Forest Ecosystems

RESEARCH Open Access

# A fine-scale assessment of the ecosystem service-disservice dichotomy in the context of urban ecosystems affected by alien plant invasions

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## Abstract

**Background:** Natural resources within and around urban landscapes are under increasing pressure from ongoing urbanisation, and management efforts aimed at ensuring the sustainable provision of ecosystem services (ES) are an important response. Given the limited resources available for assessing urban ES in many cities, practical approaches for integrating ES in decision-making process are needed.

**Methods:** We apply remote sensing techniques (integrating LiDAR data with high-resolution multispectral imagery) and combined these with supplementary spatial data to develop a replicable approach for assessing the role of urban vegetation (including invasive alien plants) in providing ES and ecosystem disservices (EDS). We identify areas denoting potential management trade-offs based on the spatial distribution of ES and EDS using a local-scale case study in the city of Cape Town, South Africa. Situated within a global biodiversity hotspot, Cape Town must contend with widespread invasions of alien plants (especially trees and shrubs) along with complex socio-political challenges. This represents a useful system to examine the challenges in managing ES and EDS in the context of urban plant invasions.

**Results:** Areas of high ES provision (for example carbon sequestration, shade and visual amenity) are characterized by the presence of large trees. However, many of these areas also result in numerous EDS due to invasions of alien trees and shrubs – particularly along rivers, in wetlands and along the urban edge where tall alien trees have established and spread into the natural vegetation (for example increased water consumption, increased fire risk and reduced soil quality). This suggests significant trade-offs regarding the management of species and the ES and EDS they provide.

**Conclusions:** The approach applied here can be used to provide recommendations and to guide city planners and managers to fine-tune management interventions at local scales to maximise the provision of ES.

**Keywords:** Biodiversity, Biological invasions, Ecosystem disservices, Ecosystem services, Remote sensing, Trade-offs, Tree invasions, Urban plant invasions

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## Background

Global urbanisation is increasing rapidly, placing enormous pressures on natural resources within and around urban centres. Satisfying the increasing demand for ecosystem services (ES), ensuring human well-being, and preventing the accelerating loss of biodiversity in and around urban areas remains a significant challenging (Haase et al. 2014). ES assessments are important for determining the vulnerability and resilience of urban areas and their residents to potential disruptions in the generation of ES when exposed to change (Gómez-Baggethun and Barton 2013).

Urban vegetation, particularly trees, provide many benefits that can enhance the well-being of urban residents (Jim and Chen 2008; Nowak et al. 2008; Escobedo et al. 2010). These include provisioning services such as food, water and timber; regulating services that positively affect climate, floods and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling. However, urban ecosystems also generate functions, processes and attributes that can result in perceived or real negative impacts on human well-being (such as aesthetic, economic, environmental, health and social problems), termed ecosystem disservices (EDS) (Roy et al. 2012; Shackleton et al. 2016; Potgieter et al. 2017; Vaz et al. 2017).

Mapping urban vegetation and the ES and EDS they provide is important for decision makers and managers, as it helps them identify areas to prioritise for management. However, mapping plant species in urban environments presents numerous challenges due to their fine-scale spatial variation (Welch 1982) and high species diversity (native and alien), often representing novel ecosystems in terms of their composition (Wu 2014). Research demonstrating the potential of high-resolution images for assessing urban ecosystems functions and services is still emerging (e.g. Derkzen et al. 2015; Alonzo et al. 2016; Maragno et al. 2018; Zhao et al. 2019). Global and regional studies, although useful for international policy and science have been conducted at too coarse a resolution to be very useful for the management of services at local planning levels. Through freely accessible remotely-sensed data at higher resolutions and more robust analytical tools, remote sensing technology can make important contributions to multi-scale urban ecological assessments (Mathieu et al. 2007; Salehi et al. 2012; Raciti et al. 2014). Land cover information from remote sensing is a suitable starting point. By supplementing urban landscape features with additional data, the state of urban ecosystems and their capacities to supply ES can be assessed and mapped at different spatial scales.

Urban floras comprise a high proportion of alien tree species, many of which were intentionally introduced to provide, augment or restore ES (Potgieter et al. 2017). A trend in human preferences for particular plant traits has led to an increase in the proportion of alien trees in many urban areas around the world (Dickie et al. 2014), compounded by escaped woody ornamentals (Potgieter et al. 2017). Many alien tree taxa have subsequently spread and become invasive, threatening the delivery of ES (van Wilgen et al. 2008; van Wilgen 2012) and creating novel suites of EDS such as increased safety and security risks (Potgieter et al. 2018, 2019a). Understanding the ES-EDS dichotomy in the context of urban landscapes is important for promoting the development of resilient and sustainable cities (Carpenter et al. 2006; Liu et al. 2007). Decisions around managing invasive alien plants (IAPs) (sensu Richardson et al. 2000) in urban areas are fundamentally determined by their capacity to create negative impacts (EDS) and provide benefits (ES) (Vaz et al. 2017; Potgieter et al. 2018). Managing urban ecosystems to enhance the provisioning of ES while reducing EDS is a major challenge. Approaches aimed at optimising specific ES exclusively may exacerbate associated EDS, and those aimed solely at reducing EDS may reduce ES (Shackleton et al. 2016). For example, planting Black Locust (*Robinia pseudoacacia* L., Fabaceae) in urban areas for aesthetic purposes, shade, or to provide resources for honey-producing bees, may also provide EDS such as altered soil fertility and reduced species richness (Marozas et al. 2015). Given the limited resources available for assessing urban ES and EDS in many cities, practical approaches that integrate ES and EDS in the decision-making process are needed.

Predicting the effect of IAPs on a given ES is challenging as our knowledge of the mechanisms by which IAPs affect ES remain limited (Charles and Dukes 2007; Pejchar and Mooney 2009), and the metrics used to quantify urban ES (particularly in the context of IAPs) are still crude (Naidoo et al. 2008; Bennett et al. 2009). This lack of understanding on how to measure and predict the effects of IAPs on ES, particularly in urban areas, limits our ability to effectively prioritize and manage invasions. Remotely sensed maps of biological invasions may be used to inform ES assessments. Although many methods have been proposed for quantifying urban ES (e.g. Gómez-Baggethun and Barton 2013), many at fine spatial scales (e.g. Wurster and Artmann 2014; Haas and Ban 2016), few studies have attempted to combine remote sensing technologies to infer ES provided by IAPs in an urban context.

