustainable urban development.

## 4.1 Introduction

Networks of green space along urban-to-rural gradients are increasingly recognized as important in conserving biodiversity, providing ecosystem services, and supporting the health and wellbeing of urban residents (Beninde et al, 2015; Dinnie et al, 2013). Typically, highly protected nature reserves are the main sources of biodiversity in the gradient. Rural land uses are predominantly vegetated and connected to agricultural production such as farming and pasture, and also forested areas. Urban areas, by contrast, are densely built spaces with a high degree of impervious cover, thereby vegetation patches are more disturbed (Antrop, 2004). Urban expansion requiring the conversion of natural habitats (e.g. forested areas, vegetation remnants, and even agricultural land) into built environments or highly urbanized green spaces can cause a reduction in the biodiversity of green spaces (Ambardar et al, 2018; Foley et al, 2012; Stanback & Seifert, 2005).

In urban environments, the use of land is extremely intensive where ecological strategies have to compete with economic and social interests in a decision-making process (Lima et al, 2020), and thus conservation efforts to protect large urban reserves that retain areas of quality 'interior' habitat can face many challenges (Donaldson et al, 2017). While traditional approaches to urban conservation are interested in the preservation of large nature reserves (Gibbs et al, 2011), a more recent urban ecological approach has suggested the maintenance and restoration of urban landscape integrity by creating networks of interconnected habitat, using a combination of large reserves and green space on private land and in public 'open space' areas (Kamal et al, 2015). Although small urban green spaces can be of limited value compared to large nature reserves, they are not without ecological value in the urban matrix as they can provide additional green resources, habitat connectivity (Donaldson et al, 2017), human well-being, and various ecosystem services to provide cumulative benefits at a regional level (Bertram & Rehdanz, 2015). However, smaller habitat remnants outside the protected area network have still received relatively little research attention from ecologists (Blair, 1996). Therefore, information on the ecological value and the ecological role of all urban land types is required to make ecologically responsible urban zoning decisions.

With the rarity of large green open spaces (an average 18-hole golf course covers almost 60 ha) and transplanting of big trees (Salgot et al, 2012), urban golf courses are a special land-use in the spotlight for growing recognition of their ecological roles. The majority of comparative studies between golf course and other urban land-use categories have focused on biodiversity assessments using species richness and abundance (Petrosillo et al, 2019). Most of these studies have been carried out at fine scales using site-based methods investigating specific golf courses at specific locations (Chapter 2). Thus, an understanding of the roles of vegetation within golf courses at the landscape scale in an urban matrix is very limited. Meanwhile, urban land-uses are very complex (Alexander et al, 2019) as they are controlled by anthropogenic factors. Vegetation within green spaces in urban landscapes are ever changing, not only naturally and predictably, but also randomly (Theobald et al, 2000). Hence, interpreting the vegetation condition within an urban landscape can be difficult. Understanding the characteristics of vegetation within golf course and other urban land-use categories can help prioritize the strategic management of vegetation in fragmented landscapes so that it provides the greatest benefit to humans and biodiversity (Fontana et al, 2011).

The development of remote sensing technology facilitates the monitoring of a range of remotely detectable properties of vegetation (Lawley et al, 2016). The changes and differences of the green leaves from plants and canopy spectral characteristics obtained remotely with different sensors can be interpreted into vegetation (Xue & Su, 2017). The validation process has confirmed that vegetation spectral characteristics have strong correlations with vegetation characteristics of interest measured in situ, such as vegetation cover, leaf area index (LAI), biomass, growth, health, and vigor (Evans et al, 2012; Xue & Su, 2017), and thus the remotely sensed vegetation indices are good proxies of vegetation health. Geographic Information System (GIS) techniques can also allow monitoring of the landscape pattern structure of vegetation from multi-scale land-cover maps (Ostapowicz et al, 2008). Despite the limitations of remote sensing technology in detecting vegetation attributes such as vegetation composition and abundance or stem density, they can offer broad scale repeatable and automated methods for monitoring indicators of vegetation condition, which can improve monitoring for answering ecological questions at the landscape scale.

To understanding the ecological role of urban golf courses at a landscape scale, the first step in answering the research question regarding their roles in the maintenance of vegetation cover and connectivity during a long urbanization period has been quantified in Chapter 3 by a time-series analysis of Landsat images. The findings were that urbanization requiring a rapid conversion of natural land into settlement areas has led to significant loss of vegetation cover in the Perth Metropolitan Region during the last 30 years (1988-2018). In such context, golf courses were found to have roles in maintaining vegetation cover and connectivity temporally during the urbanization process (Chapter 3); however, the extent to which vegetation varied spatially among golf courses and other urban land-use categories (both in natural conservation land and settlement areas) are still unknown.

This chapter will examine the significance of golf course in maintaining vegetation by comparing spatially their vegetation attributes with other land-use categories and among golf courses. Here, I hypothesize that changes to land use translate directly and instantly to changes in vegetation attribute characteristics, which lead to differences of vegetation attribute characteristics within golf courses compared to natural, un-developed land-uses, rural land-use and with land-use in settlement areas (e.g., industrial, residential, commercial land-uses). Also, such variation of vegetation attributes is expected to vary among golf courses of difference size, ownership, and their degree of linkage to other vegetated areas. This chapter was conducted at a landscape scale using high resolution satellite PlanetScope Images to address the following research questions: (1) How do the vegetation characteristics (vegetation cover, native vegetation cover, and vegetation fragmentation) within golf courses differ to that of other land uses? and (2) How do the vegetation characteristics vary across golf courses of different characteristics (size, ownership and location)?

This chapter further examines the implications that golf courses and other green spaces may contribute to vegetation conservation for urban landscape management, biodiversity conservation strategy and urban planning.

## 4.2 Methods

### 4.2.1 Study area

The study covers four sub-regions (Northwest, Middle Central, Inner Central and South West) of the Perth Metropolitan Region (Figure 4.1), located in the southwest Botanical District and part of a global biodiversity hotspot which has a Mediterranean-type climate, described in Chapter 3.

Historically, the area was first settled by Europeans in 1829 when the Swan River Colony was established by the British, with land cleared of vegetation used largely for agriculture such as grazing and cropping (Department of Treasury and Finance, 2004). The population was very small until the discovery of gold in Western Australia in 1900s. Significant residential and industrial development occurred in the post-war years (World War I and II). Urbanization expanded greatly from the 1960s into the 1980s, and further expansion occurred from the 1990s. Recently, the population of Western Australia has grown faster than the national average (annual growth of 1.5%, compared with 1.2% nationally) (Department of Treasury and

Finance, 2004). The population of the Perth Metropolitan Region was expected to increase by an additional one million people in two decades (Australian Bureau of Statistics (ABS), 2013). However, as Perth is one of the least dense cities in the world, its urban footprint has become larger than many cities with the same or bigger population (Demographia, 2017). The Perth Metropolitan region encompasses residential, rural-residential and rural areas, commercial, industrial and other urban land use, and a network of green spaces and protected area networks as a result of successful attempts by local and state governments to manage development to protect biodiversity and human well-being (The Western Australian Planning Commission, 2014).

The land-use categories were classified and are shown in Figure 4.1 and qualified in Table 4.1 using the shape file formats of the Region Scheme map, Regional Special Area map and Local Scheme map from the Department of Planning, Land and Heritage of the Government of Western Australia (Department of Planning Lands and Heritage, 2019a; b; Western Australian Planning Commission, 2019a).

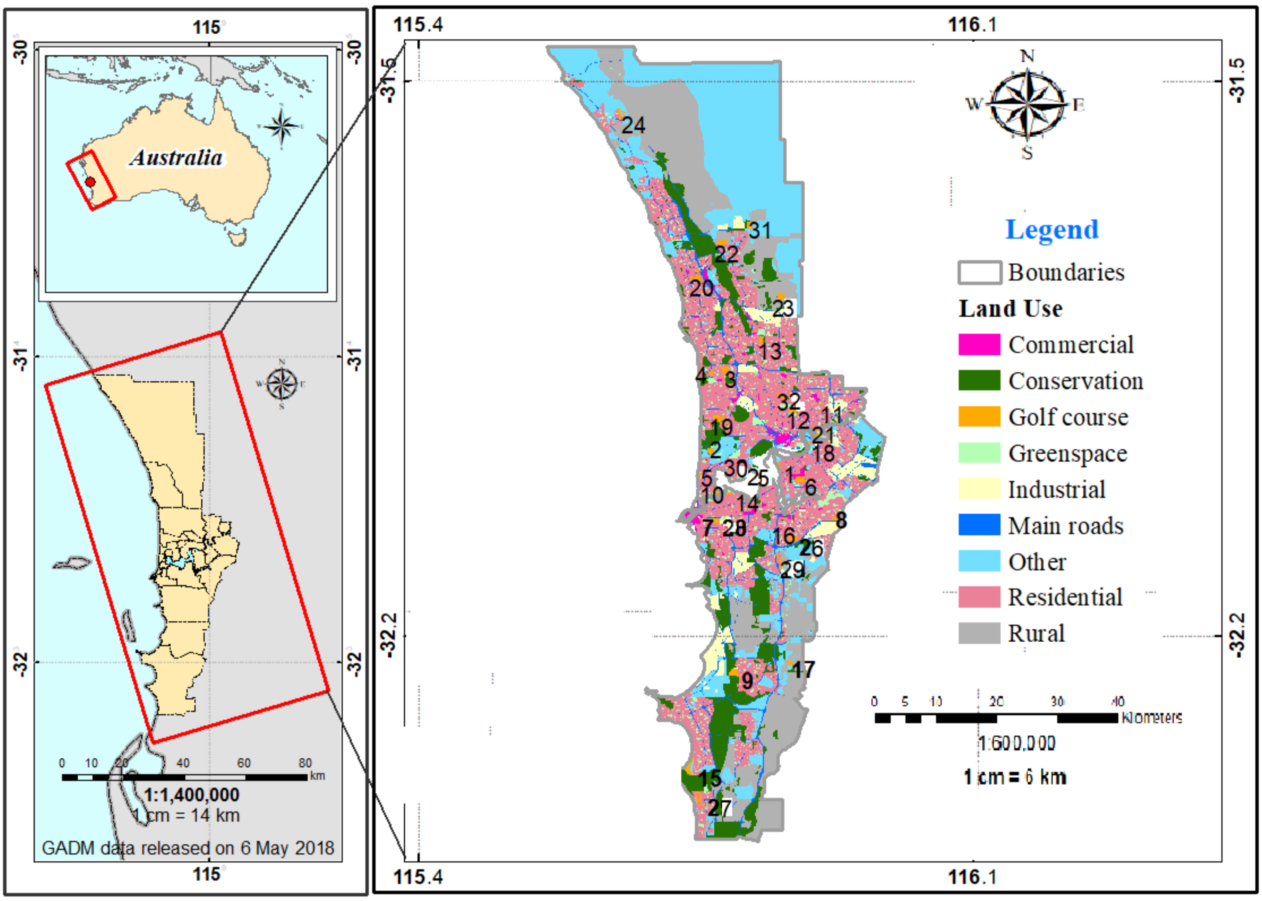


**Figure 4. 1 The location of the study area in the Perth Metropolitan region, Australia (note that the land-cover was given in Figure 3.1). See Table 4.2 for the names of the numbered golf courses**

**Table 4. 1 Areas and percentages of each land-use categories in the study area**

| Land-use | Area (ha) | Land-use (%total area) |
|---|---|---|
| Residential | 48,794 | 27.9 |
| Commercial | 1,897 | 1.1 |
| Industrial | 6,718 | 3.8 |
| Main roads | 6,542 | 3.7 |
| Rural | 35,370 | 20.2 |
| Other | 46,739 | 26.7 |
| Green space | 7,039 | 4 |
| Golf course | 1,792 | 1 |
| Conservation | 19,960 | 11.4 |
| **Total** | **174,851** | **100** |

There are 34 golf courses in the study area (Figure 4.1). This study excluded two mini golf courses, and thus 32 golf courses (numbered in the map) are included in the analysis. Additionally, those golf courses vary in size, ownership, and connectivity to other vegetation areas as described in Table 4.2.

**Table 4. 2 Key characteristics of the 32 golf courses**

| No. | Name of golf course | Size (ha) | Linkage to other vegetation | Golf course type | Number of holes |
|---|---|---|---|---|---|
| 1 | Royal Perth Golf Club | 35.16 | Isolated | Private | 18 |
| 2 | Cottesloe Golf Course | 61.26 | Adjacent | Private | 18 |
| 3 | Lake Karrinyup Golf Course | 102.76 | Adjacent | Private | 18 |
| 4 | Hamersley Golf Course | 45.99 | Isolated | Public | 18 |
| 5 | Seaview Golf Course | 18.1 | Isolated | Private | 9 |
| 6 | Collier Park Golf Course | 89.26 | Isolated | Public | 9 |
| 7 | Royal Fremantle Golf Course | 55.81 | Isolated | Private | 18 |
| 8 | Whaleback Golf Course | 56.93 | Isolated | Public | 18 |
| 9 | Kwinana Golf Club | 107.22 | Adjacent | Semi-private | 18 |
| 10 | Mosman Park Golf Course | 24.8 | Adjacent | Semi-private | 9 |
| 11 | Bayswater Golf Course | 9.33 | Isolated | Public | 9 |
| 12 | Mount Lawley Golf Club | 67.41 | Isolated | Private | 18 |
| 13 | Marangaroo Golf Course | 55.63 | Adjacent | Public | 18 |
| 14 | Point Walter Golf Course | 24.91 | Isolated | Public | 9 |
| 15 | The Links Kennedy Bay | 107.54 | Adjacent | Public | 18 |
| 16 | Melville Glades Golf Course | 67.09 | Isolated | Private | 18 |
| 17 | Marri Park Golf Course | 49.13 | Adjacent | Public | 18 |
| 18 | Maylands Peninsula Golf Course | 51.87 | Adjacent | Public | 18 |
| 19 | Wembley Golf Course | 128.96 | Adjacent | Public | >18 |

| | | | | | |
|---|---|---|---|---|---|
| 20 | Joondalup Resort Golf Course | 108.93 | Isolated | Public | >18 |
| 21 | Burswood Golf Course | 13.93 | Isolated | Public | 18 |
| 22 | Carramar Golf Course | 64.96 | Isolated | public | 18 |
| 23 | Lakelands Country Club | 81.17 | Isolated | Private | 18 |
| 24 | Sun City Country Club | 55.75 | Isolated | Private | 18 |
| 25 | Nedlands Golf Club | 18 | Isolated | Private | 9 |
| 26 | Melville Golf Centre | 8.58 | Isolated | Public | 9 |
| 27 | Secret Harbour Links Golf Course | 80.59 | Isolated | public | 18 |
| 28 | Fremantle Public Golf Course | 17.2 | Isolated | Public | 9 |
| 29 | Glen Iris Public Golf Course | 52.33 | Isolated | Private | 18 |
| 30 | Lake Claremont Golf Course | 4.13 | Adjacent | Public | 9 |
| 31 | Wanneroo Golf Club | 49.42 | Adjacent | Private | 18 |
| 32 | Western Australian Golf Club | 43.09 | Isolated | Private | 18 |

### 4.2.2 Research approach

The steps taken in this study are summarized in a flow diagram (Figure 4.2).

*PlanetScope data*

Thirteen PlanetScope (PS) 4-band MS analytic data products –Ortho Scene (Level 3B) with a spatial resolution of 3 m, for early summer (3rd December 2019 and 17th December 2019) were acquired directly from Planet Labs Inc to use in this research. The PlanetScope (PS) constellation consistscomposed of more than 150 "Dove" microsatellites which allows to make daily revisits to be made to mostnearly any global locations. These satellites cover the whole Earth atwith 3 m  pixels every day (about five days for S2). SuchThe availability of medium-resolution imagery collected over sites that other satellites may have missed, makesing PlanetScope a greatsuitable choice for this chapter to monitor spatially vegetation attributes among different land-use categories. The Level 3B images were orthorectified by ground control points and fine digital elevation models (DEMs) to achieve <10 m root means square error (RMSE) positional accuracy. Surface reflectance products were used to allow the removal of atmospheric artefacts and improved consistency between images acquired at different times. Therefore, there is no longer a need for atmospheric correction of these images (Planet, 2019).

*Classification*

Land cover classification was performed using an object-based classification method. This method is suitable for high-resolution satellite images such as PlanetScope where vegetation cover is resolved by multiple pixels. This method takes image objects with a set of similar pixels as the basic unit (Tuzcu et al, 2019), based on spectral and contextual information in the image. The object-based image classification was done using the commercially available software eCognition 8.4 under a trial version (Trimble Geospatial, 2019).