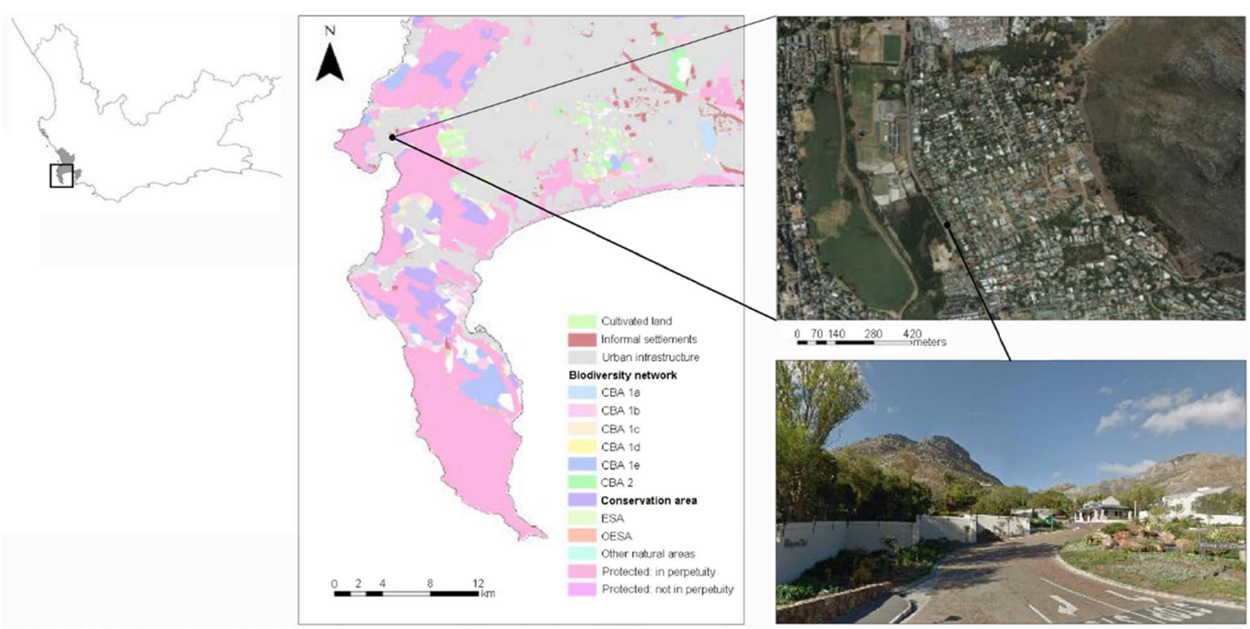
This study aims to develop a replicable approach to assess the role of urban vegetation (including IAPs) in providing ES and EDS at a local-scale, using the city of Cape Town as a case study. We apply remote sensing techniques (integrating LiDAR data with high resolution multispectral imagery) and supplementary spatial data to identify areas of high ES (and EDS) provision. We discuss the trade-offs associated with managing ES and EDS and the challenges in developing and implementing IAP management in urban areas. The approach applied in this study can be adopted by managers in all urban settings to guide the selection and prioritization of areas for IAP and/or ES management at the local scale.

## Methods

### Study area

The study site comprises an area (±2 km$^2$ in extent) in the residential suburb of Hout Bay, located in the city of Cape Town, South Africa (Fig. 1). It is bordered by Table Mountain National Park in the east and by the Atlantic Ocean to the south. The dominant natural vegetation in the city is fynbos, a short shrubland vegetation type which forms part of the Cape Floristic Region and holds exceptionally high diversity and endemism (Cowling et al. 1996). The fynbos biome is characteristically depauperate of native trees while widespread invasions of alien trees and shrubs such as Australian acacias, hakeas and pines dominate many parts of the landscape (Cowling and Richardson 1995), threatening the delivery of ES (van Wilgen et al. 2008; van Wilgen 2012). For example, *Acacia saligna* which was introduced to stabilise shifting sands has spread far beyond sites of formal plantings; it now negatively impacts biodiversity, surface water runoff, and exacerbates wildfires (van Wilgen and Richardson 1985; Le Maitre et al. 2002; Yelenik et al. 2004, 2007). However, despite the negative impacts of IAPs, some species remain beneficial to many urban residents (Gaertner et al. 2016; Potgieter et al. 2019b) namely through recreation, shade and visual amenity. This situation provides a unique opportunity to examine the applicability of remote sensing techniques for the spatially-explicit assessment of the role of urban vegetation (especially alien trees) in providing ES (and EDS) within this fine scale urban context.

Following the spatially entrenched apartheid form of South African cities, Cape Town remains highly divided, socially and spatially (Watson 2009). Rapid growth in informal settlements is a prominent feature of urbanisation in South Africa - a vestige of apartheid policies and practices. While most informal settlements are located on the urban peripheries or in and around areas of low-cost housing, some have developed in middle- to upper-class neighbourhoods, such as Hout Bay (see Ballard 2004). Three very disparate communities are currently located within Hout Bay. The mostly white middle- to upper income residents reside in the valley and along the mountain slopes in houses that reflect a high socio-economic position. Another community close to the harbour consists of both low-income coloured residents who reside in hostels and flats, and middle-income white and coloured residents, who live higher up the slopes of Hangberg in an area known as Hout Bay Heights. The third community, which has developed most recently, is the informal settlement of Imizamo Yethu comprising mostly low-income Black African residents. Established on an old forestry site in 1991 to accommodate people who were illegally occupying land elsewhere in Hout




*CBA – Critical Biodiverse Areas; ESA – Ecological Support Areas; OESA – Other Ecological Support Areas.

**Fig. 1** Location of the study area (±2 km$^2$) within the city of Cape Town municipal boundary in the Western Cape, South Africa

Bay, Imizamo Yethu is characterized by poor basic service provision (e.g. education, housing, nutrition and healthcare), declining living conditions, environmental unsustainability, and poverty.

The study site has several key features that make it a useful study system: a) a range of land cover/land uses; b) significant socio-economic stratification; c) the urban-wildland interface; d) diversity and abundance of alien and native vegetation; and e) different plant invasion densities within the urban fabric and outside the urban edge.

### Analytical framework

We developed an approach which combines remote sensing techniques (integrating LiDAR data with high-resolution multispectral imagery) and supplementary spatial data (such as OpenStreetMap) with invasive alien species density data to assess the role of urban vegetation (including invasive alien plants) in providing ES and EDS at a local scale (Fig. 2). We identified areas with potential management trade-offs based on the spatial distribution of ES and EDS using a local-scale case study in the city of Cape Town, South Africa.

### LiDAR data and multispectral imagery

The LiDAR (Light Detection and Ranging) system is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. It provides three-dimensional data with high levels of horizontal and vertical accuracy. A key advantage of LiDAR over traditional optical sensors is its ability to estimate the heights of trees and shrubs with high vertical accuracy. There are, however, difficulties in accurately classifying vegetation from other land cover features such as buildings based solely on height information. Therefore, both multispectral satellite imagery and height information obtained from LiDAR data should be combined for accurate classification of detailed vegetation components. The airborne LiDAR data collected in February 2014 was provided by the Centre for Geographic Analysis and SPOT-7 images (consisting of red, green, blue and near-infrared image bands; 1.5 m spatial resolution) were acquired from the South African Space Agency (SANSA) (image acquisition: 11 November 2016).

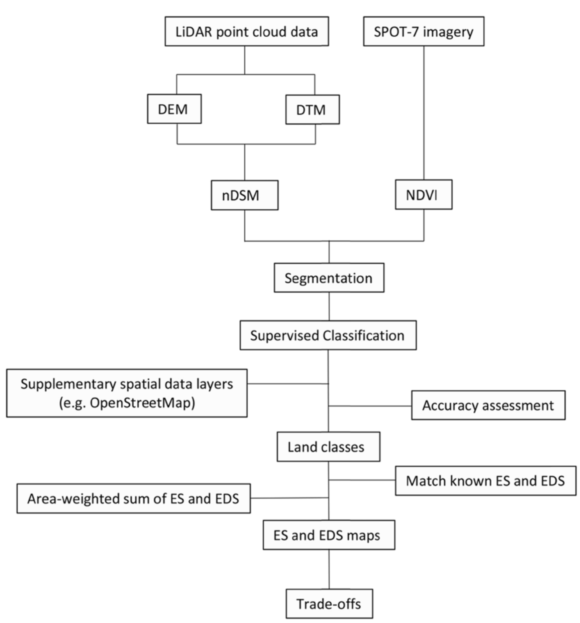



**Fig. 2** Schematic representation of the methodology followed in developing the land classification and final map of ecosystem services/disservices

Using ArcGIS 10.4, a normalized digital surface model (nDSM) was generated from LiDAR cloud point data (with a spatial resolution of 1.5 m) to extract absolute height information by subtracting the digital surface model (DSM) from the digital terrain model (DTM). The nDSM represents the relative object height information for features, i.e., the LiDAR data has been corrected relative to the bare earth terrain. The next step involved calculating the Normalized Difference Vegetation Index (NDVI) on the near-infrared band and red band of the SPOT-7 image. All pixels with NDVI greater than 0.25 were considered to meet the threshold for containing vegetation and were included in the analysis. The methodology followed to develop the land classification and final ecosystem service-disservice maps is outlined in Fig. 2.

For the segmentation and classification of the LiDAR-derived nDSM and SPOT-7 imagery, the object-based image analysis software eCognition® Developer 8.7 (Definiens 2005) was used. We first used multiresolution segmentation to identify objects with correlated characteristics in terms of reflectance and height. In this step, we fused the nDSM and the NDVI derived from the SPOT-7 imagery for the segmentation process. This method identifies geographical features using scale homogeneity parameters obtained from the SPOT-7 imagery spectral reflectance and the height value of the nDSM. Smoothness was adjusted to optimize each segment's spectral homogeneity and spatial complexity. Segments were classified by a supervised method into the following six classes based on the mean nDSM height and NDVI in each object: 'Bare ground': nDSM < 0.25 m, NDVI < 0.25; 'Grass': nDSM < 0.25 m, NDVI > = 0.25; 'Shrubs': nDSM > = 0.25 m < 3 m, NDVI > = 0.25; 'Infrastructure': nDSM > = 0.25 m, NDVI < 0.25; 'Trees': nDSM > = 3.0 m < 10 m, NDVI > = 0.25; 'Tall trees': nDSM > = 10 m, NDVI > = 0.25. The final land classifications are detailed in Fig. 3a.


**Fig. 3 a** Land classification following LiDAR data and SPOT-7 image fusion; **b** Areas of high to low ecosystem service provision (per 100 m grid cell); **c** Areas of high to low ecosystem disservice provision (per 100 m grid cell); **d** Ecosystem service-disservice dichotomy showing areas of high to low ecosystem service-disservice provision - denoting potential management trade-offs

A classification accuracy assessment was carried out using a class area-weighted, stratified random sample of 168 points and validated using ground truthing (performed from 20 to 21 August 2018). The points selected for each class were spatially dispersed and proportional to their importance in terms of area covered. The final land classification map was adjusted to account for the classification errors. A confusion matrix was produced, and the overall accuracy and the kappa coefficient was calculated.

### Ecosystem service and disservices

Urban areas undergo significant land cover (and land use) changes. Such changes impact the capacity of ecosystems to provide ES to urban residents. Land cover was used as a proxy measure of ES - mapping land cover gives an initial indication of the potential ES and EDS provision or reduction. Remote sensing serves as a useful tool for land use/land cover classification.

ES and EDS were matched with our final land classification derived from the remotely sensed LiDAR and multispectral image classification, aerial photographs, and supplementary spatial data (OpenStreetMap). ES and EDS were categorised according to Potgieter et al. (2017) and those associated with each respective land class applicable to the study area are detailed in Table 1. A grid comprising 100 by 100 m cells was laid over the study area. The area covered by each land class within each grid cell was calculated and weighted based on the sum of corresponding ES and EDS detailed in Table 1. As no information was available on the importance of the different ES or EDS they were weighted equally in the assessment (Wainger et al. 2010). For example, a grid cell may comprise tall trees in a residential garden which provide a range of ES:

**Table 1** Accuracy matrix for the land classification

| Class | Ground truth | | | | | | User accuracy (%) |
|---|---|---|---|---|---|---|---|
| | Bare ground | Grass | Shrubs | Trees | Tall trees | Infrastructure | |
| Bare Ground | 22 | 2 | 1 | 1 | 0 | 3 | 75.86 |
| Grass | 4 | 20 | 2 | 0 | 0 | 0 | 76.92 |
| Shrubs | 0 | 2 | 36 | 1 | 0 | 0 | 92.31 |
| Trees | 0 | 0 | 1 | 31 | 1 | 0 | 93.94 |
| Tall Trees | 0 | 0 | 0 | 2 | 17 | 0 | 89.47 |
| Infrastructure | 3 | 0 | 1 | 0 | 0 | 18 | 81.82 |
| Producer's accuracy (%) | 75.86 | 83.33 | 87.80 | 88.57 | 94.44 | 85.71 | |

Total accuracy: 85.71%; kappa coefficient: 0.826

recreation, spiritual interaction, visual amenity, provision of sense-of-place, increased property value, shade provision, climate regulation, improved air quality, carbon sequestration, stormwater runoff mitigation, habitat provision, increased nutrient cycling, pollination, primary production and soil formation. Conversely, they may also result in EDS: increased maintenance costs, generation of green waste, increased water consumption, pollen allergies, infrastructural damage and safety hazard. Such ES and EDS were acquired from the literature and cited in Table 2 accordingly. The area-weighted sum of ES and EDS per land class within the grid cell was calculated.