The object-based classification of images to identify the vegetation cover was undertaken as follows. Firstly, the four bands of PlanetScope images were segmented to identify individual objects in the scene using a "Bottom-Up" algorithm, "multi-resolution segmentation", in which all bands and VIs were used to split the original image into the object segments that have similar spectral characteristics, shape, size, color, and pixel topology. The next step was the object classification process using "Assign class" and "Fuzzy membership" algorithms to assign each object identified by the segmentation process to a class based on features and criteria set by the user to identify vegetation and lawn, and a non-vegetation class within each image. A total of 600 random points were selected for two classes (non-vegetation and vegetation). For each class, 75% of the data was used for training samples, while the remaining 25% was used for validation.

Accuracy assessment of vegetation classification was performed using confusion matrix analysis. This analysis produced the overall classification accuracy (OA), Kappa coefficient, and user's accuracy (UA) and producer's accuracy (PA) for each classified class.

*MSPA analysis*

Morphological Spatial Pattern Analysis (MSPA) was used to describe the spatial configuration of the ecosystem at the pixel level based on the concept of "habitat availability" and "graphic theory" as described in Chapter 3. The output of the MSPA analysis includes the seven structural categories belonging to two groups (1) urban vegetation patches (*Cores*, *Edge*, *Perforation* and *Islets*) and (2) urban vegetation paths (*Bridges*, *Branches* and *Loops*) (Ossola et al, 2019). Each of these categories was described at the pixel level by Vogt et al (2007) and described in ecological meaning terms based on the concept of "habitat availability" and "graphic theory" (Pascual-Hortal & Saura, 2006; Saura et al, 2011; Velázquez et al, 2019) as described in Chapter 3 (Table 3.1).

In order to undertake the MSPA analysis, the input data (foreground class) were defined. The binary maps (vegetation and non-vegetation) obtained from classification of PlanetScope 3B images were used as input data with the vegetation being defined as the foreground pixels (green landscape) in the MSPA approach using the MSPA-Toolbox for ArcGIS. The output of MSPA analysis that classified vegetation/green space into seven habitat classes (*Core*, *Edge*, *Perforation*, *Islet*, *Bridge*, *Loop*, *Branch*) were used to calculate six fragmentation indicators for each land-use category and each golf course (Table 4.3) for further comparative analysis.

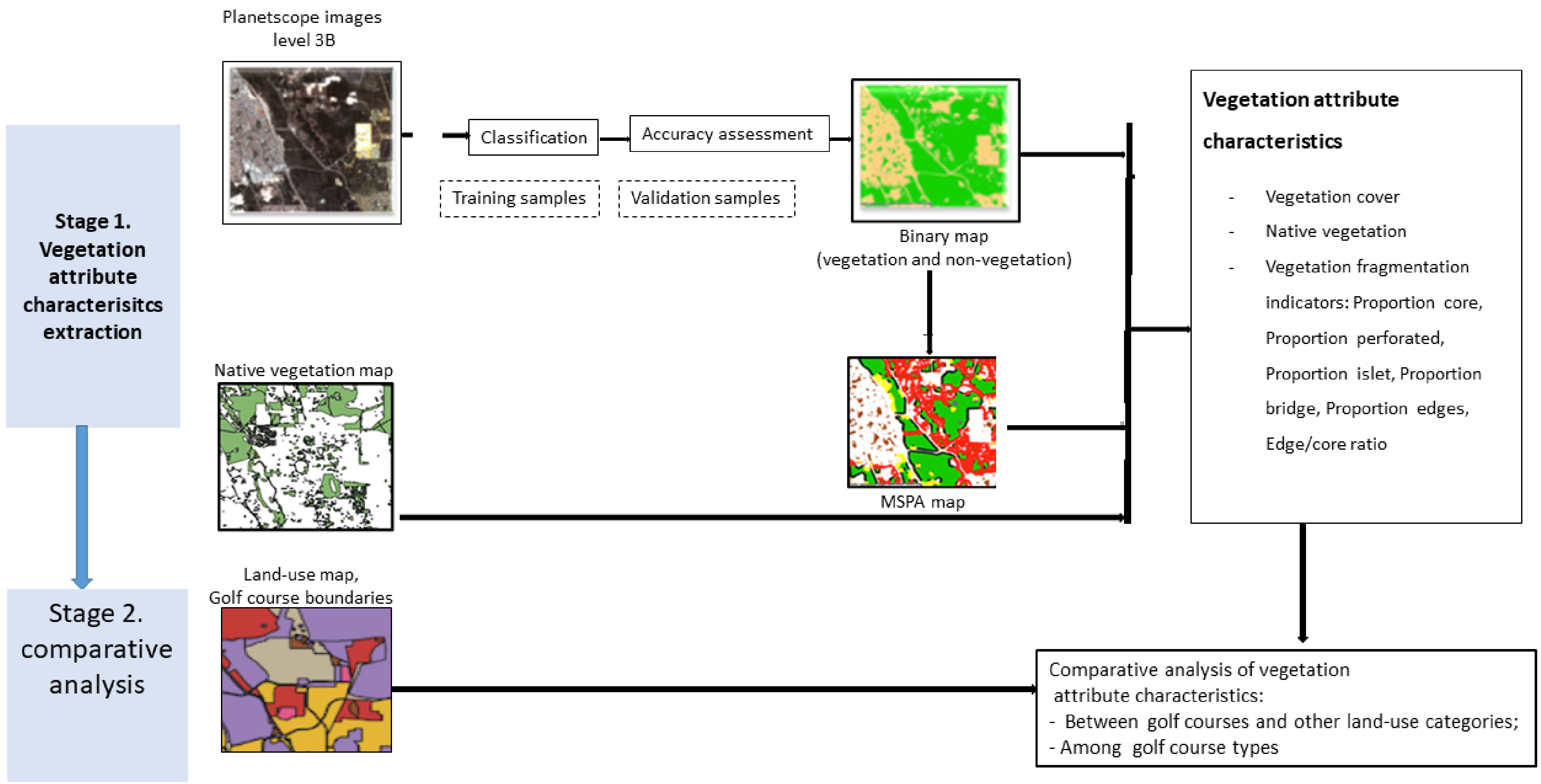


**Figure 4. 2 Flow diagram of the methodology followed in this study. MSPA is Morphological Spatial Pattern Analysis**

**Table 4. 3 Vegetation Fragmentation attributes, corresponding fragmentation indicators, and formulae for calculation (described in Ossola et al (2019))**

| Ecological proxy | Fragmentation Indicator | Formulation |
|---|---|---|
| Availability of interior forest habitat | Proportion *Core* | $\frac{\textit{Core}\text{ area}}{\text{Total vegetation area}}$ |
| *Edge* effects on forest interior | Proportion *perforated* | $\frac{\textit{Perforated}\text{ area}}{\text{Total vegetation area}}$ |
| Isolated non-*Core* habitat, or potential stepping stone | Proportion *Islet* | $\frac{\textit{Islet}\text{ vegetation area}}{\text{Total vegetation area}}$ |
| Structural connectivity of interior forest habitat | Proportion *Bridge* | $\frac{\textit{Bridge}\text{ area}}{\text{Total vegetation area}}$ |
| *Edge* habitat and *Edge* effects on interior forest habitat | Proportion *Edges* | $\frac{\textit{Edge} + \textit{perforated} + \textit{Branch} + \textit{Loop} + \textit{Bridge}}{\text{Total vegetation area}}$ |
| Proportion of *Edge* versus interior forest habitat | *Edge*/*Core* ratio | $\frac{\textit{Edge} + \textit{perforated} + \textit{Branch} + \textit{Loop} + \textit{Bridge}}{\textit{Core}\text{ vegetation area}}$ |

While the proportion *Core* indicates lower levels of fragmentation, proportion *Islet* indicates the vegetation cover in the form of isolated non-*Core* vegetation patches as habitat "stepping stones" between *Core* forest patches, and thus indicates more fragmentation (Ossola et al, 2019). Additionally, proportion *perforated* indicates the degree that *Edge* effects are introduced into the *Core* interior when there are non-vegetation patches present within *Core* habitats, whereas proportion *Edge* expresses the significance of outer *Edge* habitats. These two indicators show high levels of forest fragmentation. Moreover, the *Edge*/*Core* ratio represents the relative abundance of *Core* versus *Edge* habitat. Higher values in the *Edge*/*Core* ratio indicate more fragmentation and values >1 indicate that the land-use contains more *Edge* habitat than interior habitat. However, the values of these indicators should be very low if the area of *Core* vegetation is not enough to permit *Perforation* and *Edge* (Ossola et al, 2019). Finally, proportion *Bridge* indicates the levels of connectivity between forest patches but may not indicate lower levels of fragmentation in each type of land-use and in each golf course (Ossola et al, 2019).

*Comparative analyses*

I selected eight land-use categories representing the main components in the urban landscape, as follows: Conservatin (1), Golf course (2), Green space (3); Rural (4), Commercial (5), Industrial (6), Residential (7); Main road (8), and Other land-use (9) (Table 4.4).

**Table 4. 4 Description of land-use categories**

| No. | Land-use category | Description |
|---|---|---|
| 1 | Conservation | Land of Bush Forever areas (described by Department of Planning (2010)); areas of biodiversity conservation significance within National Parks and State and other, conservation reserves, and all classified environmental conditions, special control areas which are of conservation concerns as dedicated in the Regional Scheme map, Regional Special Area map, Local Scheme map as well as small-parks from the OSM platform. |
| 2 | Golf course | There are 32 golf courses distributed in the study area (Figure 4.1 and Table 4.2). |
| 3 | Green space | The urban parks and other land used as set aside areas for public open space, provide for a range of active and passive recreation uses. |
| 4 | Rural | Land in rural zones cater for a wide range of land uses including agriculture, primary production, animal premises, basic raw material extraction, biodiversity conservation, natural resource management, tourism, regional facilities and public purposes including waste infrastructure. |
| 5 | Commercial | The land used to provide for a range of shops, offices, restaurants and other commercial outlets in defined townsites or activity centers, a wide variety of active uses on a street level; a mix of varied but compatible land uses such as offices, showrooms, amusement centers, eating establishments and appropriate industrial activities. |
| 6 | Industrial | Land of industrial activities to provide a broad range of industrial uses, service and storage activities. |
| 7 | Residential | Land-use areas provide for a range of housing and a choice of residential densities to meet the needs of the community by facilitating and encouraging high quality design, built form and streetscapes throughout residential areas. |
| 8 | Main road | The planned road network of the Western Australian Road (under the Main Roads Act 1930), and the planning responsibilities are shared by the Western Australian Planning Commission and local governments. |
| 9 | Other land-use | The land-use categories which are not classified as those above. They include designated land for future industrial development, urban development, transitional zone following the lifting of an urban deferred zoning, land of educational institutions, a broad range of essential public facilities such as halls, theatres, art galleries, educational, health and social care facilities, accommodation for the aged, other services and other mixed land-use. |

These land-use categories are popular in ecological comparative research in urban landscapes (Blair, 1996; Threlfall et al, 2016a). The land-use categories were classified and qualified using the shape file formats of the Region Scheme map, Regional Special Area map and Local Scheme map from the Department of Planning, Land and Heritage of the Government of Western Australia (Department of Planning Lands and Heritage, 2019a; b; Western Australian Planning Commission, 2019a). The boundaries were double checked and fixed with other land-use databases such as OpenStreetMap (OSM) and the latest high-resolution Google Earth satellite image to reduce any errors caused by out-of-date information of land-use in a highly dynamic urban landscape. All OSM data were downloaded from the Geofabrik website[1].

I summarized the average values of native vegetation cover, and vegetation fragmentation indicators by land-use categories. Native vegetation cover was extracted from the native vegetation extent dataset of the Department of Planning, Land and Heritage of the Government of Western Australia (Government of Western Australia, 2020). All analyses were conducted using ArcGis version 10.3.

To compare differences in vegetation attribute characteristics [vegetation indices of vegetation cover (proxy of vegetation health), native vegetation cover, and vegetation fragmentation indicators] among golf courses of different characteristics, I categorized golf courses into different types in terms of (1) golf course size (Small: <40 ha, Moderate: 40-70 ha, Large: >70 ha); (2) golf course ownership (Public, Private, Semi-Private); and (3) the location of golf courses relative to vegetated areas (adjacent; isolated). Because of non-normal distribution of the dataset, the nonparametric Kruskal–Wallis H test was employed to assess significant differences between vegetation parameters among golf course types, which was followed by post hoc Dunn's multiple-comparison tests with adjustments using Bonferroni (Dinno, 2015) to compare the significance of variation between the golf course types.

[1] http://download.geofabrik.de

## 4.3 Results

### 4.3.1 Variation of vegetation attribute characteristics among land-use categories

*Vegetation cover and native vegetation cover*

Using PlanetScope images for classification and extraction of vegetation cover, the analysis had the overall accuracy (OA) of classification of 89% and the kappa coefficient of 93%. In the study area, Golf course and Commercial land-use account for only a small proportion (1%) of the total study area. Industrial land, Green space, and Main roads account for around 3-4% while Conservation land accounts for more than 11%. Residential, Rural, and Other land categories are significant land-uses each accounting for more than 20% of the total land (Table 4.5).

**Table 4. 5 Absolute and percent area of land and vegetation cover in the land-use classes in the study area**

| Land-use | Vegetation cover (ha) | Vegetation cover [1] | Native vegetation cover (ha) | Native vegetation cover[2] | Native vegetation cover[3] |
|---|---|---|---|---|---|
| Conservation | 15,487 | 77.6 | 14,344 | 92.6 | 71.9 |
| Golf course | 689 | 38.4 | 250 | 36.3 | 14.0 |
| Green space | 1,946 | 27.6 | 719 | 36.9 | 10.2 |
| Rural | 19,049 | 53.9 | 13,436 | 70.5 | 38.0 |
| Commercial | 100 | 5.3 | 37 | 36.8 | 1.9 |
| Industrial | 405 | 6.0 | 218 | 53.8 | 3.2 |
| Residential | 2,6988 | 5.5 | 388 | 14.4 | 0.8 |
| Main roads | 1,291 | 19.7 | 613 | 47.5 | 9.4 |
| Other | 28,223 | 60.4 | 20,727 | 73.4 | 44.4 |
| **Total** | **69,887** | **40** | **50,73** | **72.6** | **29** |

[1] %Vegetation cover = (Vegetation cover area * 100)/ Total land-use area
[2] Proportion native vegetation cover = (Native vegetation cover area * 100)/ Total vegetation cover
[3]%Native vegetation cover = (Native vegetation cover area * 100)/ Total land-use area

Vegetation cover proportion is highest in Conservation land (77.6%), followed by Rural and Other land (53.9% and 60.4%, respectively). In contrast, the Commercial, Industrial and Residential land-use categories have a low proportion of vegetation cover, around 5-6% of the total area. Golf courses, Greenspace, and Main roads are categories with moderate levels of vegetation cover in the urban-rural gradient (38%, 27%, and 19%, respectively) (Table 4.5).

The highest native vegetation cover proportion per total vegetation area is in Conservation land (92.6%). The Rural and Other land categories also have over 70% total vegetation cover, mostly remnant native vegetation. Industrial land, despite containing a small proportion of total vegetation cover, has up to 50% of native vegetation. Only 36% of the vegetation cover in Golf courses, Green space, and Commercial land is native vegetation. Vegetation in Residential land has the lowest proportion of native vegetation (14%) (Table 4.5).

*Vegetation fragmentation indicators*

*Core* habitat is only significant in Conservation land where the proportion of *Core* is above 0.4 while that of all the other land-uses is under 0.1. In contrast, the proportion of *Islet* is higher (above 0.8) in land-uses with highly intensive management (Industrial, Commercial and Residential), is lower (above 0.5) in Golf course, Main Road, Green space, Rural, Other land use, and is lowest in Conservation land (only around 0.1).

Only Conservation, Rural and Other land use are found to have a very low proportion of *perforated* habitat (<0.008). Meanwhile the proportion of *Edges* is higher in Conservation land, Rural, Other land use, Golf courses and Green space than the highly intensive land-uses (Commercial, Industrial, Residential). This could be an indication that there is not enough *Core* vegetation in some types of land-use to permit *Perforation* or not enough *Core* vegetation to permit *Edges*. Moreover, the relative abundance of *Core* versus *Edge* habitat (*Edge*/*Core* ratio) is very low in Conservation land while higher values occur in the Residential and Main roads land use categories (Figure 4.3).

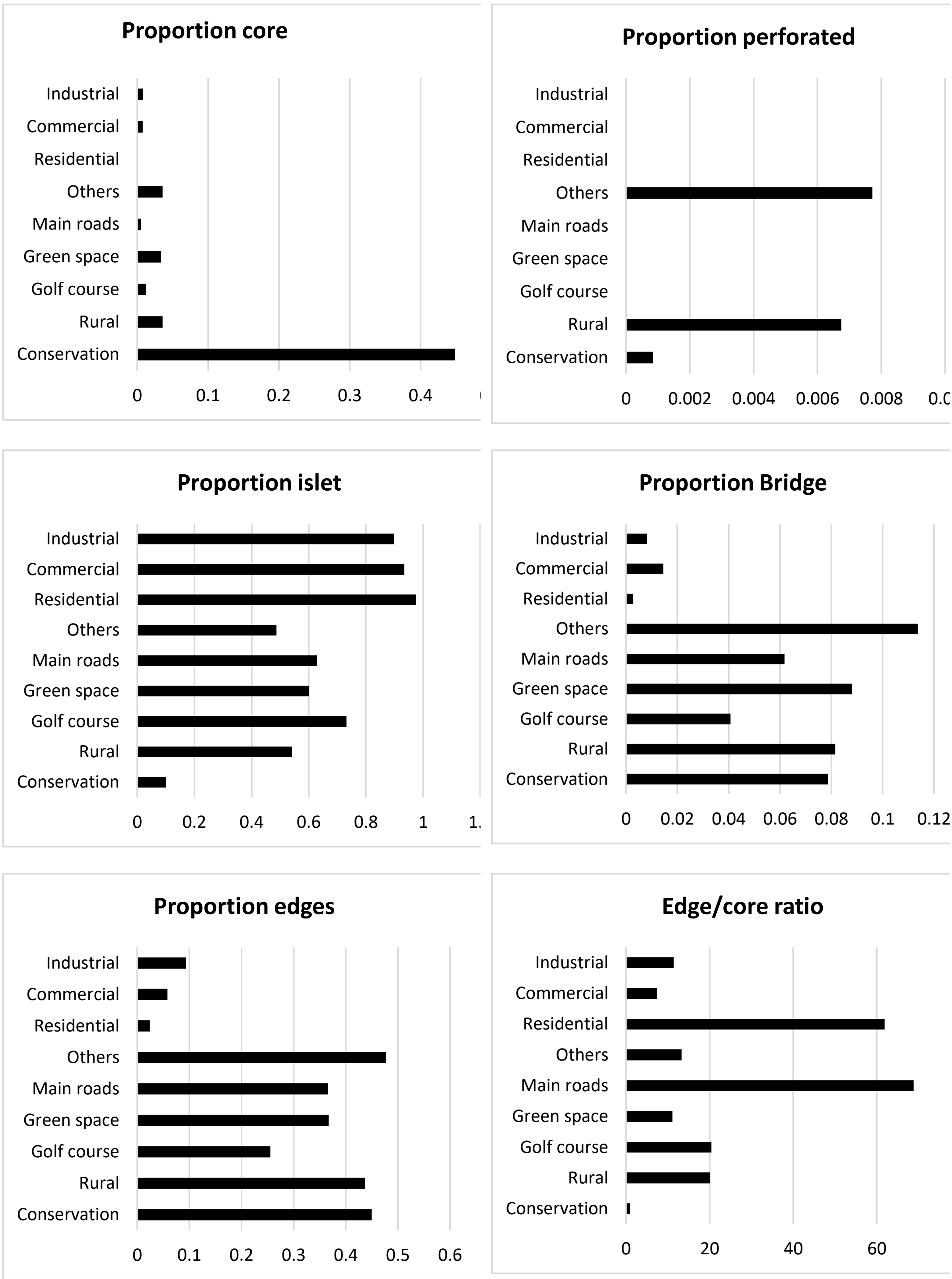


**Figure 4. 3 Vegetation fragmentation indicators among land-use categories**

### 4.3.2 Variation of vegetation attribute characteristics among golf courses

Variations in the vegetation attribute characteristics among golf course types are displayed in Table 4.6, Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8. In terms of golf course size, there were significant differences (P value < 0.05) in vegetation cover proportion, native vegetation cover proportion, and vegetation fragmentation indicators (proportion *Core* and *Edge*/*Core* ratio) among three types of golf course (small, medium and large). Typically, the larger golf courses have a higher proportion of vegetation cover and native vegetation cover (Figure 4.4). Also, the proportion of *Core* is higher in larger golf courses.

**Table 4. 6 Kruskal–Wallis test for the variation of vegetation attributes characteristics among golf course types**

| Golf course characteristic | Variable (Vegetation attribute) | Chi square | Significant level (P value) |
|---|---|---|---|
| **Golf course size (small: <40 ha; moderate: 40-70 ha; large: >70ha)** | Proportion vegetation cover | 6.00 | 0.01426 * |
| | Proportion native vegetation cover | 12.12 | 0.0004 *** |
| | Proportion *Bridge* | 0.87 | 0.64 |
| | Proportion *Islet* | 3.95 | 0.13 |
| | Proportion *Core* | 6.17 | 0.04 * |
| | Proportion *Edge* | 4.09 | 0.12 |
| | *Edge*/*Core* ratio | 6.61 | 0.03 * |
| **Linkage to vegetated area** | Proportion vegetation cover | 6.00 | 0.01426 * |
| | Proportion native vegetation cover | 12.12 | 0.0004 *** |
| | Proportion *Bridge* | 7.3 | 0.006** |
| | Proportion *Islet* | 16.57 | 4.6e-05 *** |
| | Proportion *Core* | 3.65 | 0.1611 |
| | Proportion *Edge* | 18 | 1.4e-05*** |
| | *Edge*/*Core* ratio | 3.81 | 0.05 * |
| **Ownership** | Proportion vegetation cover | 0.49 | 0.9 |
| | Proportion native vegetation cover | 5 | 0.17 |
| | Proportion *Bridge* | 0.79 | 0.85 |
| | Proportion *Islet* | 4 | 0.25 |
| | Proportion *Core* | 3.65 | 0.85 |
| | Proportion *Edge* | 2 | 0.55 |
| | *Edge*/*Core* ratio | 3.81 | 0.5 |

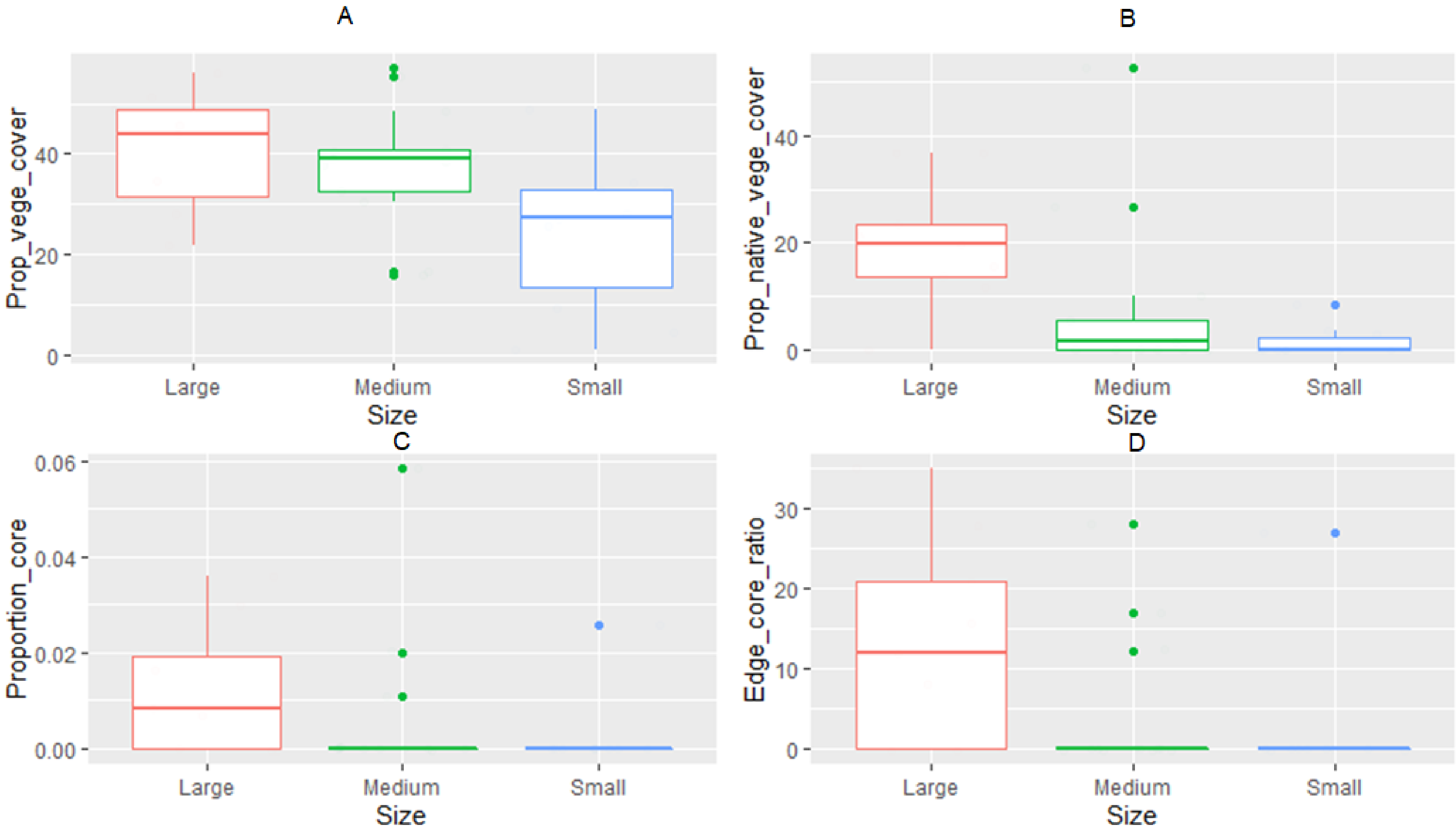


**Figure 4. 4 Box plots of vegetation attribute characteristics (A) – Proportion of vegetation cover; (B) Proportion of native vegetation; (C) – Proportion *Core*; (D) – *Edge*/*Core* ratio for golf courses in three size classes (Large, Medium, Small)**

For golf courses of different ownership classes, there were no significant differences in vegetation attributes with all P values >0.05 (Table 4.6). However, the location of golf courses is one of the important characteristics that affect the vegetation attributes within them. Two types of golf courses (adjacent to and isolated from external vegetated areas) showed differences in their vegetation attribute characteristics (vegetation cover proportion, native vegetation proportion, *Islet* proportion, *Edge* proportion and *Edge*/*Core* ratio) (Table 4.5). Golf courses that are adjacent to vegetation in nature reserves, urban parks and other vegetated areas have a higher proportion of vegetation cover, native vegetation cover and proportion *Bridge*, and lower proportion of *Islet* (Figure 4.5).

The differences of vegetation characteristics between golf courses of different sizes and locations are clearly indicated in Figure 4.6. While the Hamersley Public Golf Course is a small, isolated golf course with no vegetation connection to any external vegetation, Lake Karrinyup Country Club is a larger golf course, and its vegetation is connected with other surrounding green spaces. Furthermore, Hamersley Public Golf Course doesn't contain any native vegetation and all of the vegetation cover is classified as *Islets*. In contrast, Lake Karrinyup Country Club has huger conservation value because of the existence of a significant area of native vegetation. Also, because of the link to the neighboring vegetation, this larger golf course contains vegetation not only as *Islets* but also as *Bridges*.

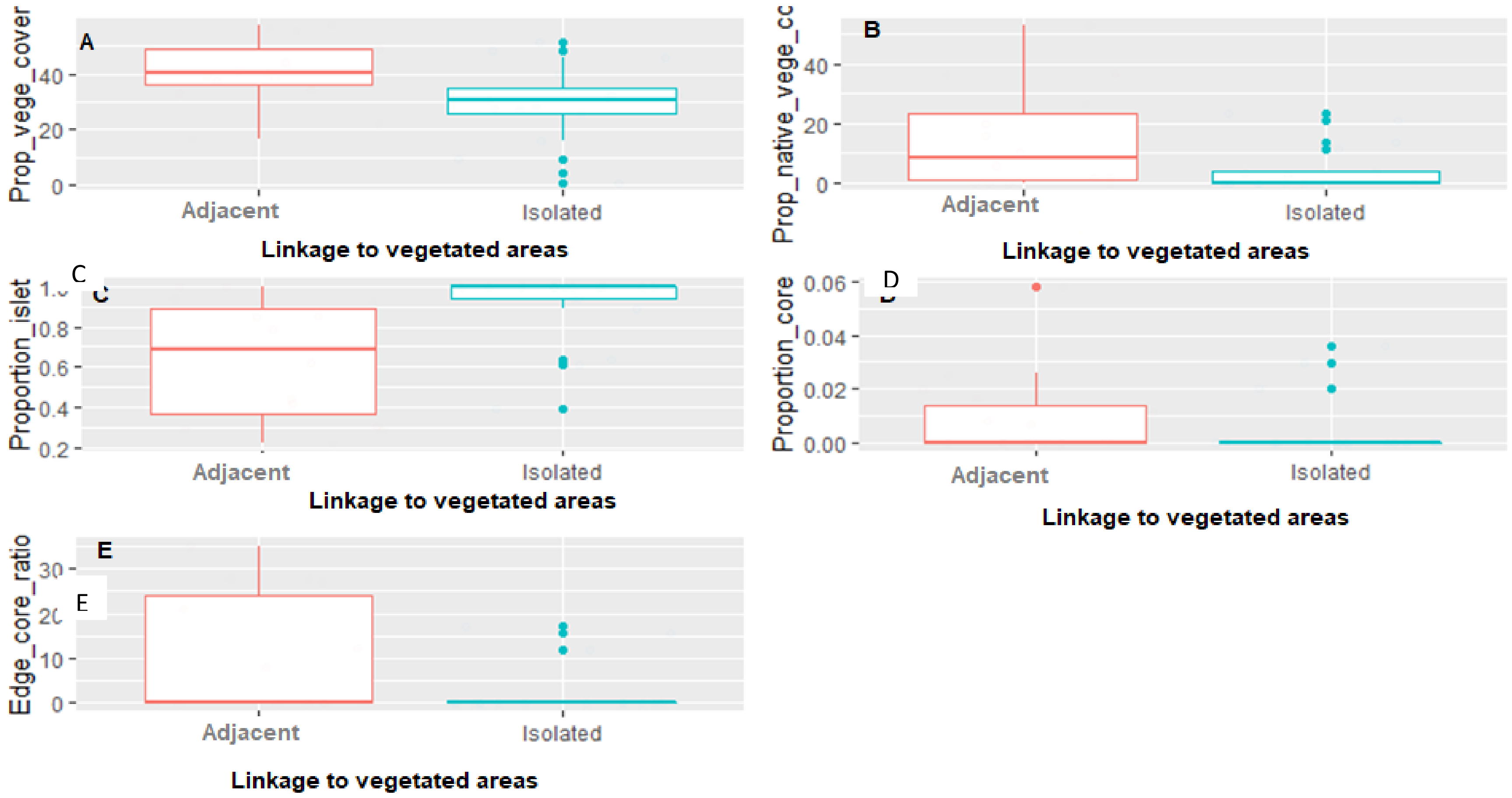


**Figure 4. 5 Box plots of vegetation attribute characteristics in golf courses that are adjacent or isolated to other vegetated areas. (A) Proportion of vegetation cover, (B) proportion of native vegetation cover, (C) proportion *Islet*, (D) proportion *Core* and (E) *Edge/Core* ratio**