Separate maps detailing areas of low to high provision of ES and EDS were developed and combined to form an overall depiction of ES-EDS provision. Areas with high provision of both ES and EDS are likely to result in trade-offs regarding the management of species and the ES and EDS they provide. This was achieved by subtracting the overall (net) area-weighted EDS from the net area-weighted ES for each grid cell. Trade-offs occur when the increase in one ES results in a reduction of another desirable service or an increase in a disservice, while synergies exist when the enhancement of one ES has a positive effect on another (Haase et al. 2012, Dobbs et al. 2014). In the context of this study, EDS refer to both a reduction in ES (e.g. reduced soil quality) and/or the creation of a new EDS (e.g. infrastructural damage). While the relationship between biodiversity and the provision of ES remains contested (e.g. Egoh et al. 2009), most studies associate high species richness with a high levels of ES provision (Balvanera et al. 2006; Benayas et al. 2009). Maintaining biodiversity is considered as an efficient way to enhance ES. Our study area comprises key biodiversity areas (Fig. 1) and these were included in the ES-EDS spatial assessment i.e. areas of high biodiversity correspond to areas of high ES provision.

## Additional information and tools

We incorporated supplementary spatial data from different sources to improve the accuracy of our classification (see Table 3). These included spatial data from OpenStreetMap (OSM), invasive alien plant (IAP) density data from the City of Cape Town Invasive Species Unit (Biodiversity Management Branch; hereafter ISU), and multiple spatial data layers obtained from the City of Cape Town's open data portal.

### OpenStreetMap

Volunteered geographic information (VGI) is a method for collecting and disseminating geospatial data primarily acquired through the voluntary efforts of citizens. One of the most utilized and popular VGI-platforms is OpenStreetMap (OSM) (http://www.osmfoundation.org), a project providing freely exportable maps of cities worldwide. Data in OSM are obtained from a community of volunteers whom create spatial data by tracing non-copyrighted, aerial imagery or generating data directly using GPS devices. Maps include information on roads, railways, buildings, waterways and points of interests such as parks, commercial centres, leisure centres and commercial activities. While the coverage and quality of such data may vary across locations, it has the potential to provide an important research tool, particularly where data from more traditional sources are limited or non-existent.

The OSM vector data for the study area was downloaded in July 2018 using the ArcGIS Editor for OSM in ArcGIS 10.4. All relevant OSM thematic layers were included in the classification process.

### Invasive alien plants

We obtained spatial data (acquisition date August 2016) on IAP density from the ISU; such data is used to inform invasive species management across the city (Gaertner et al. 2016). The ISU conducts clearing operations in areas managed by multiple departments within the city, including many conservation areas. At each area identified as a priority for control operations, the ISU conducts a site assessment in which management units (MU) are delineated and surveyed and baseline

**Table 2** Ecosystem services and disservices associated with urban vegetation within the study area

| Ecosystem service category | Ecosystem services | Example | Reference |
|---|---|---|---|
| Cultural | Recreation | Picnicking under tall shade-providing trees (e.g. *Pinus pinea*) | Potgieter et al. (2019b) |
| | Physical, intellectual and spiritual interactions with nature, including aesthetic values, inspiration and cognitive development, and spiritual enrichment | Well managed urban green spaces with abundant vegetation | Bastian et al. (2012); Dobbs et al. (2011) |
| | Visual amenity, ornamental purposes and landscape re-greening | Private residential gardens | Dickie et al. (2014); Carruthers et al. (2011); Kull et al. (2011); Le Maitre et al. (2011); Shackleton et al. (2016) |
| | Provision of a 'sense of place' | | Dickie et al. (2014) |
| | Heritage | *Pinus pinea* trees planted in the seventeenth century by the early settlers, have significant heritage value | Gaertner et al. (2016) |
| | Increased property values | | Soares et al. (2011) |
| Provisioning | Firewood | Trees such as *Acacia* sp., *Eucalyptus* sp. or *Pinus* sp. can be used for firewood | Dickie et al. (2014) |
| | Construction material | Trees such as *Eucalyptus* sp. or *Pinus* sp. can be used for poles | Dickie et al. (2014) |
| | Medicinal value | Essential oils provided by *Eucalyptus* sp. | |
| | Fodder | *Eucalyptus camaldulensis* used as fodder | Bernholt et al. (2009) |
| | Food | *Eucalyptus* sp. (especially *E. cladocalyx*) are important for honey production | |
| Regulating | Shade | Shade from tall trees with wide canopy such as *Pinus pinea* | Potgieter et al. (2019b); |
| | Climate regulation | Cooling effects (by transpiration) of street trees such as *Platanus* × *acerifolia* | Jim and Chen (2009) |
| | Air quality | Reduced emissions of air pollutants by *Platanus* × *acerifolia* | McPherson (2003) |
| | Flood attenuation | Wetlands | |
| | Barrier | *Pinus* sp. used as a barrier plant | |
| | Carbon sequestration | Trees such as *Platanus* × *acerifolia* sequester carbon | Potgieter et al. (2017) |
| | Nitrogen fixation | *Acacia* sp. fix nitrogen, enriching the soil | Qiu (2015); Dickie et al. (2014); van Wilgen and Richardson (2014); de Wit et al. (2001) |
| | Erosion control | Erosion control by trees such *Ailanthus altissima* | Sladonja et al. (2015); Kowarik and Säumel (2007) |
| | Energy saving | Changes in building energy use from shade trees such as *Platanus* × *acerifolia* | McPherson (2003) |
| | Stormwater runoff mitigation | | |
| Supporting | Habitat provision | Tall alien trees such as eucalypts and pines provide nesting sites for birds with which many urban dwellers can enjoy encounters. | McPherson et al. (2011) |
| | Nutrient cycling | | |
| | Pollination | *Robinia pseudoacacia* in urban areas provides resources for honey producing bees | Hausman et al. (2015) |
| | Primary production | | |
| | Soil formation | | |