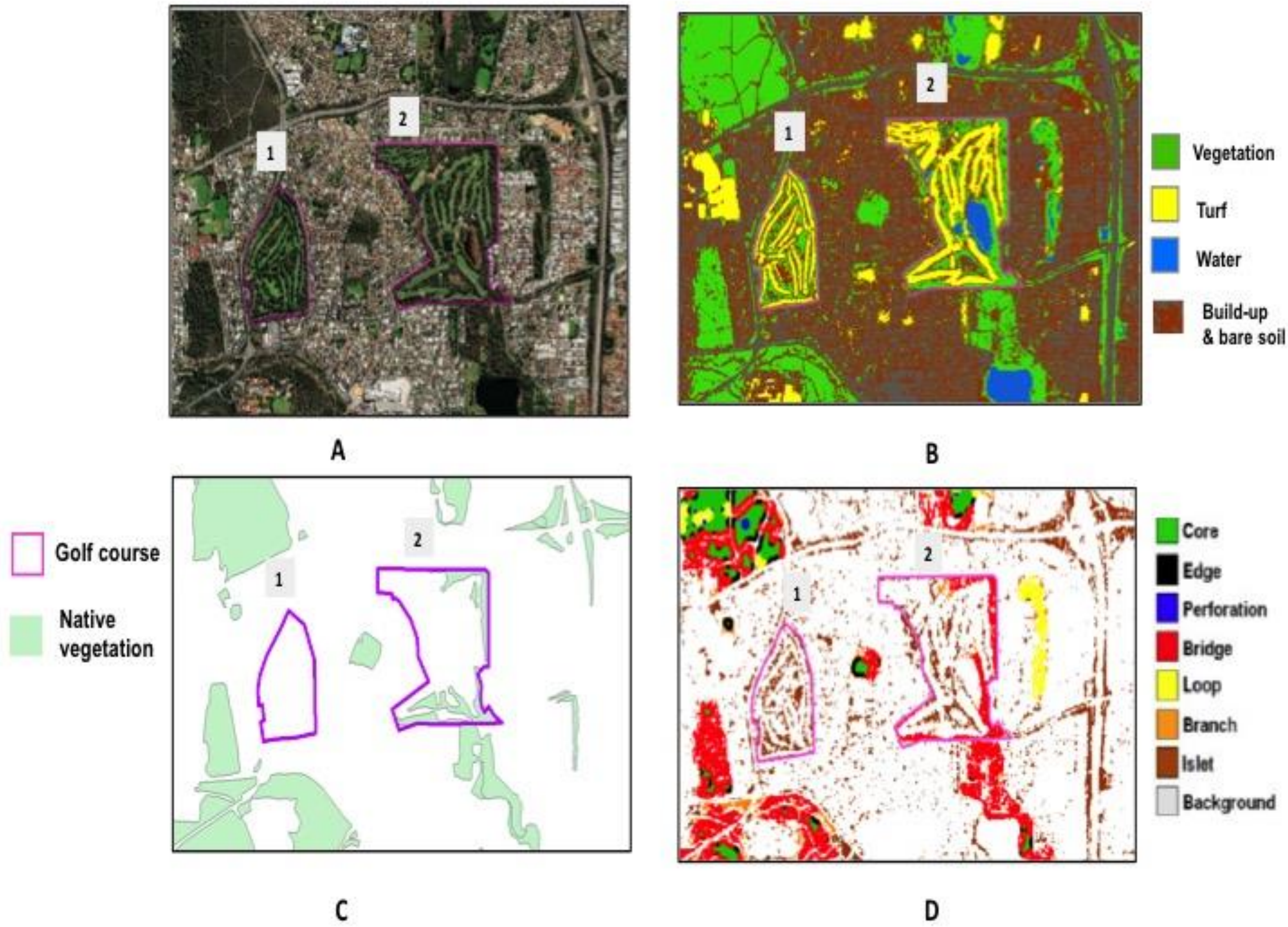


**Figure 4. 6 Vegetation in and around a small, isolated golf course (1. Hamersley Public Golf Course), and a large and connected golf course (2. Lake Karrinyup Country Club) and their surroundings. (A) Google Earth image; (B) land cover classification; (C) native vegetation distribution; (D) MSPA classes**

## 4.4 Discussion

### 4.4.1 Variation of vegetation attribute characteristics among land-uses

Overall, this Chapter found that (for the given region this refer to) vegetation cover  40% in which Conservation land, Rural land and other areas contain the most significant proportion of the vegetation cover as well as native vegetation cover (77%, 53% and 60%, respectively) (Table 4.5). Golf courses, however, are a large urban green space that contain a moderate proportion of vegetation cover (38%) which is higher than that of other Urban green spaces and Main roads, and much higher than that of highly intensive neighborhoods (Commercial, Industrial and Residential) (Table 4.5). The proportion of native vegetation (per total vegetation cover area) in Golf courses is as high as that of other Green spaces but is lower than Conservation, Rural, Main roads, but higher than Residential land in the urban-rural gradient.

These results differ to those of a parallel study (Hodgkison et al, 2007a), undertaken in Queensland, which found that golf courses that retained a greater area of native vegetation than the remaining green spaces in urban landscapes can support a greater diversity of wildlife (urban bat and bird assemblages). Golf courses in Perth with moderate proportions of native vegetation cover (36%) should also be habitats for wildlife in urban landscapes. Additionally, the finding that the remaining native vegetation patches in the Swan Coastal Plain are distributed in all types of land-use from protected areas (Conservation) to highly intensive urban areas indicate that it is necessary to pay attention to conservation activities both within and outside the formal protected area network.

Among off-reserve land-uses, there are considerable areas of land with natural habitats but where future urban and industrial development is planned. These areas are vulnerable to future urban development as they have already been zoned for non-conservation purposes. Perth has experienced urbanization due to rapid population growth and low-density housing developments over the past decades and will continue removing some of the remaining vegetation in coming decades.

In terms of vegetation fragmentation indicators, Golf courses are a type of green space having a high level of vegetation fragmentation (displayed by its *Islet* proportion being just lower than Commercial, Residential and Industrial, but higher than all the other land use categories) in an urban landscape. This is because there are grassed areas existing within green spaces that interrupted the connectivity of overstorey vegetation in the Golf courses. This means that the status of the threatened species that live there will be critical and conservation actions need to be taken for those critically endangered ecological communities in such highly fragmented patches.

The Conservation land is the major contributor to the maintenance of large-scale natural patches with the highest proportion *Core* being above 0.4 which is much higher than that of all other land-uses (under 0.1), and thus indicates lower levels of vegetation fragmentation (Figure 4.3). The proportion of *Islet* is also lowest in the Conservation land in the urban landscape. In contrast, highly intensive land-uses (e.g. Residential, Industrial, Commercial) in this urban landscape are highly fragmented with a very high proportion of *Islet*, low proportion of *Core*, and low proportion of *Bridge*. Despite the insignificance of the *Core* habitat, Golf courses together with Conservation, Green spaces, Rural, and Main roads contribute significantly to the structural connectivity between *Core* forest patches of the green space network in this landscape. Normally, the fragmentation levels are indicated by the proportion of *Edge* and the proportion *perforated* expressing the degree to which *Edge* effects are introduced into the *Core* interior, representing non-vegetation patches within primarily compact vegetation patches. However, in this urban landscape, some land-use types have limited areas of vegetation and very low or zero values of those indicators could be an indication that there is not enough *Core* vegetation to permit *Perforation* and *Edge*.

Vegetation cover in all land use categories in this urban landscape can play the role of ecological land-use complementation which may not be established for conservation purposes but collectively interacting with other green spaces to support biodiversity in a fragmented urban matrix (Colding, 2007). All vegetation cover will contribute significantly to improve gene flow of wildlife populations especially migrating ones such as amphibians, birds, and insects by providing suitable habitats for reproduction and green corridors for dispersal, thus preventing or reducing isolation and loss of genetic variability (Burgin & Wotherspoon, 2009; Dobbs & Potter, 2015; Saarikivi et al, 2013). Hence, my results suggest that golf courses and other urban land-uses should be integrated into urban planning and conservation strategies for better outcomes of conservation in cities. Despite golf courses and other urban land-uses having vegetation that is much more isolated than conservation land, they do contain native vegetation patches. The native vegetation in these two land-use categories is however more threatened because it is in small, isolated natural patches that do not connect to each other. Therefore, to maintain native vegetation biodiversity, it is necessary to consider conservation activities in both conservation land, and in off-reserve, highly fragmented land-use categories of urban landscapes.

### 4.4.2 Variation of vegetation attribute characteristics among golf course types

Statistical tests revealed that the linkage of Golf courses to other urban vegetated areas displayed effects on vegetation attribute characteristics within golf courses. Golf courses adjacent to vegetated areas of parks and conservation land have higher proportion of native vegetation and higher level of connectivity (higher *Bridge* proportion and lower proportion of *Islet* proportion). Conversely, those isolated from the other vegetated area in the green network of urban spaces have lower native vegetation cover and higher fragmentation (Figure 4.5). This indicated that the golf courses connected to other vegetated areas have higher conservation values and these golf courses should therefore be included in conservation strategies. However, the golf courses isolated from vegetated areas should not be excluded because they are often more threatened, and actions need to be taken.

Additionally, golf course size is a characteristic affecting the proportion of total vegetation cover as well as native vegetation. Higher proportion of native vegetation was found in larger golf courses. Moreover, it seems that large golf courses contain higher proportions of *Core* habitat than medium and small golf courses. This also suggests that, with a limited land area, small golf courses are being used intensively, and thus have less ecological values. This study further confirmed the role of habitat size in maintaining vegetation in a human-managed landscape. Previous studied indicated the limited capacity of small remnant woodland patches to support diversity (Jim & Chen, 2016) and native-species propagules due to the lack of habitat connectivity (MacArthur & Wilson, 2001). Large golf courses, especially those linked to other green spaces, therefore are more important nodes in the urban green matrix than the small, isolated golf courses, and thus require an appropriate management action.

Although, elsewhere in the world, it was estimated that at least half of the golf courses' land is green-space, which is subject to low intensities of management intervention, such as forest (Doll & Duinker, 2020), our study found that the vegetated area in golf courses is lower than this estimation with most of the golf courses in Perth have vegetation cover of less than 50%. Despite the moderate vegetation cover of golf courses in the Perth Metropolitan Region, more than half (most are the large size golf courses) contain remnant Swan Coastal plain native vegetation. Golf courses that are linked to other vegetated areas are of value, not only their contribution to connectivity of the vegetation cover network, but also in maintaining native vegetation. As mentioned in Chapter 3, native vegetation in this part of Australia lies within an internationally recognized biodiversity hotspot, and contains critical ecological communities (e.g. Tuart and Banksia woodlands) (Department of Parks and Wildlife, 2016). Hence, the remaining patches existing in the urban matrix of the Swan Coastal Plain, both inside and outside conservation land (e.g., golf course and other green spaces) are critical (Department of Conservation and Land Management, 2002), and it is possible that some become threatened communities in isolated golf courses. Moreover, in urban landscapes, the proportion of native vegetation has a positive correlation with wildlife diversity, and the effective management of green space containing native vegetation patches has positive effects on urban food webs (Chace & Walsh, 2006; Ikin et al, 2013). Despite accounting for only 1% of the total land area, golf courses in the Perth Metropolitan Region can contain indigenous flora and fauna, and some form a link between fragmented areas of bush land. Thus they can play a role in management actions to increase native vegetation in green spaces and contribute to the composition of urban food webs (Threlfall et al, 2017). While the golf course has to operate for recreational and commercial purposes, not for conservation, there is a duty of care to manage these areas in a responsible and sustainable manner.

### 4.4.3 Implication of land-use, conservation associated policies and urban planning

In the human-managed landscape, there are multiple and potentially conflicting and opportunistic goals of management actions employed in urban green spaces (Threlfall et al, 2017). While the demands of using land for urban development is increasing and the area for conservation land is limited with high cost to maintain them, my results support opportunities for coordinating green spaces of all land-use types within urban boundaries in the conservation of biodiversity and ecosystem management (Colding, 2007). Large golf courses that are linked to other vegetated land and have high levels of biodiversity connectivity and native vegetation cover must be involved in conservation strategies for corridor and buffer zones to support conservation land. Lessons must be learned and incorporated into planning for involving both public and private green space owners to take actions together in maintaining vegetation in the whole landscape. For example, coordinated efforts may be more achievable in publicly managed green space such as parks, gardens and golf courses managed for the same purpose (e.g. recreation), and this can lead to an increase in homogeneous habitats that are connected to each other (Threlfall et al, 2016a). However, coordinating ‘bottom up’ management by privately land owners is likely to be challenging (Threlfall et al, 2017).

Golf courses, with their heavily humanized footprints, are unlikely to have the same level of ecological values as undisturbed natural habitats (Doll & Duinker, 2020). Also, course managers may prefer to maintain vistas over preserving a healthy tree canopy and remove regenerating trees to satisfy golfers’ desire of sweeping views of greens and water bodies. Moreover, in order to meet the commercial target of increasing financial benefits, course managers can increase the number of holes in the courses by clearing natural bush. Therefore, maintaining and improving patches of vegetation within golf courses are always a challenge. Despite these assertions, the value of well-treed courses as ecologically significant spaces has been well documented over the past two decades (Jim & Chen, 2016; Terman, 1997; Threlfall et al, 2016a; Yasuda & Koike, 2006). Therefore, in the pursuit of long-term ecological integrity, improved golf course management is of the utmost importance. Designing naturalistic golf courses with large areas of vegetation, and respecting the remnant patches will be important for maintaining ecological functions of golf courses (Tapias & Salgot, 2006; Terman, 1997).

### 4.4.4 Limitations and further research

This study used remotely sensed tools to measure attributes of vegetation from high resolution satellite imagery (PlanetScope 3 m x 3 m) and the existing native vegetation and land-use maps covering a large area of urban landscape. The study focused on the vegetation features including vegetation cover, native vegetation cover, and vegetation fragmentation indicators. However, due to limitations of remote sensing technology in detecting vegetation attributes, other vegetation characteristics such as vegetation composition, species composition and abundance, vegetation structure (vegetation cover, height, and stem density) have not been included in this research, and thus further comparative analysis of vegetation composition, function and structure within golf courses and other land-uses should be explored in the future. Furthermore, management input of golf courses was not included as a variable in this study, and it is likely that intensive management would affect the vegetation characteristics to some extent (Jim & Chen, 2016). As the outcomes of management activities on urban vegetation are likely to be context-dependent, future studies should include a specific focus on landscape context and green space type, comparing the outcomes of these efforts in dense urban areas, as well as in urban fringe environments.

## 4.5 Conclusions

This study compared the vegetation attributes within golf courses with those in other land-use categories in an urban landscape using remotely sensed data. This study confirmed that vegetation in golf courses, despite consisting of remnant patches of native vegetation, are more fragmented compared to Conservation and Rural land categories, but less fragmented than intensively used land such as Residential, Commercial and Industrial. Among golf courses, golf course size and location and ownership have strongly influenced the vegetation characteristics.

This study suggests that vegetation cover in all land use categories in urban landscapes can play a role in ecological land-use complementation even on land which may not be established for conservation purposes. This will be by collectively interacting with other green spaces to support biodiversity and ecological services in a fragmented urban matrix. Future studies are required to determine vegetation composition and structure attributes as well as the impacts of golf courses' management inputs on vegetation characteristics for better conservation of urban vegetation.

# Chapter 5 Cooling effects of vegetation in the city: The role of golf courses


## Abstract

Increased heat in urban environments, often termed “urban heat islands”, is among the most severe problems confronting cities worldwide. Finding ways to reduce urban temperatures is important to protect city residents particularly with projections of climate-induced temperature increases. While large urban green spaces such as parks and nature reserves are widely recognized for their benefits in mitigating urban temperatures, the role of urban golf courses is poorly quantified. This chapter assesses the role of golf courses in reducing urban land surface temperature (LST), compared to other urban land-uses, and determines the factors that influence the cooling effects using multispectral, high resolution airborne imagery (0.3 x 0.3 m). The results suggest that urban golf courses have the second lowest LST after conservation land, and thus have strong capacity for summer urban heat mitigation. The effect of distance to water bodies and vegetation structure are the most important factors contributing to cooling effects. Specifically, the area of green spaces covered with tall trees (>10 m) and large vegetation patches have strong effects in reducing LST. This suggests that increasing the proportion of big trees and reducing insolation in golf courses and other land-use categories will decrease urban LST and benefit wildlife in those habitats as well as improving the microclimate for urban residents.


## 5.1 Introduction

Urban development has transformed the land cover of cities worldwide from natural to anthropogenic landscapes, causing changes in the biological and physical characteristics of the transformed surfaces (Al-Manni et al, 2007). These changes often result in environmental degradation leading to negative impacts on the quality of life for city dwellers (Lin et al, 2017). One of the consequences of urbanization is the relatively higher temperature in urban than in surrounding suburban/rural areas, with this termed as “urban heat islands” (O’Malley et al, 2014). Over recent decades, extreme summer heat has become more frequent across many cities in the world, making urban heat an increasingly important topic in environmental research (Ramamurthy & Bou-Zeid, 2016; Tan et al, 2010). It is projected that this problem will increase in many regions of the world under the influence of climate change (IPCC, 2021).

Extreme temperatures have serious impacts on human health, such as heat rash, sunburn, fainting, and heat exhaustion (Baccini et al, 2008; Gasparrini et al, 2015), impacting the life quality of city dwellers (Heaviside et al, 2017). A large number of deaths related to heat occurred during heat waves in Chicago in 1995, and in 16 European countries in 2003 (Baccini et al, 2008). Moreover, rising temperatures in urban areas creates an uncomfortable environment for residents which results in increasing demand for energy for cooling systems in their homes during extreme heat events (Lundgren-Kownacki et al, 2018). Therefore, understanding the spatial distribution of temperature and underlying drivers associated with cooling effects in urban landscapes is a key concern for urban planners.

In order to deal with urban heat issues, studies have been undertaken to identify the dynamics of warming in urban areas (Jain et al, 2020). In general, an increase in urban green space results in a cooling effect, whilst impervious land-covers lead to a warming effect (Aram et al, 2019; Giridharan & Emmanuel, 2018). Concrete, asphalt, stone, and metal all absorb and retain solar energy, but unlike more natural areas, they store and slowly release this heat back into the atmosphere (Oke, 1982). Grass, trees, and other vegetation have a natural heating and cooling cycle that is disrupted by urban structures. Vegetation cools the surrounding area by providing shade and through evapotranspiration. Shaded surfaces may be 10-25°C cooler than unshaded surfaces (Akbari, Kurn et al. 1997). Evapotranspiration can help reduce peak summer temperatures by 1–5°C (Huang, Akbari et al. 1990). Therefore, the abundance, or lack, of vegetation in a city can have effects on the rate of atmospheric carbon dioxide sequestration and the amount of heat that the city retains (Duncan et al, 2019; Wong & Yu, 2005). Whether urban vegetation occurs as large nature reserves or as more fragmented and less functionally healthy green spaces for purposes other than conservation (such as public parks, golf courses, cemeteries, military bases, hospitals, university campuses or street trees) they are critically important in cooling cities and making them more livable (Alavipanah et al, 2015). Therefore, livable city planning should require a flexible approach that takes advantages of all opportunities to retain green spaces, combining efforts both in formal parks and other recreational spaces.

Golf courses are a type of recreational green space established for commercial and public purposes. They are often a controversial land-use due to their heavy use of water, chemical herbicides and exotic ornamental vegetation (Chapter 2), and this has led to various criticisms from ecologists (Guzmán & Fernández, 2014). However, other studies have confirmed the ecological values of golf courses in terms of biodiversity conservation both as a habitat for wildlife (Colding & Folke, 2009; Terman, 1997) and the connectivity of vegetation networks in urban landscapes (Chapter 3). Moreover, the rough (out of play) vegetated areas and irrigated lawns in golf courses are expected to play a role in cooling cities (Fung & Jim, 2017). However, the ecological value of golf courses in reducing urban heat has been largely ignored by ecologists (Fung & Jim, 2017).

Recently, remote sensing-based studies have allowed researchers to assess the spatial distribution of Land Surface Temperature (LST) in urban areas and to establish correlations between vegetation and urban LST models (Deilami et al, 2016; Shandas et al, 2019; Weng, 2009). However, most studies have used low and moderate resolution satellite imageries, such as MODIS or Landsat, to calculate LST as a proxy of urban heat (Wang et al, 2020; Zhang et al, 2004). However, these approaches don't provide information about how vegetation characteristics such as fragmentation, vertical structure, and health impact on the local cooling effect. The moderate resolution (30 m) satellite imagery (the Landsat Thematic Mapper (TM)) sensor limits the capacity to detect vegetation of different height classes and their associated LST variability. In contrast, airborne high spatial resolution imagery (0.3 m) has much greater capacity to detect more detailed vegetation characteristics such as vegetation height classes (Evans et al, 2012). Furthermore, studies that have investigated variation in LST among urban formal parks, open spaces and residential gardens (Bokaie et al, 2016; Fu & Weng, 2016; Rinner & Hussain, 2011) have not included golf courses as a separate urban land-use. Not surprisingly then, urban planners often lack information for planning urban development that can reduce heat exposure.

This chapter examines the hypotheses that golf courses in urban landscapes can play a role in cooling urban environment; and that the characteristics of vegetation structure (height class and spatial configuration) influences variations in LST in urban landscapes. The objectives of this chapter therefore were to (1) compare the land surface temperature within golf courses with those of other urban land-use categories, and (2) determine the influences of different vegetation characteristics and geographic location on the capacity of golf courses for urban heat reduction.

This case study was conducted in the suburbs of Perth, Western Australia, using high resolution (0.3 m), multispectral airborne imagery. This builds on the results of Chapter 3 and Chapter 4 which found that long term urbanization in Perth was associated with vegetation loss and fragmentation, whilst golf courses played a role in maintaining vegetation cover, and vegetation connectivity in the urban landscape. Thus, findings from this research will illustrate the potential of using golf courses as a green space out-side protected area networks and to guide planning of vegetation configuration and vegetation management to optimize cooling at the local- and city-scales.

## 5.2 Methods

### 5.2.1 Study area

*General description of the study area*

Perth is located between latitudes -31.953512 and longitudes 115.857048 (Figure 5.1). The Perth Metropolitan area covers 6,418 $km^2$, with a population density of 317.7 people per square kilometer. Perth has a Mediterranean-type climate with hot and dry summers, lasting from December to March. Meanwhile winters are cool and wet (Duncan et al, 2019). Extreme heat events (substantial rises in the temperature, duration and frequency of very hot days) have increased in Perth over the past two decades, and are projected to increase in coming years (Whetton et al, 2016). These events pose health risks for urban citizens especially the elderly, young, sick, and people from lower socio-economic areas (Environmental Protection Authority, 2015).

Perth has experienced extensive urban expansion since the 1980s (Subas, 2014). The expansive growth of the Perth metropolitan area has caused sustainability concerns due to large-scale conversion of natural land to impervious surfaces (Subas, 2014). The CSIRO has projected that by 2030 the annually averaged warming of this region will be about 0.5 to 1.2 degrees Celsius above 1986–2005 levels (Whetton et al, 2016). Therefore, the Western Australian government issued a long term strategic guide for the development of Perth by 2050, that identified redugcing the urban heat as one of sixteen aspirations under the strategy for the Planning Commission, State and Local Government by expanding tree canopy in high urban heat risk areas (Environmental Protection Authority, 2015; The WA Local Government Association (WALGA), 2021).

*Spatial subdivision of the study area*

The research interest of this Chapter focuses on the western suburbs (WESROC suburbs) and the Joondalup suburbs of Perth which cover 16,205 ha (Figure 5.1). The WESROC suburbs (also known as the golden triangle) are a group of old suburbs established prior to the first urban development planning of Perth (i.e. pre-1950s), and located west of the city's central business district and north of the Swan River. Joondalup comprises new suburbs established in the 1990s. These suburbs, established through different times in the history of Perth's planning with different urban designing styles, are considered representative of residential suburbs across Perth's urban landscape, and in cities elsewhere in developed countries in the world.

In order to better describe the study area based on knowledge of local land use properties, development intensity, and socio-economic levels, two sub-levels of the study area were defined as follows: (1) WESROC included the old suburbs, which is characterized by low to moderate density residential areas, recreation, nature reserve, and wetlands; and (2) Joondalup is a younger urban area which was developed as a result of northerly urban expansion following extensive urban expansion in the 1990s, and is characterized by dense commercial and residential areas. In these areas, there are seven golf courses (public, private and semi-private), varying in size (Small: <40 ha, Moderate: 40-70 ha, Large: >70 ha) established over time. They include (1) Joondalup Resort Golf Club, (2) Wembley Golf Course, (3) Cottesloe Golf Course, (4) Claremont Golf Course, (5) Sea View Golf Club, (6) Nedlands Golf Club, (7) Mosman Park Golf Course (Figure 5.1).

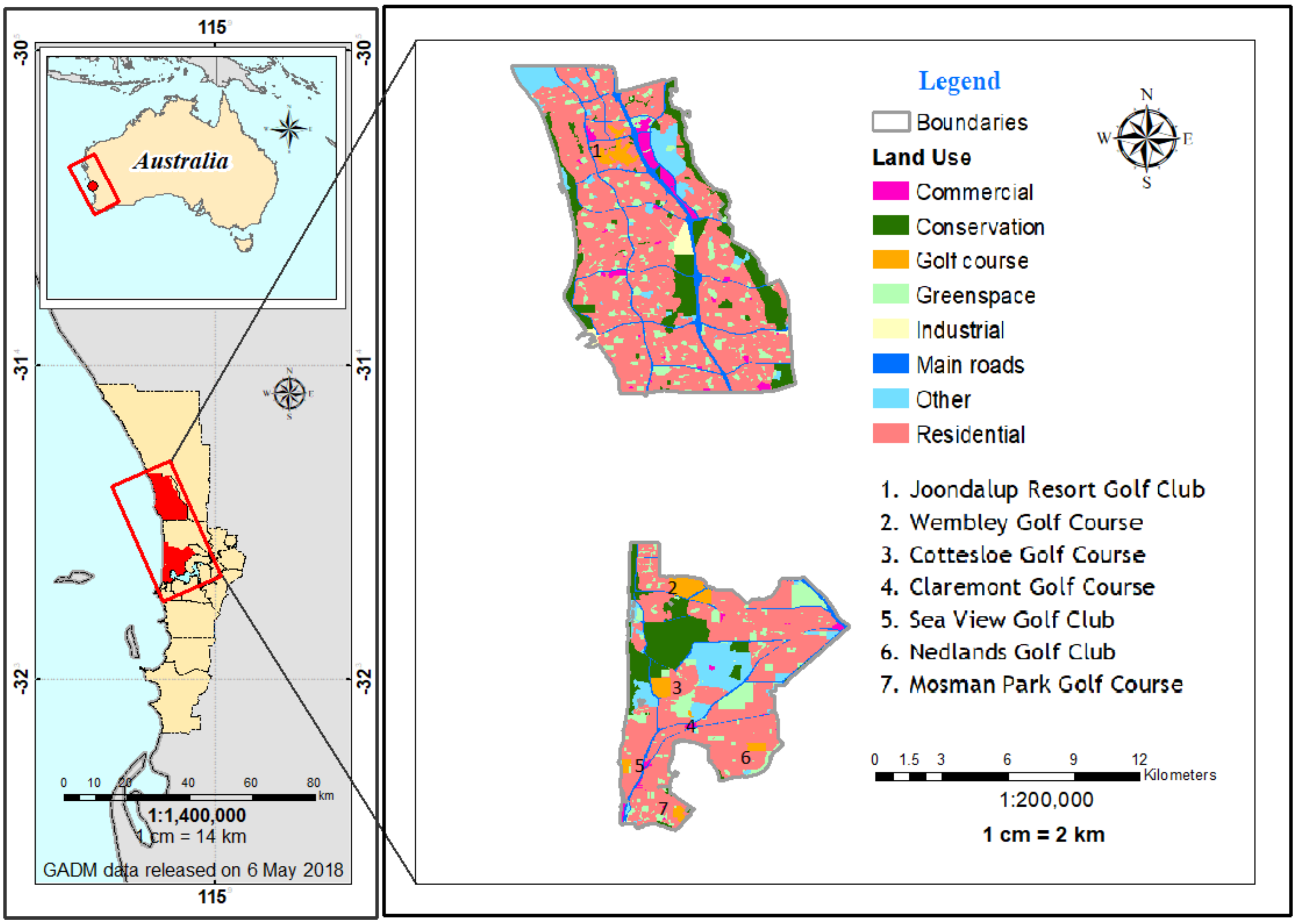


**Figure 5. 1 Study area showing location of the seven golf courses used in this chapter and the associated land use**

### 5.2.2 Data sources and geospatial analyses

To provide accurate information about the daytime land surface temperature (LST) in relation to urban land use, land cover and vegetation characteristics the study used multispectral, high resolution airborne imagery (0.3 x 0.3 m), acquired at ~11:00-13:00 h on a typical hot summer's days (10$^{th}$ and 11$^{th}$ March 2020) with a daily maximum temperature at Perth Metro station (site number: 009225) of 35.1 $^{0}$C for both 10$^{th}$ and 11$^{th}$ March 2020 (Bureau of Meteorology, 2020).

High resolution RGB, seven band multispectral and long wave thermal radiation were acquired concurrently using the custom ArborCam$^{TM}$ vegetation monitoring system (ArborCarbon Pty Ltd). Imagery was acquired on dedicated flights using a customized Piper PA-28 aircraft with specifications outlined in .

**Table 5. 1 Acquisition parameters and resulting image Ground Sample Distance (GSD) for each of the imaging sensors for the two study sites.**

| | WESROC councils | City of Joondalup |
|---|---|---|
| Acquisition date | 10$^{th}$ March 2020 | 10$^{th}$ & 11$^{th}$ Match 2020 |
| Acquisition height | 2440 m | 3048 m |
| High resolution RGB:GSD | 0.08 m | 0.1 m |
| Multispectral: GSD | 0.24 m | 0.3 m |
| Thermal: GSD | 1.0 m | 1.25 m |

The Multispectral sensor captures seven distinct narrow multispectral bands (maximum FWHM 10 nm), strategically located between 450 and 780 nm of the electromagnetic spectrum.

Long wave thermal Infra-red radiation (Thermal IR 7500 - 14000 nm) was converted to LST in degrees Celsius by applying a standard emissivity correction across the scene of 0.95 to produce a single-band 32-bit raster, with each pixel representing land surface temperature.

All imagery was orthorectified and radiometrically corrected using a series of propriety image processing workflows. A Digital Surface Model (DSM) was generated using a Structure from Motion processing technique during orthorectification. This DSM was further classified to identify ground surface pixels, which were then interpolated to produce a Digital Terrain Model (DTM). The difference between the DSM and DTM was calculated to determine the Feature Height Model. Final imagery was converted to units of surface reflectance using radiometric targets placed throughout the scene. Finally, vegetation within the scene was classified using a segmentation and supervised classification approach.

*NDVI calculation*

Normalized Difference Vegetation Index (NDVI) maps were obtained by calculating the ratio between the red (R) and near infrared (NIR) using Equation 1 (Tucker, 1979):

$$NDVI = (NIR - red)/(NIR + red) \quad (1)$$

*Morphological Spatial Pattern Analysis (MSPA)*

MSPA was employed in this research for analysis of spatial configuration of vegetation cover (turf and all other vegetation types) based on the concept of "habitat availability" and "graphic theory" (Pascual-Hortal & Saura, 2006; Saura et al, 2011; Velázquez et al, 2019) as described in Chapter 3 (Table 3.1).

*Land-use data*

We selected eight land-use categories representing the main components in the urban landscape, as follows: Conservation land (1); Golf course (2); Green space (3); Commercial (4); Industrial (5); Residential (6); Main Road (7); Other land-use (8) as described in Chapter 4 (Table 4.4). Such a selection of land-use categories is common in comparative ecological research in urban landscapes (Blair, 1996; Threlfall et al, 2016a) and are expected to have different LST values due to different land cover components.

### 5.2.3 Statistical analyses

In order to address objective 1 (comparing the variation of LST among land-use categories and among golf courses), LST mean values were derived for each of the eight land-use categories using vector data analysis (zonal statistics) in ArcGIS 10.3 and descriptive statistics in R 3.6.1. The land-use layer (Figure 5.1) was used to define zonal boundaries.

To address objective 2 (examining the factors influencing the cooling effects of golf courses), the variation and correlation of LST with each driving factor (Figure 5.4) was derived. I randomly generated more than 500 random points within the seven golf courses and the study area. Values for each independent variable were assigned to each point using Extract Multi Values to Points tool in ArcGIS 10.3. All geographical analyses were conducted using ArcGIS version 10.3 and statistical analyses were performed in R 3.6.1 (R *Core* Team, 2017). Based on the initial description of the relationship between LST and the variables, a multiple linear regression model was built with the F-statistic in R 3.6.1 to describe the effects of vegetation characteristics and geographic location that drive LST.

The explanatory variables examined are listed in Table 5.2 These variables were subdivided into four groups: vegetation height class, MSPA class, NDVI and distance to water resources (Table 5.2). Previous studies have explored the distance to the coast as a factor impacting urban temperature (Ossola et al, 2021). However, the study area has a network of the ocean, the estuary of the Swan River, and groundwater derived lakes. These water bodies are suspected to influence the LST, and thus the distance to the water resources (ocean, lakes, river) was measured using the near tool in ArcGIS 10.3. The values were added to random points as an independent variable in the regression analysis.

**Table 5. 2 Independent variables considered in the multivariate model of LST within golf courses and other land use categories**

| Variable | Description |
|---|---|
| **Vegetation height class** | |
| Non_vegetation | Non-vegetation cover area |
| Turf | The top layer of a grassy area |
| 0-3 m | Vegetation of 0-3 m height |
| 3-10 m | Vegetation of 3-10 m height |
| 10-15 m | Vegetation of 10-15 m height |
| >15 m | Vegetation of >15 m height |
| **MSPA Class** | |
| *Bridge* | The striped ecological vegetation that connects two *Cores*, which is equivalent to the connecting corridor |
| *Core* | Large-scale natural patches with high connectivity |
| *Edge* | The transition zone between vegetation and non-vegetation areas. |
| *Islet* | Small natural patches that are isolated and do not connect to each other |
| *Loop* | Connecting corridor inside a large natural patch |
| *Perforation* | Unnatural patch inside the *Core* area. |
| **Distance to water resource** | The nearest distance from the sample point to the water resources (lake, river and coast) |
| **NDVI** | Normalized different vegetation index: NDVI = (NIR – RED)/NIR + RED)<br>NIR – reflection in the near-infrared spectrum<br>RED – reflection in the red range of the spectrum |

In terms of vegetation variables, previous studies have focused on the vegetation cover (Ossola et al, 2021) and vegetation types (grass, shrubs, and trees) (Duncan et al, 2019). In this Chapter more details of vertical vegetation structure are explored (where vegetation is classified to different height classes (Table 5.2) and spatial vegetation configuration where vegetation is classified into different habitat types (MSPA classes) based on the patch size and their connectivity to other vegetation areas (Table 5.2) and they are added to random points for the regression analysis.