**Table 2** Ecosystem services and disservices associated with urban vegetation within the study area *(Continued)*

| Ecosystem service category | Ecosystem services | Example | Reference |
|---|---|---|---|
| Cultural and Aesthetic | Loss of sense of place and aesthetic values[a] | Loss of sense of place and aesthetic values due to the presence of invasive alien plant species | de Wit et al. (2001); Le Maitre et al. (2011) |
| | Unattractive species or landscapes | Ugly' landscapes dominated by *Acacia* species. Neglected vacant lots overgrown with 'weedy' vegetation | Carruthers et al. (2011) |
| | Obscuring good views | Tall trees such as *Pinus* sp. can block good views | Roy et al. (2012) |
| Economic Problem | Increased maintenance costs | Grooming of street trees or sweeping up of leaf litter in streets | Roy et al. (2012) |
| | Cost of irrigation | Alien plants in gardens require supplementary irrigation during the dry season | Roy et al. (2012) |
| | Reduced property value[a] | Invasive plants blocking good views can reduce property prices | Roy et al. (2012) |
| Environmental Problem | Generating green waste | Increased green waste from gardens | Roy et al. (2012) |
| | Increased water consumption | Increased water consumption by alien and invasive trees such as *Acacia* sp. and *Eucalyptus* sp. | Carruthers et al. (2011); Kull et al. (2011); Le Maitre et al. (2002, 2011); van Wilgen and Richardson (2014) |
| | Reduced soil quality[a] | Modification of soil quality and promotion of soil erosion | de Wit et al. (2001); Shackleton et al. (2016) |
| | Disruption of soil-nutrient cycling, carbon and nitrogen fixation[a] | Invasive alien trees and shrubs such as *Acacia* sp. fix nitrogen | Yelenik et al. (2004); Gaertner et al. (2014); Qiu (2015) |
| | Displacement of native plant species / Reduced species richness[a] | Invasive alien trees and shrubs spreading into natural areas can disrupt native fynbos plant species and continued spread may reduce native species richness | Carruthers et al. (2011); Dickie et al. (2014); Kull et al. (2011); Le Maitre et al. (2011); Shackleton et al. (2016); van Wilgen and Richardson (2014); Vicente et al. (2013) |
| Health | Reduced air quality[a] | Emissions of Biogenic Volatile Organic Compounds reducing air quality | Potgieter et al. (2017) |
| | Increasing attack by associated insects and other animals | Areas with dense vegetation can harbour potentially dangerous animals such as venomous snakes | Roy et al. (2012) |
| | Pollen allergies | Pollen allergy and/or dermatitis caused by *A. altissima*, *Acacia dealbata*, *Cortaderia selloana*, and *Schinus terebinthifolius* | Pyšek and Richardson (2010) |
| | Poisoning | Cardiac problems and poisoning from *Echium plantagineum* | Pyšek and Richardson (2010) |
| Leisure and Recreation | Reduced recreation[a] | Presence of invasive species considered unpleasant for recreation | Vaz et al. (2017) |
| | Physical injury | Physical injury through contact with plant spines or thorns | Pyšek and Richardson (2010); Shackleton et al. (2016) |
| Material | Infrastructural damage | Roots of *Ailanthus altissima* damaging paved surfaces and boundary walls | Celesti-Grapow and Blasi (2004); Potgieter et al. (2019b) |
| Safety and Security | Fears of insects and other animals | Areas with dense vegetation can be invoke fear due to the possible presence of distasteful animals such as insects or snakes | Vaz et al. (2017) |
| | Increased crime risk | Criminal activity in dense vegetation close to informal settlement | Potgieter et al. (2019a) |
| Safety and Security / Environmental Problem | Increased fire risk (safety risk to infrastructure, but also impacting on native plants due to increased frequency and intensity of fires) | Increased fire risk due to tree invasions along the urban edge | Gaertner et al. (2014); Le Maitre et al. (2011); van Wilgen and Richardson (2014); Potgieter et al. (2018) |
| Safety and Security / Material | Safety hazard | Tall trees blown over in strong winds | Potgieter et al. (2019b) |

[a]Ecosystem disservices resulting from a reduction in ecosystem services

**Table 3** Supplementary spatial data and corresponding sources included in the classification process

| Spatial Data | Data Source |
|---|---|
| Indigenous vegetation remnants | City of Cape Town data portal; South African National Biodiversity Institute (SANBI) BGIS data portal |
| Biodiversity Network (CBA Rank) | SANBI BGIS data portal |
| Dams, aquifers, rivers, wetlands | City of Cape Town data portal; Invasive Species Unit (August 2016) |
| Flood prone areas | Directorate: Disaster Risk Reduction; Invasive Species Unit (August 2016) |
| Roads, buildings, points of interest | OpenStreetMap |
| Urban edge | City of Cape Town data portal |
| Community parks | City of Cape Town data portal |
| Greenbelts | City of Cape Town data portal |
| IAP density data | Invasive Species Unit (August 2016) |

information captured (see Potgieter et al. 2018). All IAPs present within each MU are listed and categorised according to predefined size categories used to describe the age of plants. The density of alien plant cover (% cover) is also estimated for each MU.

IAP cover was delineated using 1) density data from ISU site assessments and 2) the total area of trees and tall trees (> 3 m) outside of the urban edge (as per our land classification) - fynbos is typically depauperate of trees (Rundel et al. 2014) and plant species taller than 3 m are likely to be alien (Richardson et al. 1996). The area covered by these delineations within each grid cell was calculated and weighted based on the sum of corresponding ES and EDS detailed in Table 2. The total area for all MU's within the AOI was 4.6 ha.

## Results

An accuracy assessment of the land classification map yielded an accuracy of 85.71% and a Kappa coefficient of 0.826 (Table 1). The 'Bare ground' class yielded the lowest accuracy with a user's accuracy of 75.86%, followed by 'Grass' at 76.92%. The discrimination of bare ground proved problematic at times as it was confused with dry or patchy grass. Furthermore, there were several tree-covered areas that were confused with shrubs or tall trees, largely due to minor height discrepancies.

### Ecosystem services

Areas of high ES provision were characterized by the presence of large trees, which can sequester more carbon, provide more shade for people, and serve as habitat for fauna (Table 2). These areas occur predominantly along the urban edge (comprising invasive alien trees which have established and spread into the natural vegetation) and in the gardens of (affluent) residential properties (Fig. 3b). Other areas of high ES provision include urban green spaces, such as community parks, river networks and wetlands. Such areas are important in creating recreational spaces, reducing flood risk and cooling urban micro-climates (Table 2).

Areas of lowest ES provision occur in the township and informal settlement of Imizamo Yethu which is characterised by little to no vegetation, dense informal structures, and bare ground. Other areas of low ES provision included infrastructure such as large building surrounded by impervious surfaces and bare ground (Fig. 3b).

### Ecosystem disservices

Areas resulting in high EDS coincide with areas densely invaded by IAPs – particularly where alien plants invade along rivers and within wetlands (Fig. 3c). Other areas with high EDS occur along the urban edge where tall alien trees have established and started to spread into the natural vegetation. EDS include increased water consumption (environmental problems), increased fire and crime risk (safety and security), reduced soil quality (environmental problems), or a loss of sense of place and aesthetic values (cultural and aesthetic) (Table 2).

Moderate EDS are associate with areas comprising trees and shrubs (native or alien) such as private gardens, public open space and vacant lots. This is due to EDS such as increased water consumption (environmental problems), increased maintenance costs (economic problems), safety hazard (safety and security), infrastructural damage (material) or obscuring good views (cultural and aesthetic) (Table 2).

Areas associated with low EDS occur outside the urban edge in uninvaded natural vegetation. Areas comprising dense infrastructure (such as the informal settlement of Imizamo Yethu), impervious surfaces or bare ground resulted in moderate EDS. Such areas are more acutely associated with low ES provision (e.g. lack of shade, recreation and sense of place) than high EDS, however, characteristics of such an environment can create EDS (e.g. bare compacted ground or impervious surfaces can enable flooding and increase the ambient temperature).

### Trade-offs

Areas with high supply of both ES and EDS are likely to result in trade-offs regarding the management of species and the ES and EDS they provide (Fig. 3d). Many of the associated EDS are due to the presence of IAPs - several grid cells identified as important for the provision of ES, comprise IAPs. For example, grid cell 68 contains a river and wetland (vital for ES such as water provision, groundwater recharge and flood attenuation), but is densely invaded by alien aquatic plants (which some residents may find aesthetically appealing; Potgieter et al. 2019b), such as *Nasturtium officinale* and *Myriophyllum aquaticum*, which can reduce stream flows and water quality (Fig. 3d). Grid cell 108 comprises many species of alien trees and shrubs such as *Acacia* spp., *Eucalyptus* spp. and *Pinus* spp., which provide ES such as carbon sequestration, firewood, habitat provision and shade. However, these taxa are invasive and create EDS such as increased water consumption, increased fire risk and the displacement of native plant species (van Wilgen and Richardson 2014).

Residential gardens represent areas of moderate ES-EDS provision, i.e. there is moderate provision of both ES and EDS (Fig. 3d). A high proportion of urban vegetation provides many key ES, such as carbon sequestration, shade, and visual amenity. However, there are several associated EDS, such as increased water consumption, production of green waste, and increased maintenance and clean-up costs.

## Discussion

Developing approaches that can holistically map ES (and EDS) have been identified as a major research gap (de Groot et al. 2010a,b). We assessed multiple ES and EDS, integrating LiDAR data with high resolution multispectral imagery and applying supplementary spatially-explicit data proxies at a local scale to identify areas of high and low ES and EDS provision. In doing so, we also identified areas denoting potential management trade-offs. This approach can be applied to different urban areas where baseline information on urban vegetation is available and can be used to prioritise the conservation of areas of high provision of ES to maintain human well-being. Conversely, areas of high EDS or low ES provision could be prioritised for management interventions that restore and improve human well-being.

### Invasive alien plants and the ecosystem service – disservice dichotomy

Areas of high ES provision such as residential property gardens and urban green spaces are characterized by the presence of large trees (Fig. 3). Urban trees provide diverse aesthetic, economic, health, psychological and social benefits for urban residents (Roy et al. 2012) including: reduction in carbon pollution, improving air quality, reducing storm-water flooding, conserving energy, and reducing noise (Table 2). However, many of these areas also result in numerous EDS (e.g. increased fire risk and water consumption) due to invasions of alien trees and shrubs – particularly along rivers and within wetlands and along the urban edge where tall alien trees have established and started to spread into the natural vegetation. This suggests significant trade-offs regarding the management of species and the ES and EDS they provide.

Urban planners and managers are faced with many trade-offs in the decision-making process as each area (regional or local) is governed by different ecological, economic, and social variables. Stakeholders in urban areas often have opposing views regarding the benefits and negative impacts of IAPs, and consequently, conflicts over the management of IAPs are emerging (Dickie et al. 2014; Gaertner et al. 2017). IAPs may provide provisioning ES (e.g. firewood), but significantly threaten biodiversity, which can lead to conflicts over whether to manage for the former or the latter (van Wilgen 2012). Therefore, many IAPs within urban areas may need to be tolerated at specific sites for a combination of social and pragmatic reasons (Gaertner et al. 2016). Careful evaluation of the ES-EDS dichotomy in the context of urban plant invasions may allow conflicts to be mitigated and managed in more efficient ways (Dickie et al. 2014; Potgieter et al. 2017).

Several grid cells identified as important for the provision of ES, comprise IAPs which can in turn result in numerous EDS (Fig. 4). Residential properties along the urban edge share a border with fynbos vegetation here (Alston and Richardson 2006), and these properties serve as sources of alien plant propagules, which disperse, establish and spread into the surrounding natural vegetation, threatening biodiversity. While providing several ES such as firewood and carbon sequestration, the increase in biomass resulting from alien plant invasions close to urban infrastructure represents a substantial fire risk (Fig. 5), threatening property and the safety of people (van Wilgen and Scott 2001; van Wilgen et al. 2012). Furthermore, invasive alien trees and shrubs alter the vegetation structure (forming dense stands and growing taller than the surrounding fynbos vegetation; van Wilgen and Richardson 1985), providing cover for vagrants and those engaged in criminal activity. Potgieter et al. (2018) found that factors related to safety and security are most important for setting spatially-explicit management priorities in Cape Town. Accordingly, invaded areas along the urban edge (e.g. Figure 5) should receive a high priority for management. Areas identified as important in the provision of ES (e.g. urban green spaces and surrounding natural vegetation) should be monitored to ensure the continued provision of ES and maintenance of biodiversity.