## 5.3 Results

### 5.3.1 Variation of land surface temperature (LST) among land-use categories and among golf courses

Overall, the Conservation land was the coolest land-use category (mean LST of approximately 30 $^{0}$C). Golf courses had the second lowest mean LST (around 31 $^{0}$C) in the study area (Figure 5.2A), and thus when they were established in the dense urban area, Golf courses played the role as cool islands (Figure 5.2B).

These land-uses were followed by the Green space land-use category. In contrast, the average LST for Industrial, Residential and Main road land uses were highest and ranged from approximately 35 $^{0}$C to 37 $^{0}$C. The land use types in the order of highest to lowest temperatures were Main roads, Residential, Industrial, Other, Commercial, Green space, Golf course and Conservation (Figure 5.2A).

However, the LST was different among the seven studied golf courses and varied significantly with the mean LST within these golf courses ranging from the lowest (around 29 $^{0}$C) for Nedlands to the highest (around 32 $^{0}$C) for Joondalup (Figure 5.2B). These results indicate that the golf courses have different capacities to cool their local environments, and that there may be underlying drivers that lead to this variation.

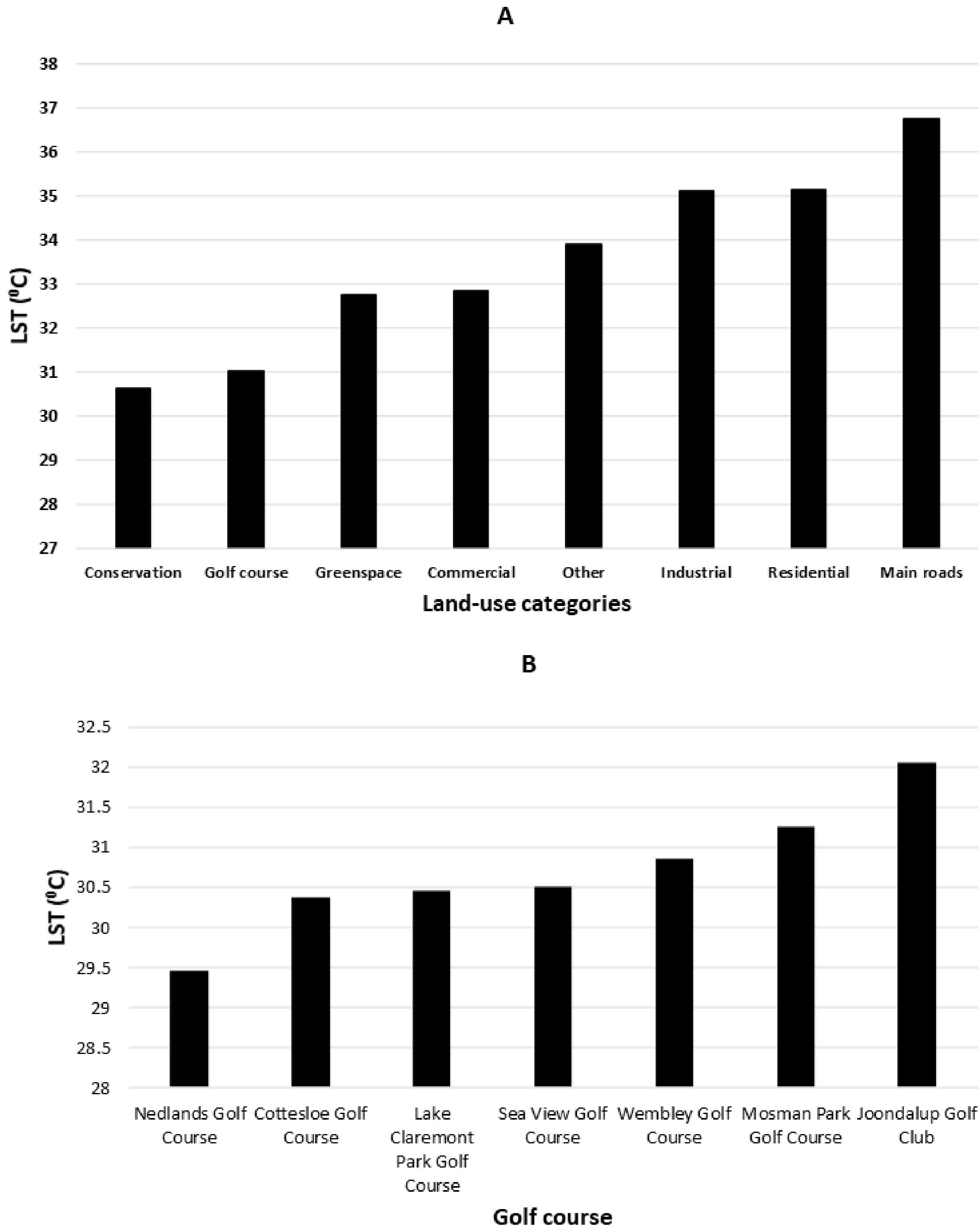


**Figure 5. 2 Variation of the mean values of LST among (A) land-use categories and (B) selected golf courses**

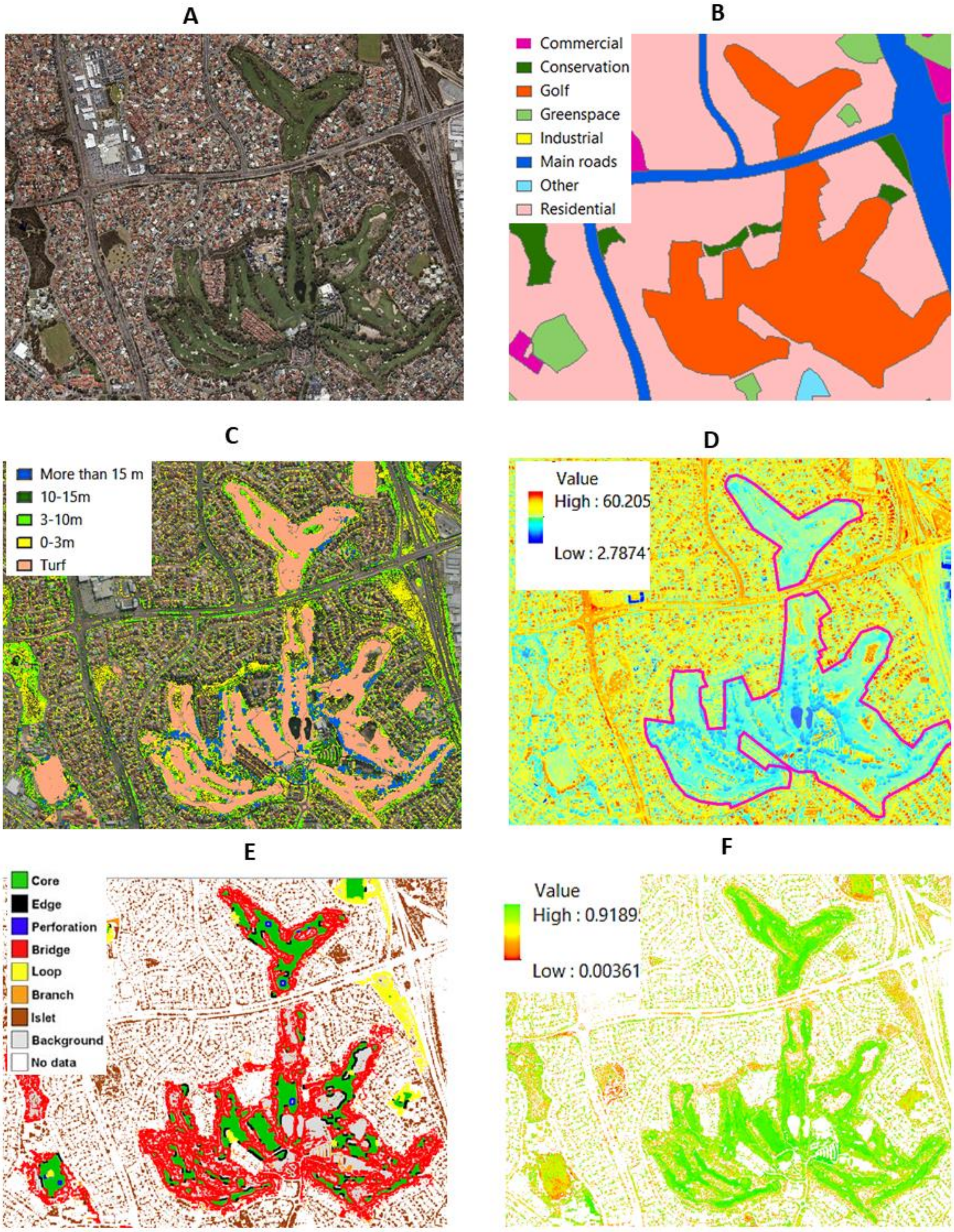


**Figure 5. 3 Joondalup golf club and surroundings in the city of Joondalup, Perth, WA. (A) Airborne image; (B) Details of the Land-use categories; (C) High resolution vegetation map of different height classes; (D) Day time LST; (E) MSPA classes; (F) NDVI map. Data was collected on typical late summer days (maximum temperature 35.1°C) - 10th and 11th March 2020**

### 5.3.2 Factors influence cooling effects of golf courses

There was a positive relationship between LST and distance to water resources (Figure 5.4B) which indicates the availability of water resources in the cities will help to cool down in the hot summer days.

Moreover, vegetation characteristics are factors that also impact cooling. Figure 5.4C clearly shows the LST in non-vegetated areas is much higher than any type of vegetation (LST median is around 35 $^{0}$C) indicating the role of vegetation coverage in providing a cooling effect.

Within areas of vegetation cover, NDVI values reflect vegetation health, and these show a strongly negative relationship with LST (R=0.77). This means that the green, healthy vegetation will have stronger capacity in cooling urban areas (Figure 5.4A).

However, not all types of vegetation have the same cooling effects. Vertical structure and horizontal configuration of vegetation further determine the capacity of vegetation in cooling. Vertically, the taller vegetation is, the cooler the temperature is (Figure 5.4C and Table 5.4) with vegetation of >10m height having a median LST of around 27 $^{0}$C. Meanwhile, 0-3 m high vegetation has a mean LST of around 29 $^{0}$C and turf LST is around 33 $^{0}$C (Figure 5.4C).

The size of vegetation patches and the linkages among them also have cooling effects (Figure 5.4D). A large vegetation patch combined of the outer *Edge* and *Core* area has a low LST at around 27-28$^{o}$C. The *Bridge* class that connects two *Cores* area also has the similar low LST (Figure 5.4D). The *Islet* representing small, isolated patches and *Perforation* representing the inner *Edge* have the highest LST (Figure 5.4D).

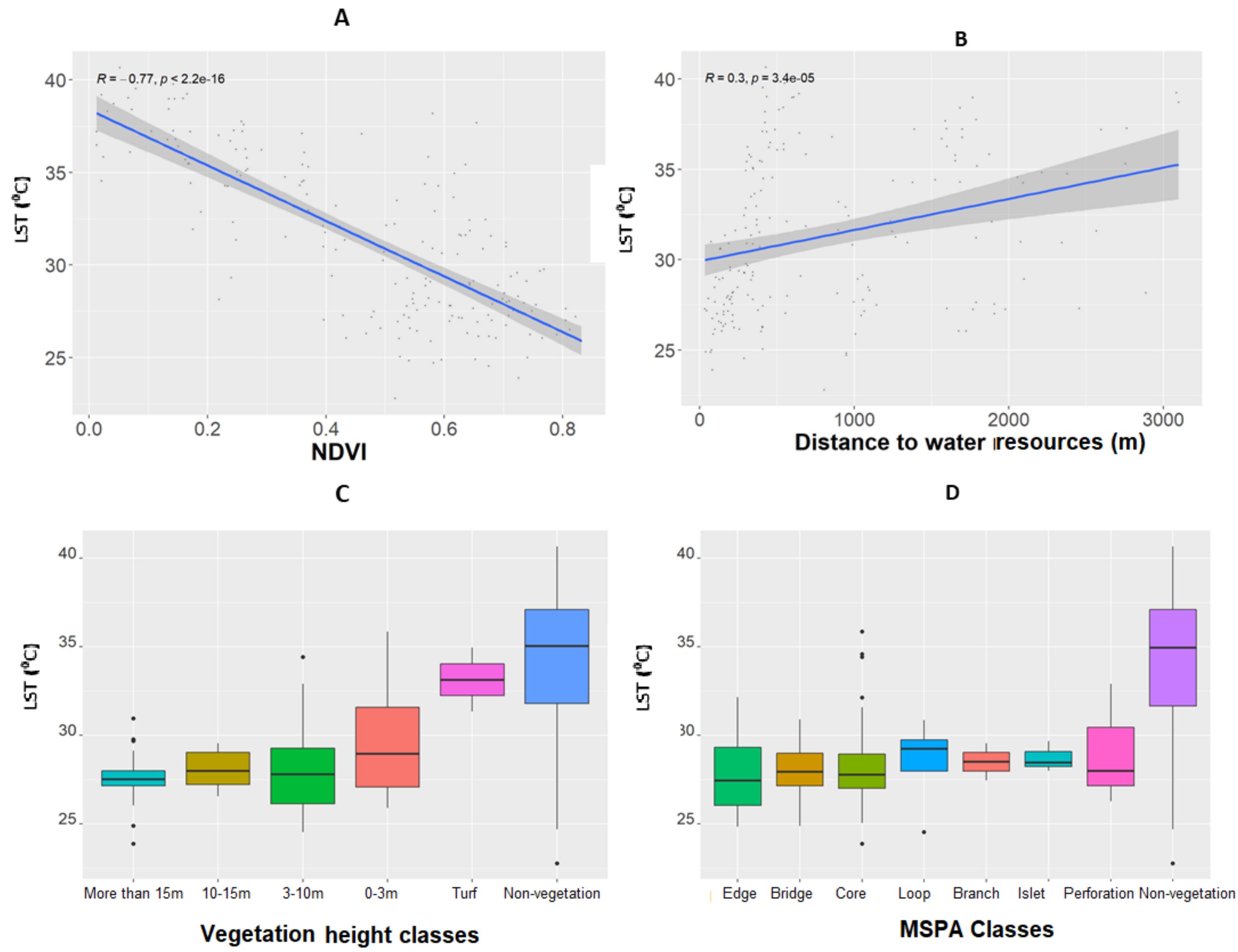


**Figure 5. 4 A - Relationship between LST and NDVI; B - Relationship between LST and distance to the water resources; C – Variation of LST among vegetation high classes; D – Variation of LST among MSPA classes**

The multiple linear regression model for predicting LST had a R-squared value of 0.72 (P <0.0001) indicating that LST is closely related to the vegetation variables and distance to the water resources (Table 5.3). However, in the subset of vegetation height classes variables, only the coefficient of vegetation 10-15 m and >15m had a P-value < 0.05 (Table 5.4).

Similarly, among MSPA variables, only the classes representing large patches (*Core*, *Edge*) have P-values of <0.05 (Table 5.4). This means that taller vegetation (10-15 m and >15 m) and large patches of vegetation that combine outer *Edge* and *Core* areas had significant effects on LST. Moreover, the multi-regression model further determined that the important factors influencing LST were the health of vegetation indicated by the NDVI value and the distance to the water resources) (with coefficients having P-values < 0.01) (Table 5.4). This suggests that these six independent variables are statistically significant predictors of the LST.