| Ecosystem services | | | Ecosystem disservices | |
|---|---|---|---|---|
| Heritage | Firewood** | Energy saving | Reduced species richness | Pollen allergies* |
| Visual amenity | Medicine*(**) | Runoff mitigation | Increased water consumption | Reduced air quality (bVOC emissions)* |
| Sense of place | Climate regulation | Shade | Disruption of soil-nutrient cycling | Increased attacks from animals |
| Recreation | Air quality | Nitrogen fixation* | Increased maintenance costs | Reduced recreation |
| Spiritual enrichment | Flood attenuation | Habitat provision | Increased clean-up costs | Leaf litter/debris* |
| Construction material** | Barrier/windbreak | Nutrient cycling | Reduced property value | Increased crime risk |
| Fodder*(**) | Carbon sequestration | Pollination* | Loss of sense of place and aesthetic values** | Increased fire risk |
| Food*(**) | Erosion control | Primary production | Unattractive species or landscapes** | Safety hazard |
| | | Soil formation | Obscuring mountain views** | Fear of animals** |

*Species level information is required to confirm ecosystem service / disservice provision (bVOC = Biogenic Volatile Organic Compound).
**Stakeholder engagement is required to determine ecosystem service / disservice provision.

**Fig. 4** An example of the ecosystem service-disservice trade-offs associated with invasive alien plant species at the urban-wildland interface

## Decision-making and management

The nature of people and their discount rates that favour immediate over delayed gratification may be driving decisions about ES, even when such decisions might interfere with ES that are necessary for the long-term sustainability of human well-being (Foley et al. 2005).

The emphasis on provisioning ES may be due to their more tangible and easily quantifiable character, whereas the importance of cultural, regulating, and supporting services are more difficult to quantify (Potgieter et al. 2017). Particularly, research on cultural ES are generally subjective and socially value-laden (related more to the individual than to ecosystem conditions) as each individual or each group of individuals has different value systems and priorities. Various aspects like experience, habits, belief systems, behavioural traditions, and general political and socio-economic status should be considered (Vaz et al. 2017; Shackleton et al. 2019). Social values related to preferences, importance, measures and principles, and assessment need to be plural, participatory and best embedded within transdisciplinary research (Pascual et al. 2017). Indeed, community engagement is crucial, and quantifications based on interviews, questionnaires or additional information sources can strengthen ES

**Fig. 5** Google Street View can be used to determine key vegetation characteristics and associated ecosystem services and disservices at specific locations. Tall, dense stands of invasive *Acacia* sp., *Eucalyptus* sp. and *Pinus* sp. behind a residential property on the urban edge are visible; these present a substantial fire risk (imagery date: 09/2009). A pile of wood (likely to be used as firewood) collected from these invasive stands is also clearly visible, highlighting an ecosystem service provided by the invasive alien trees

assessments and better inform management strategies (Sherrouse et al. 2011). Research on the application of remote sensing in the field of alien species and ES continues to progress as technology and our understanding of the ways in which ES are mediated by alien species improves (e.g. Lafortezza and Giannico 2017; Pettorelli et al. 2017; Vaz et al. 2019).

Each urban area presents a unique set of challenges requiring city-specific management strategies (Irlich et al. 2017). The challenge in prioritising areas for management at the local scale is to weigh factors relating to biodiversity conservation, ES (and EDS) and social tradeoffs. For example, managers must decide whether to prioritise areas which have negative indirect long-term impacts on biodiversity and regulating and supporting services (such as increased soil erosion and reduced soil quality) or to prioritise areas based on the negative direct short-term impacts on provisioning services (such as water supply).

Decisions must be made on whether to manage for enhanced ES provision, or to minimise EDS - high priority areas for management include those which result in EDS (including a reduction in ES provision). For example, areas along the urban edge invaded with alien trees and shrubs which negatively impact on biodiversity and ES (such as the displacement of native plant species and reduced soil quality) and result in EDS such as increase fire and crime risk (Potgieter et al. 2018, 2019b). Such decisions are largely context-specific, and managers need to consider the knock-on effects when managing to reduce EDS or enhance specific ES, as other ES may be indirectly disrupted, or novel EDS created. For example, planting trees in the informal settlement of Imizamo Yethu with the intention of providing ES (such as shade) and enhancing human well-being may have the opposite effect as trees may blow over in high winds and increase the risk of fires. Such decisions need to be transparent and must consider opinions of a wide range of stakeholders including the public and those involved in urban planning and ecosystem management decisions (Novoa et al. 2018).

Careful consideration must also be given to the existing supply and demand of ES beneficiaries and their perceptions of ecosystem components (Burkhard et al. 2012; Shackleton et al. 2019). Stakeholder engagement is needed to gauge the ES demand and this information can be aligned with spatial assessments of ES provision to identify areas that have the potential to unlock the required ES to meet this demand. Importantly, however, ES demand is likely to be highly variable and context-specific (e.g. along the socioeconomic gradient) (Syrbe and Grunewald 2017). Understanding the ways in which people perceive nature is also crucial for developing effective management strategies to conserve and maintain biodiversity, ES and human well-being (Shackleton et al. 2019). This is especially important in urban areas which generally have a greater number and diversity of stakeholders compared to rural areas (Gaston et al. 2013). Indeed, perceptions of urban vegetation and the ES and EDS they provide can differ markedly between individuals or groups of people (Shackleton et al. 2016; Kueffer and Kull 2017; Potgieter et al. 2019b).

#### Socio-economic context

Socio-economic conditions within the urban milieu influence the spatial heterogeneity in the provision of ES (de Groot et al. 2010a, b). Areas of lowest ES provision occur in the township and informal settlement area of Imizamo Yethu which is characterised by little to no vegetation, dense informal structures, impervious surfaces and bare ground (Fig. 3b). These features result in low ES provision and can facilitate flooding and increase the ambient temperature.