**Table 5. 3 Performance of best multivariate model for predicting LST**

| Model | R-squared | Adjusted R-squared | P-value |
|---|---|---|---|
| Thermal = Vegetation Strata + MSPA classes + Distance to water resource + NDVI | 0.72 | 0.7008 | <2.2e-16 |

**Table 5. 4 Estimates for each independent variable from the multivariate model in Table 5.3 for predicting LST in Perth, Australia**

| Variable | Coefficients | Std. Error | z value | Pr (>\|Z\|) |
|---|---|---|---|---|
| Intercept | 3.830e+01 | 2.006e+00 | 19.094 | < 2e-16 *** |
| **Vegetation strata** | | | | |
| Non-vegetation | 1.640e-02 | 1.177e+00 | 0.014 | 0.98889 |
| Turf | 1.501e+00 | 2.033e+00 | 0.738 | 0.46142 |
| 3-10 m | -1.353e+00 | 7.696e-01 | -1.758 | 0.08057 |
| 10-15 m | -2.068e+00 | 8.442e-01 | -2.450 | 0.01531 * |
| >15 m | -1.953e+00 | 8.410e-01 | -2.322 | 0.02140 * |
| **MSPA Class** | | | | |
| *Bridge* | -1.408e+00 | 1.815e+00 | -0.776 | 0.43904 |
| *Core* | -2.774e+00 | 1.741e+00 | -1.593 | 0.011305 * |
| *Edge* | -4.151e+00 | 1.862e+00 | -2.230 | 0.02709 * |
| *Islet* | 2.656e-01 | 2.166e+00 | 0.123 | 0.90253 |
| *Loop* | -8.312e-01 | 2.106e+00 - | 0.395 | 0.69363 |
| *Perforation* | 2.535e+00 | 2.206e+00 - | 1.149 | 0.25228 |
| **NDVI** | -1.109e+01 | 1.011e+00 | -10.968 | < 2e-16 *** |
| **Distance to the water resources** | 8.072e-04 | 2.525e-04 | 3.196 | 0.00166 ** |

***P < 0.001; **P < 0.01; *P < 0.05

## 5.4 Discussion

### 5.4.1 Golf courses as localized cool spots can contribute to urban cooling strategy

The findings indicated that urban Golf courses have lower temperatures than most other urban land-use categories (except Conservation land). This means that in a warming climate, golf courses, with almost all their surface area covered with vegetation, ponds and turf (Chapter 4) will become cool-islands and natural havens in cities where most of the surface are dominated by building structures and heat-absorbing concrete. Green spaces in golf courses include both irrigated fairway areas and out-of-play areas but the cooling effects of Golf courses are strongest for woodlands with complex multiple-tiered biomass structure, this supports reports from several other studies in Hong Kong (Fung & Jim, 2017; 2019).

In industrial and commercial land uses, the buildings often have flat concrete or metallic roofs, as seen on the aerial imagery. Concrete surfaces are reported to have low albedo from 0.1 to 0.35 (Taha, 1997). In contrast, the vegetation acts as a buffer between the ground and solar heat radiation, which helps to reduce the LST (Akbari et al, 2008). The similarity in low temperatures of Golf courses and Conservation land, thus, can be explained by similar surface characteristics related to their vegetation cover.

The findings here agreed with the previous studies from both Sydney, Australia and the northern hemisphere (in Toronto, Canada) which has confirmed that mean temperatures are significantly lower for parks and recreational land uses than highly intensive urban land-use such as industrial and commercial areas (Matthew Adams, 2015; Rinner & Hussain, 2011). Thus future changes in land-use from forest and grasslands to new urban developments (Industrial, Commercial, Residential) will have the potential to enhance temperature increases caused by climate change (Matthew Adams, 2015). The UHI problem is serious in Australia's hotter cities such as Perth, Adelaide and Alice Springs (Yenneti et al, 2020). This is due to the large number of impervious surfaces as a result of urbanization. Other Mediterranean-climate cities are predicted to have increases in average minimum temperatures compared to other rural areas (Polydoros et al, 2018). Therefore, urban planning in urban areas in hot dry climates should pay more attention to design cool islands to mitigate UHI and its impacts on city residents. With the cooling effects of Golf courses shown in this chapter, urban golf courses should be considered as a type of cooling island in urban planning within urban heat mitigation strategies.

### 5.4.2 Vegetation characteristics influence cooling effects of urban green spaces

Previous studies have confirmed the role of vegetation coverage in mitigating urban heat (Duncan et al, 2019; Ossola et al, 2021; Whetton et al, 2016) which can help to explain why urban areas can heat up easily and stay hotter (Oliveira et al, 2011; Ossola et al, 2021). However, very few studies have examined the details of vertical vegetation structure (vegetation height classes) and the spatial arrangement of vegetation patches and their cooling influences on urban green spaces. The results in this Chapter suggest that urban canopies (>10 m tall) will have the strongest effects in reducing urban temperatures while shorter vegetation, including turf grass, is less effective. This provides a new insight into the relationship between vegetation and urban heat and indicates that urban heat mitigation strategies using green spaces should not only focus on the amount of vegetation coverage, as indicated in previous studies, but also structure of vegetation within it. Due to the limited space for vegetation in urban areas, it is necessary to maximize the effects of green space by maintaining and increasing the number of big trees to regulate temperature and improve the urban microclimate.

Moreover, this study also determined that vegetation complexity in terms of spatial configuration and arrangement can facilitate management of urban heat. The results showed stronger cooling effects of large vegetation patches (*Core* area and their outer *Edge*) as well as the vegetation paths that linked *Cores* (*Bridge*) as being more effective vegetation structures than the small, isolated patches (*Islet*). This finding is consistent with previous studies (Bao et al, 2016; Kong et al, 2014; Kowe et al, 2021; Zhang et al, 2009) showing patch size is an important factor in reducing LST because the larger the patch, the more shading area was provided to its peripheral region. Also, a larger vegetation patch could have more interior areas which are less affected by the ambient environment, while smaller, isolated patches (*Islets*) tend to have a greater proportion of edge areas, and thus are vulnerable to disturbance from the peripheral region (Jiao et al, 2017).

In addition, this study also provided the new insight that vegetation connectivity is another factor in improving cooling effects of urban green spaces. The connectivity of vegetation cover is not only cover type, but also important vegetation cover indicators which contribute to decreasing surface temperature in urban areas (Xie et al, 2014; Xie et al, 2015). Moreover, vegetation categories contribute to the connectivity such as branch, and bridge are good for energy transmission, and thus decreasing surface temperature which was used for mapping the function of releasing surface temperature (Xie et al, 2015). Therefore, increasing urban vegetation, maintaining large patches of vegetation and reducing insolation can lead to decreases in urban LST. Hence, urban planning should consider the size of green spaces to operate as cooling islands without becoming masked by surrounding buildings. Additionally, this study also provided the new insight that vegetation connectivity is another factor in improving cooling effects of urban green spaces. The connectivity of vegetation cover is not only cover type, but also important vegetation cover indicator which contributes to decreasing surface temperature in urban areas (Xie et al, 2014; Xie et al, 2015). Moreover, vegetation categories contribute to the connectivity such as branch, and bridge are good for energy transmission, and thus decreasing surface temperature which was used for mapping the function of releasing surface temperature (Xie et al, 2015). Therefore, increasing urban vegetation, maintaining large patches of vegetation and reducing insolation can lead to decreases in urban LST. Hence, urban planning should consider the size of green spaces to operate as cooling islands without becoming masked by surrounding buildings.

Additionally, vegetation health is an important factor influencing its effect in cooling urban areas. The healthy vegetation patches with NDVI values from 0.6-0.8 had the strongest cooling effects (Figure 5.4A). Therefore, together with maintaining water bodies in combination with protecting and restoring big trees in large patches, caring for vegetation health is vital to ensure the cooling effects of green spaces are optimized.

The results of Chapter 4 indicated that the proportion of vegetation (without turf) is highest in Conservation land with the majority of the vegetation as *Core* and *Bridge* areas. This aspect of vegetation coverage having a high connectivity appears to be an important factor in making conservation land have the strongest capacity in reducing urban temperature. Vegetation within Golf courses, despite being more fragmented as indicated by greater proportions of *Islets* (Chapter 4), is still effective in reducing urban temperature. This might be explained by the vegetation within golf courses being healthy (Chapter 4) with a high proportion of tall trees, and these being factors that help increase the cooling effects of golf course vegetation. Furthermore, the golf courses are very close to or include water bodies. The strong effectiveness of the presence of water bodies in mitigating urban temperature was also indicated in this study (Figure 5.4B and Table 5.4)

Based on the findings of this chapter, in urban landscapes large green spaces like golf courses are important in mitigating urban heat. In cities with Mediterranean climate, green spaces such as golf courses have heat alleviating effects for the wildlife living in those green space habitats. The green spaces can improve the microclimate for city dwellers and can offer additional heat mitigation strategies in cities that are fast growing and dominated by impervious surfaces. Golf courses can provide multiple benefits such as maintaining vegetation cover and connectivity following long periods of urbanization (Chapter 3), with high coverage, health and connectivity in comparison with other land-uses along an urban – rural gradient (Chapter 4) and they can also play a role as cooling islands in urban environments.

### 5.4.3 Implication for vegetation management and urban planning

The urban heat island effect is most perceptible during summer and will be further exacerbated by increasing temperatures caused by a changing climate. In the Mediterranean climate of Perth, heat conditions typically last from December until the end of March. For south-western Australia, the CSIRO has projected that by 2030 the annually averaged warming will be about 0.5 to 1.2 degrees Celsius above 1986–2005 levels (Whetton et al, 2016). Extreme temperatures will also increase, with projected increases in the temperature, frequency, and duration of very hot days. These issues will be exacerbated by increasing hard surfaces and loss of green space in urban infill areas and new development areas (Environmental Protection Authority, 2015). The elderly, young, sick, and people from lower socio-economic areas are at most risk from new or exacerbated health issues and increased mortality due to heat in addition to health risks from poor air quality (Environmental Protection Authority, 2015). This study confirmed that the best way of mitigating the urban heat island effect is to increase the proportion of trees and green spaces in urban areas. A key consideration for mitigating the effects of heat will be increasing canopy cover across suburbs. The WAPC's Urban Forest of Perth and Peel Statistical Report analyzed the proportion of tree canopy cover at the suburb and street level (Western Australian Planning Commission, 2014). The report shows the reduced canopy cover in urban development areas across the Perth and Peel regions (Western Australian Planning Commission, 2014) which is consistent with the findings from chapter 3 of this thesis. A Green Network strategy covering the entire Perth and Peel regions will help to guide development of local greening or urban forest strategies. The strategy should aim to improve and retain large mature trees in planned green spaces as well as on streets and in gardens (Environmental Protection Authority, 2015).

This chapter suggests that urban vegetation management approaches are required that mitigate urban heat: (1) increasing the total proportion of vegetation cover; (2) maintaining the area of big trees; (3) preserving large patches of vegetation (*Core* area), and (4) improving vegetation health. Overall, it was found that golf courses are a type of large urban green space that can contribute significantly to mitigation of LST in urban landscapes. Vegetation in golf courses, despite being more fragmented than conservation land, is healthier and still contains large trees.

Therefore, the golf course is one of the nodes in the urban green spaces networks that contribute to cooling.

In golf course management, as the big trees play an important role in reducing LST, golf course managers and designers should pay attention to the conservation of these trees. As indicated in this study and shown by a number of studies explored the tree size effect on urban heat (Armson & Ennos, 2013; Morakinyo et al, 2017; Smithers et al, 2018), the cooling benefits during daytime are improved with increase in vegetation height classes. This is because tall vegetation classes can cast more shade than lower vegetation classes, reducing surface and air temperatures (Armson & Ennos, 2013). Furthermore, tall trees cast a large shadow on the surrounding urban surfaces that limits warming of surrounding ambient air during the day. In addition, the crown base of tall trees is usually wider compared to shorter trees (Wujeska-Klause & Pfautsch, 2020). Golf course design and construction should include the significant rough areas which are often remnant vegetation not being used for infrastructure and other facilities. It is recommended that golf course managers should not only increase the natural tree canopy by planting more trees, but also actively protect big trees and large vegetation patches to improve the cooling capacity of golf courses. Golf courses were shown to be important habitat for wildlife in urban landscape (Dair & Schofield, 1990; Hodgkison et al, 2007a; Tanner & Gange, 2005; Wurl, 2019; Wurth et al, 2020), they can provide cool nesting for urban wildlife under hot conditions in summer.

Urban expansion on undeveloped land containing large patches of native vegetation that involves tree clearing should embrace tree planting for future cooling effects. This chapter suggests that increasing the urban tree canopy should benefit heat mitigation. However, it will be difficult to reach targets without promoting planting on private land. Nowhere is this more pressing than in urban environments where there is scarcity of available land with native vegetation. The established regression equation in this chapter also provides an indication of how temperature can be reduced in other urban land-use categories (e.g., Residential, Commercial areas) by tree planting and patch maintenance for improvement of well-being of city dwellers.

Novel approaches for heat reduction and livable neighborhoods policies should point out the importance of developing incentives that promote multipurpose use of land and that stimulate cooperation among people and different societal sectors to support urban green space maintenance. Golf courses are an example of commercial land that can contribute to urban heat reduction that should be integrated into livable neighborhoods policies to improve the life quality of urban citizens.

## 5.5 Conclusions

This study provides and demonstrates a robust and objective approach to quantify and compare variation of LST among urban land-use categories. From this it is clear that vertical vegetation structure and horizonal vegetation configuration and arrangement is important to urban heat reduction. Golf courses are a type of land-use having strong capacity to reduce temperatures during hot summer days. Effective management of this vegetation for urban heat reduction and livable neighborhoods should consider the maintenance of big trees and large patches of vegetation across the urban landscape. Golf courses and other private land can be integrated into urban heat reduction by improving their vegetation management.

# Chapter 6 General discussion

## 6.1 Introduction

Golf has become an increasingly popular sport leading to a rapid increase in the number of urban golf courses world-wide. Good understanding of ecological roles of golf courses could provide crucial information and tools for urban planning in integrating on- and off-reserve conservation of urban ecosystems. However, the ecological values of golf courses are not fully understood in the literature, and those in the Perth Metropolitan Region have been little studied (Chapter 2).

Due to the need to preserve and develop green resources comprising all the natural and semi-natural networks of multifunctional ecological systems in urban landscape, this PhD study has examined the ecological roles of urban golf courses, a special type of recreational land-use, which contribute to green resources in cities. This PhD study highlights the multifunctional aspects of green spaces in golf courses. In this thesis, I used the Perth Metropolitan Region as a case study of urban golf courses to address three major study questions:

1) What are the the role of golf courses in maintaining urban vegetation through a long period of urbanization?

2) How significant are golf courses in maintaining vegetation in comparison with other land-use categories?

3) What are the roles of golf courses in reducing urban temperature in comparison with other land-use categories?

The key findings are:

- Golf courses in Perth Metropolitan Region contributed to conservation of urban vegetation cover and habitat connectivity during the 30 years of urbanization (Chapter 3 of this thesis).
- Golf courses existing in urban landscapes can better maintain vegetation cover and connectivity than in highly intensive urban land-use (e.g., Residential, Industrial, Commercial and Roads) but less than for Conservation land, Rural land, and land that contains un-developed areas (in Other land categories) (Chapter 4). This chapter also determined that golf course size and location are important factors that influence their vegetation cover, native vegetation cover and vegetation connectivity.

- Golf courses can provide broader ecosystem services such as cooling effects through the provision of tree coverage and green areas that provide community values (Chapter 5). Moreover, vegetation height, vegetation fragmentation, vegetation health (NDVI) and distance to water resources are factors influencing the capacity of golf courses as well as other urban land-uses in reducing urban temperature.

As each of above research questions have been explored in Chapters 3-5, this chapter provides an overview that integrates across chapters, and discusses those findings in relation to management recommendations of different scales that could enhance the ecological value of new and existing golf courses. Lastly, this chapter addresses the need for further research in this field.

## 6.2 Landscape scale management

Like many other big cities world-wide, Perth has experienced rapid expansion of urbanization and residential development in recent decades — with no end in sight. Urbanization from 1988 to 2018 in Perth caused a loss of over 17,000 ha of vegetation (Chapter 3). This makes vegetation cover in urban areas increasingly scarce and with reduced habitat connectivity. Thus, the limited open spaces and natural areas remaining must be shared for multipurpose such as recreation, relaxation, and refuges for plants and animals. This study provides insights for urban planners interested in exploring environmental consequences of land cover changes in cities both temporally (Chapter 3) and spatially (Chapter 4) when urbanisation with massive land-use change is an inevitable process in a changing world. As a portfolio of expected ecosystem characteristics from different urban land-use categories, my research findings allow us to better weigh the costs and benefits of urban development. Some types of development, such as golf course establishment in dense urban areas, may provide an opportunity to maintain urban green resources and improve multiple ecosystem service benefits for biodiversity conservation and city dwellers.

Despite limited green resources, golf courses tend to be disregarded as having roles in conservation by urban planners. Instead, attention is often placed on environmental problems such as water waste, habitat destruction, over-fertilization, and heavy pesticide use (Guzmán & Fernández, 2014). However, this PhD study confirms the positive roles of golf course in vegetation preservation, biodiversity connectivity and mitigation of urban heat. It seems therefore, that urban planners need to pay more attention to integrate golf courses into urban planning and conservation strategies for a more sustainable urban landscape with ample room for vegetation conservation and improvement of human well-being.