Affluent areas have the capacity and resources to invest in green infrastructure such as plantings in private gardens. In so doing they can contribute to the provision of additional ES (ES synergies) such as carbon sequestration, improved air quality and stormwater runoff mitigation (from which other residents may benefit). However, lower income areas such as informal settlements do not have the same capacity or resources and rely solely on existing ES provided by the immediate environment. Indeed, this is a common theme in many rapidly urbanising African cities in which many people are still highly reliant on natural resources (including IAPs). The urban poor lack an adequate supply of basic services like electricity, healthcare, sanitation, waste disposal, and water (Goodness and Anderson 2013). Additional measures are needed to improve the supply of ES to these areas. One recommendation may be to advocate for the planting of beneficial, native, drought-resistant perennial shrubs such as honeybush (*Cyclopia* spp.) or buchu (*Agathosma* spp.), which can provide multiple ES (e.g. medicine; Petersen et al. 2012) with relatively few associated EDS. However, the practicalities of implementing such measures may prove challenging. The careful evaluation of the demands of the communities is required as there are likely to be divergent viewpoints and competing objectives. Engaging with the community is therefore a key part of the process. Similarly, managing to reduce EDS in the surrounding areas requires rigorous social assessments to avoid potential conflicts of interest. For example, clearing invasive alien trees nearby may affect the livelihoods of Imizamo Yethu residents as they may utilize these species for firewood or construction material.

### Methodological considerations

Some online resources enable a range of new remote sensing possibilities, including the use of interactive on-the-ground virtual views. Foremost among these is Google's Street View (GSV) - a free-access web technology featured in Google Maps and Google Earth. GSV provides interactive georeferenced panoramic photographs, taken at short intervals by high-resolution cameras placed on the roof of a moving car, along many roads around the world. This provides on-the-ground imagery for sites close to roads, most extensively in urban areas.

GSV can serve as a useful supplementary tool in ES assessments (e.g. Richards and Edwards 2017), particularly in urban areas. For example, once an ES- or EDS-providing area has been identified, GSV images of the site can be examined to determine accessibility, characteristics of street vegetation such as the proportion of streetscape 'green' coverage, and in some cases individual plant species. Occasionally, a direct link between surrounding vegetation and ES can be detected (Fig. 5).

### Limitations

Direct remote sensing of ES is challenging - ES are often intangible in that they are defined by ecosystem functions and processes that involve a temporal component. Biodiversity and habitat functions are particularly difficult to map remotely as they depend largely on species composition which must be measured using inventories and ground data collection (Gillespie et al. 2008). Regulating services, characterized as being of indirect use, provide the conditions that allow other directly used ES (e.g. provision of firewood) to exist (Abson and Termansen 2011). Similarly, supporting services do not directly benefit people, but are essential to the functioning of ecosystems and are therefore indirectly responsible for all other services (Haines-Young and Potschin 2010). Consequently, these services are more difficult to quantify (Rodriguez et al. 2006), particularly in urban settings.

Many ES are difficult to effectively conform to land cover as an ES proxy, as genus- or species-level information is required. For example, food (provisioning), nitrogen fixation (regulating) and pollination (supporting) require detailed information on the species traits facilitating the provision of ES (Table 1). As a result, such ES may be overrepresented in this approach. The diversity of species in urban areas makes species-level image classification particularly challenging. Coarse spatial and spectral resolutions make it difficult to separate native and alien species in mixed species assemblages. Species mapping efforts are usually limited to a small subset of species that are canopy dominants and that are sufficiently distinct to enable remote detection. The presence of many alien species (mainly herbaceous plants) may not be discernible even using the newest high-resolution sensors (e.g. GeoEye-1). In addition, phenological changes of vegetation due to the presence of alien species might not be recognizable if there is no distinct flowering pattern because of the coarse spectral resolution of high spatial resolution images.

Acquiring affordable data at an appropriate resolution around the same time period may be challenging when following the approach developed here. Data should be acquired at the highest spatial resolution possible to ensure accurate classification, and all datasets should, as much as is possible, be temporally aligned. Ensuring the data at least matches seasonally, should be the minimum requirement.

Some ES are more significant than others (McPherson et al. 2005; Stoffberg et al. 2010; Soares et al. 2011). For example, while the value of energy savings, carbon dioxide reduction and air pollutant deposition in Lisbon were comparable to several other USA cities, the large values associated with stormwater runoff reduction and increased property value were considerably greater than values obtained in US cities (Soares et al. 2011). No information is available on the importance of different ES and EDS for our study area and these were consequently not weighted in our assessment. It is important to assign priorities to specific ES and EDS prior to performing spatial assessments.

## Conclusions

Multiple interacting environmental and socio-economic factors complicate IAP management efforts in urban areas across the globe. The challenge is for IAP managers to overcome such barriers to effectively manage urban plant invasions and ensure the continued provision of ES that are essential for human well-being. However, management decisions need to carefully consider the socio-economic ties associated with IAPs and such decisions need to be based on an understanding of plural values, be participatory and rooted within transdisciplinary research.

This study presents a reproducible and spatially-explicit assessment of ES and EDS and demonstrates an effective approach for guiding urban planners and managers to improve ES provision at the local-scale. The study also unpacks potential management trade-offs and conflicts of interest resulting from the complexities of the ES-EDS dichotomy, which requires urgent consideration to improve resilience through urban policy and planning.

#### Abbreviations

DSM: Digital Surface Model; DTM: Digital Terrain Model; EDS: Ecosystem disservices; ES: Ecosystem services; GSV: Google Street View; IAP: Invasive alien plants; ISU: Invasive Species Unit; LiDAR: Light Detection and Ranging; MU: Management Unit; nDSM: Normalised Digital Surface Model; NDVI: Normalized Difference Vegetation Index; OSM: OpenStreetMap;

SANSA: South African Space Agency; VGI: Volunteered Geographic Information

**Acknowledgements**
Funding for this work was provided by the DST-NRF Centre of Excellence for Invasion Biology, the Working for Water Programme through their collaborative research project on "Integrated Management of invasive alien species in South Africa", and the National Research Foundation, South Africa (grant 85417 to DMR). We thank the Invasive Species Unit for providing invasive plant density data. We also thank Divan Vermeulen from the Centre for Geographical Analysis, Stellenbosch University, for providing LiDAR data and additional guidance.

**Authors' contributions**
LJP, POF and DMR conceived the study; LJP performed the analyses and wrote the first draft; all authors contributed critically to successive drafts and gave final approval for publication.

**Funding**
Funding for this work was provided by the DST-NRF Centre of Excellence for Invasion Biology and the Working for Water Programme through their collaborative research project on "Integrated Management of invasive alien species in South Africa" and the National Research Foundation, South Africa (grant 85417 to DMR).

**Availability of data and materials**
The datasets used and/or analysed during the current study are available from the corresponding author on request.

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare that they have no competing interests.

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Received: 2 April 2019 Accepted: 11 September 2019
Published online: 28 October 2019

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