This study suggests that conservation of urban vegetation and wildlife should require a flexible approach that integrates both formal habitat reserves and off-reserve habitats. Golf courses are off-reserve sites occupying a small amount of space in urban areas, but many are linked to conservation land. Hence, they contribute to biodiversity connectivity of habitats and are one of the important nodes in the network of urban green space (Chapter 4). Golf courses situated between conservation land and highly intensive urban land uses (Residential, Commercial, Industrial) can serve as a protective buffer to soften the *Edge* effects as well as providing corridors for the moment of urban wildlife. In the research study area, one of the contextual examples of reserve-linked golf courses is the Wembley Golf Course which is linked to the large Bold Park of 437 ha – one of the largest remaining bushland remnants in the urban area of the Swan Coastal Plain, with over 1000 species of flora, fauna and fungi**,** including a number of priority and regionally significant species (Barnett, 2019). Therefore, the Wembley Golf Course can provide opportunities for enhancement of ecological linkages between the coast and the remnant vegetation to the south-west, including Bold Park as well as the surroundings such as Perry Lakes and Herdsman Lake to the north; Shenton Park Bushland and Kings Park to the east; and the Cottesloe Golf Course and Lake Claremont to the south (Figure 6.1). These linkages provide important corridors for animal movement between areas.

Similarly, golf course is one of the landscape elements that contribute to ecological corridors in urban environments. For example, in the city of Kwinana, because of the existence of an adjoining golf course and Rural Water Resource lands east of Bombay Boulevard, the effective management of vegetation within the golf course and the Rural Water Resource properties will increase connectivity of the two significant bushland areas of the region (City of Kwinana, 2016). Therefore, golf courses should be investigated for conservation of native vegetation in strategic locations to improve connectivity. Even some of the isolated golf courses located in residential areas still have conservation values because they include natural remnants in out-of-play areas, which contain some of the native vegetation remaining the urban landscape (Chapter 4). Also, golf courses which are isolated from other bushland (e.g., Nedlands Golf Course) can be steppingstones in the urban green network. Therefore, golf courses no matter if they are isolated or connected, deserve to be included in conservation strategy and urban planning strategies.

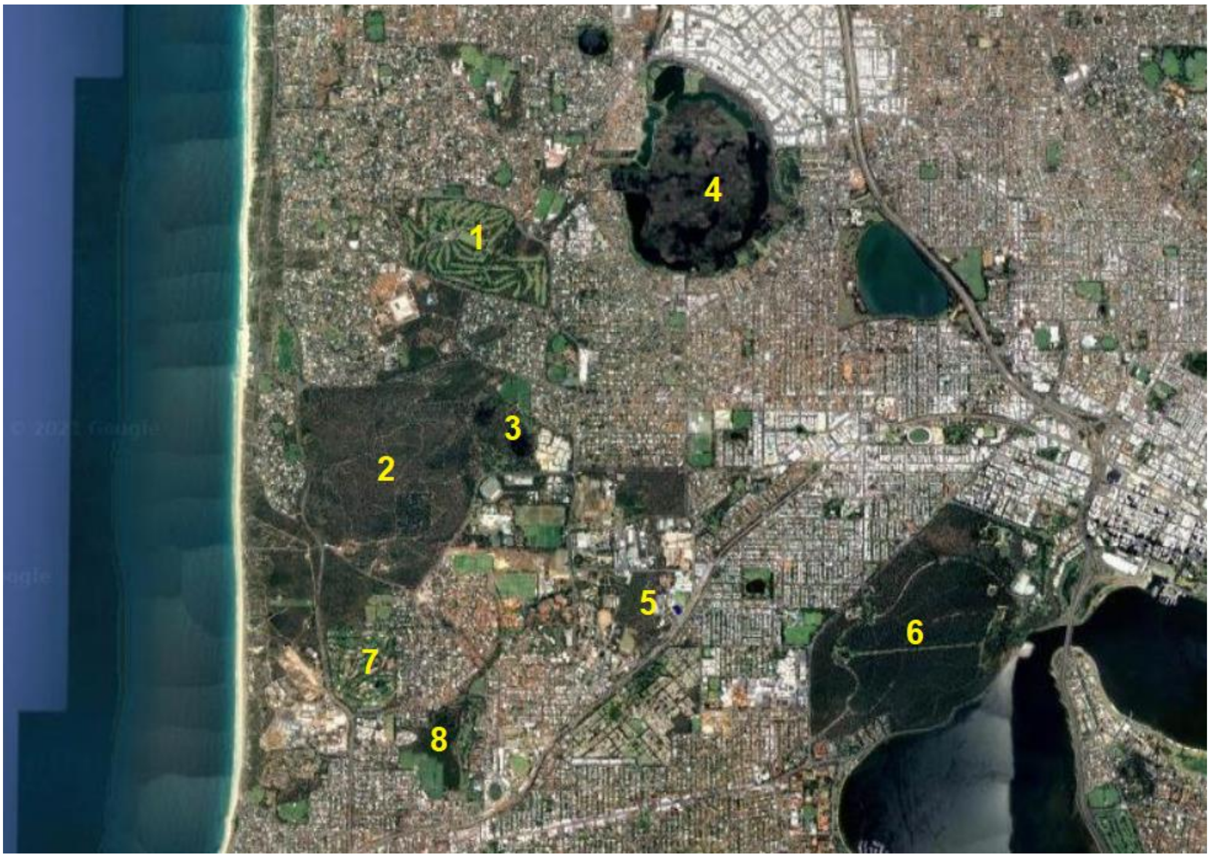


**Figure 6. 1 Google image: 1 – Wembley golf course; 2 - Bold Park; 3 - Perry Lakes; 4 - Herdsman Lake; 5 - Shenton Park Bushland; 6 - Kings Park; 7 - Cottesloe Golf Course; 8 - Lake Claremont**

Actions taken together from government authorities and golf course managers should lead to better outcomes for urban conservation. Using up-to-date vegetation changes, and vegetation fragmentation and connectivity maps associated with land-use categories such as those in Chapter 3 and Chapter 4, urban managers and urban ecologists can identify measures to maximize urban ecosystem services, and to protect and manage urban environments (Ren et al, 2017). On the one hand, the further evaluation of the impact of urban development on vegetation networks in future urban planning can be revised based on the temporal analysis of vegetation changes under urbanization (Chapter 3). On the other hand, urban conservation strategies should identify the important nodes of urban green spaces using vegetation fragmentation and connectivity maps among different land-use categories (Chapter 4). This should involve all the relevant stakeholders in the conservation strategy. Besides the importance of conservation of *Core* and *Bridge* habitats in urban landscapes, many green spaces classified as isolated also need to be prioritised in urban conservation because of their highly threatened status. The MSPA *Branch* class can be a potential corridor to connect two spatially disjunct *Core* areas if they are revegetated, and are useful in ecological restoration to increase biodiversity connectivity of the large bio-regions (Wickham et al, 2017).

In addition to their conservation values, golf courses also provide ecosystem services that can benefit local people. Despite the fact that not everyone plays golf, the golf courses not only represent an amenity for golfers and people enjoying the greenery, but they also support biodiversity and play roles as cooling islands in dense urban areas (Chapter 5). The cooling effects of golf courses are better than most urban landscapes and can benefit wildlife species living in golf course habitats and also nearby residential areas. Therefore, if golf courses were converted into residential areas, locals would lose these benefits because the development of golf courses if requiring tree planting could affect the environmental balance, especially the local micro-climate, and make some urban areas more livable (Horgan et al, 2020).

Extreme heat caused by a high impervious proportion of surfaces and low vegetation cover, and global warming contributed to health problems in 13,115 cities from 1983 to 2016 (Tuholske et al, 2021). Chapter 3 of this PhD thesis showed a similar trend of urbanisation in the Perth Metropolitan Region which raised concerns of UHI effects in this dry-hot city. Using vegetation to reduce UHI is recommended in Chapter 5 of this thesis. However, expanding urban vegetation cover by tree planting has many challenges because of the limited space available in urban landscape where the conservation target has to compete with socio-economic development goals. In this situation, green space-based commercial land-use, such as urban golf courses, can be a kind of opportunistic conservation contributing to urban green space network cover and connectivity as well as urban heat mitigation.  Therefore, golf courses should be integrated into other important strategies for human health and well-being of urban citizens.

The decisions of government authorities and urban planners will ultimately determine the net ecological impact of future golf course development by controlling future golf course development in zoning decisions. Future golf course development, whether resulting in an increase or decrease of net urban ecological values, will depend on types of land that are allowed to be converted into golf course. If the highly intensive land-uses are converted into golf courses, the net ecological values may increase. In contrast, if natural habitats are lost to the development of golf course, the net change of ecological values may decrease. Despite the positive role of golf courses in urban landscapes compared to many other types of land development, this study does not advocate for the conversion of bushland habitats into golf courses. Any golf development that involves substantial loss of native vegetation can lead to a significant loss of local biodiversity, and thus environmental impact assessment scrutiny or legislative control are essential for the development of new and existing golf course.

At the landscape scale of Perth, the Local Planning Scheme (LPS) is a legal document which may include general development requirements relevant to biodiversity conservation, such as subdivision plans, guidelines for development of building envelopes, vegetation clearing controls, requirements for rehabilitation or revegetation of degraded land, weed management, and so on. However, it contains no provisions to address issues that are relevant to 'biodiversity', but Section 6.16.2 is supported with landscape protection areas identified in the planning scheme maps. Also, Local Planning Policy (LPP) documents are prepared and adopted by local government, following community consultation, and must be consistent with the intent of the LPS (City of Kwinana, 2016). Local Planning Polices are complementary to the provisions of a Local Planning Scheme that the golf course can be integrated into the conservation strategy. However, the recognition of the roles of golf courses in urban conservation in legal documents of the government of Western Australia is still very limited. This study highlights the need for involving golf courses and other green spaces in urban planning and conservation strategies in the future.

## 6.3 Golf course management

This study revealed that golf courses in the Perth study area exhibit wide variation in ecological values (Chapter 3). This may be a consequence of zoning decisions (location and size of the golf course) and golf precinct management practices. The development of a golf course is a complex process. To deal with it, qualified professionals provide the expertise necessary to create design solutions for golf courses that are compatible with the environment (Bill Love, 2008). Golf courses can provide significant benefits to the environment if constructed and managed using best management practices. They can also result in water pollution, pesticide spills, weed incursion and the destruction of native vegetation if managed poorly. Therefore, golf course managers should recognise the importance of designing, constructing and managing golf courses in an environmentally sustainable manner. In addition, there are urban planning considerations of best management practices for landscape maintenance that need to be addressed while doing so. Furthermore, understanding of cost and benefits that golf courses can bring will help urban plans to be developed in a sustainable way.

It is important to promote awareness of golf courses as environmental assets and develop national guidelines for their management (Neylan, 2007). The official guidelines for best environmental management practices from government agencies can support golf courses to increase their ecological values and reduce their environmental costs on urban environments. Moreover, the planning decision framework for developing sustainable golf course land should be to enhance open space, as well as environmental and landscape values in the urban landscape. Bill Love (2008) recommended that the planning and design process by golf course architects should embrace preserving the site's topsoil, maintenance of valuable habitats or rare trees, incorporating the native environment and showcasing its natural beauty.

This PhD research was carried out in the Perth Metropolitan Region which includes more than 30 golf courses. Recently, many of these golf courses have made progress in addressing sustainable management to provide environmental services. Some examples are Lake Karrinyup Country Club, Wembley Golf Course, Mandurah Country Club, Gosnells Golf Course, and Royal Fremantle Golf Club which have been recognized as leading golf courses in effective water management (The Golf Course Superintendents Association of Western Australia and the Department of Water, 2013). Lake Claremont golf course, a multi-use golf course, has been involved in the Bush Forever and Conservation strategy (Town of Claremont, 2017). The Lake Claremont golf course has attempted to reduce the impact of previously clearing bushland by targeting some of their area for rehabilitation to try and establish a link to surrounding fragmented bushland between Kings Park and the coast.

However, while comprehensive guidelines for best management practices in golf courses have been developed elsewhere, such as in USA (Bill Love, 2008; California Golf Course Superintendents Association, 2020) and in Victoria, Australia (The State of Victoria Department of Environment, 2020), comprehensive guidelines for best management practices for golf courses in Western Australia are lacking especially in terms of involvement in biodiversity conservation strategies. One of the guidelines and regulations for environmental management of golf courses from the WA government is the Waterwise Golf Course Program in 2013. The program was developed by the Golf Course Superintendents Association of Western Australia (GCSAWA) and the Department of Water to ensure water-efficient operation and a resilient golf course industry. This program aims to achieve long-term water use efficiency and establish environmental principles for golf's governing bodies. Interest in the program has increased, with more than 20 golf courses now participating or registered for best practice irrigation – benefiting the health of the community and providing important green spaces (The Golf Course Superintendents Association of Western Australia and the Department of Water, 2013). In 2007, the Department of Environmental Protection and Water and Rivers Commission also developed "The Environmental Guidelines" for the establishment and maintenance of turf and grassed areas which includes recommendations for irrigation and fertiliser use of different types of turf and grass, including recreational turf grass areas in golf courses (The Swan River Trust, 2001). Local government authorities have also committed to improve their environmental accountability in aspects of municipal activities, and thus have developed environmental management plans for golf courses in their locality. City of South Perth, for example, has produced an environmental development plan for water management, soil erosion, and native plants and wildlife habitat protection of the Collier Park Golf Course (Nicle & Associates, 2004). The findings from this study can be used as a reference for the development of urban plans and conservation strategies involving golf courses in WA.

Because the well-vegetated golf courses clearly have refuge value within the context of urban landscapes (Colding & Folke, 2009; Hodgkison et al, 2007b; Terman, 1997), and many habitats on golf courses can be actively connected to larger habitat reserves (Chapter 3), this thesis suggests that the available vegetation cover in out of play areas between the greens should be increased and connected, creating wildlife corridors and effectively connecting habitat fragments. Patches of vegetation this small usually require intensive management and can be costly to maintain. However, community expectations can be high for these areas as they may often be considered the 'local patch' and voluntary community support for management may be available. Despite this, these small patches frequently degrade over time and become only trees or large shrubs over weeds. Of note is that the Perth region is vulnerable to invasion by alien grasses and geophytes (Low, 2008). This is commonly seen in Public Open Space and golf courses where small islands of bush have been left surrounded by landscaped areas. These areas are not generally considered viable for conserving biodiversity in the long term although there are some important exceptions to this rule (Del Marco et al, 2007).

Plant structure focuses on different high class levels of vegetation, from closely mowed turf to tall grasses, to low and high shrubs, and trees of all sizes providing additional habitat niches for organisms (Threlfall et al, 2017). Moreover, the existence of large trees will provide more ecological values to golf courses in terms of cooling effects (Chapter 5) suggesting the need to preserve the large trees in golf courses for higher net of ecological values. As a part of the urban green space network, golf course management goals could include the support of local biodiversity, migratory biodiversity, and the maintenance and improvement of a variety of ecosystem services. Simply implementing best management practices is the right and responsible way for golf courses to develop in a sustainable way.

## 6.4 Recommendations for further research

The ecology of golf courses has gained little attention from ecologists and remains an area for fruitful research. To achieve sustainable urban management, further research is needed to provide evidence of the extent and impact of golf course management and urban conservation. Further research that can support best golf course management practices and urban planning are proposed below.

- The assessment of vegetation trends with urbanization in Chapter 2 should be integrated with the dynamics of biodiversity and other ecological change so as to develop a more comprehensive estimation of the cost of urbanization for future sustainable urban planning. This will require detailed field assessment of biodiversity values in relation to urban development and land-use changes.
- The comparison of the ecological values among golf courses should be further developed with larger data sets and field assessment. This will allow remotely sensed data at a landscape scale to be explained in greater detail, providing enhanced information for golf course managers and urban planners to taking actions at both local and regional scales.
- Regarding the urban heat study, besides the influence of vegetation cover, structure and configuration, there is the possibility that tree species may influence cooling effects. However, this thesis has not covered this kind of data, and thus this should be pursued later.
- This study applied remote sensing technology using medium resolution satellite images (Landsat imagery), high resolution satellite images (Planet Scope imagery) and airborne high resolution multispectral imagery to monitor ecological values from vegetation cover, vegetation height classes, vegetation health and land surface temperature. It is suggested that further comparison of the effectiveness of these methods in urban monitoring should be carried out to provide cost-effective methodology for future research in urban ecology.
- Lastly, the impacts of zoning decisions and other government policies as well as current golf course management practices should be included in future urban ecology research for better recommendations of landscape management and golf course management.

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