Satellite-based annual evaporation estimates of invasive alien plant species and native vegetation in South Africa

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ABSTRACT

In this study we assessed the impact that invasive alien plant species (IAPs), and the clearing thereof by the Working for Water (WFW) programme, have on total evaporation (ET) and the availability of water resources in two highly-invaded provinces of South Africa. The Surface Energy Balance Algorithm for Land (SEBAL) model, using MODIS satellite imagery, was used to estimate the annual total ET at 250 m pixel resolution. ET was estimated for 3 climatically different years for the Western Cape and KwaZulu-Natal. The average annual ET from areas under IAPs, native vegetation, exotic plantation forestry species and control (clearing) areas were compared. The ET of the 5 dominant IAPs (*Acacia mearnsii*, *Acacia saligna*, *Eucalyptus* spp., *Hakea* spp. and *Pinus* spp.) in the Western Cape province was 895 mm, which was significantly higher than the ET of most of the native vegetation (thicket 575 mm and fynbos 520 mm), but similar to the ET of dominant exotic plantation forestry species (805 mm). On average, the ET was reduced by 13% to 780 mm, following clearing. In KwaZulu-Natal Province, the ET of the 5 dominant IAPs (*Acacia mearnsii*, *Chromoleana odorata*, *Eucalyptus* spp., *Lantana camara* and *Solanum mauritanium*) was 875 mm, which was also higher than the ET of the native vegetation (thicket 755 mm, savanna 685 mm and grassland 640 mm). Following IAP control the ET was decreased by 6%, to 825 mm.

This study has demonstrated that spatial ET data with GIS-information on land use can be used to assess the impact of IAPs, and clearing thereof, on water resources. We confirmed results from previous studies, which showed that ET from invaded areas exceeded that from native vegetation. The ET data needs further validation as validation appeared to be impossible. Our results are likely conservative since the majority of invaded areas considered in this analysis represent non-riparian areas. The impact of WFW control of densely-invaded riparian areas is likely more pronounced. We concluded that the clearing of IAPs by the WFW programme has a positive effect on the availability of water resources through a reduction in ET.

Keywords: invasive alien plants; indigenous vegetation; remote sensing; water use; evapotranspiration; SEBAL; Western Cape; KwaZulu-Natal

INTRODUCTION

Internationally, invasive alien plant species (IAPs) are recognised as the 'most important direct drivers of change in ecosystems' (Millennium Ecosystem Assessment 2005 p. 14 in Cavaleri and Sack, 2010). Although researchers believe that IAPs often have a negative impact on water resources through their high water use (ET) compared to native vegetation (Calder and Dye, 2001), little is actually known about the impact of IAPs on ecological processes (Calder and Dye, 2001; Cavaleri and Sack, 2010).

In South Africa (SA), IAPs not only impact on the water resources, but also on land productivity and biodiversity. IAPs occur across the SA landscape and it is estimated that about 10 million ha (8.28%) of SA has been invaded to some extent, at an average species density of 17% (Le Maitre et al., 2000). IAP spread and density across the Western Cape and KwaZulu-Natal provinces of SA is shown in Fig. 1 (Kotzé et al., 2010). Dense invasions are generally confined to small areas often associated with riparian zones. IAPs are controlled through legislation, with a total of 198 IAPs being declared as weeds and an additional 36 species potentially invasive (Henderson, 2001). The top ten invaders of SA are listed in Table 1 (Le Maitre et al., 2000).

Concerns about the impact of exotic plantation species on streamflow arose as early as 1932 (Dye and Bosch, 1999), which led to the establishment over time (1935–1980) of paired catchment experiments across SA, where the impact of land use changes (replacing grasslands or shrublands with exotic tree species) on streamflow were studied. It was only in the mid 1990s that the potential impact of IAPs on SA's available water resources was recognised by the government (Le Maitre et al., 1996). At the time, predictions of the impact of IAPs on water resources were based on the results from the paired catchment studies (Bosch et al., 1986), considering information on IAP spread (Versfeld et al., 1998; Görgens and Van Wilgen, 2004). Bosch et al. (1986) stated that a post-fire reduction in biomass (of fynbos, a native vegetation type) would lead to increased streamflow (Dye and Bosch, 1999). It was therefore predicted that woody IAPs would likely use significant amounts of water and reduce streamflow. These concerns and predictions led to the launch of the acclaimed Working for Water (WFW) programme in SA in 1995. The aim of this programme is to control (mainly by removing) IAPs, and in so doing protect the biodiversity and water resources of SA, whilst providing social-economic benefits to communities through job creation.

Following the launch of the WFW programme, studies continued to investigate the impact of IAPs on streamflow and total evaporation at various scales. Streamflow-biomass-based

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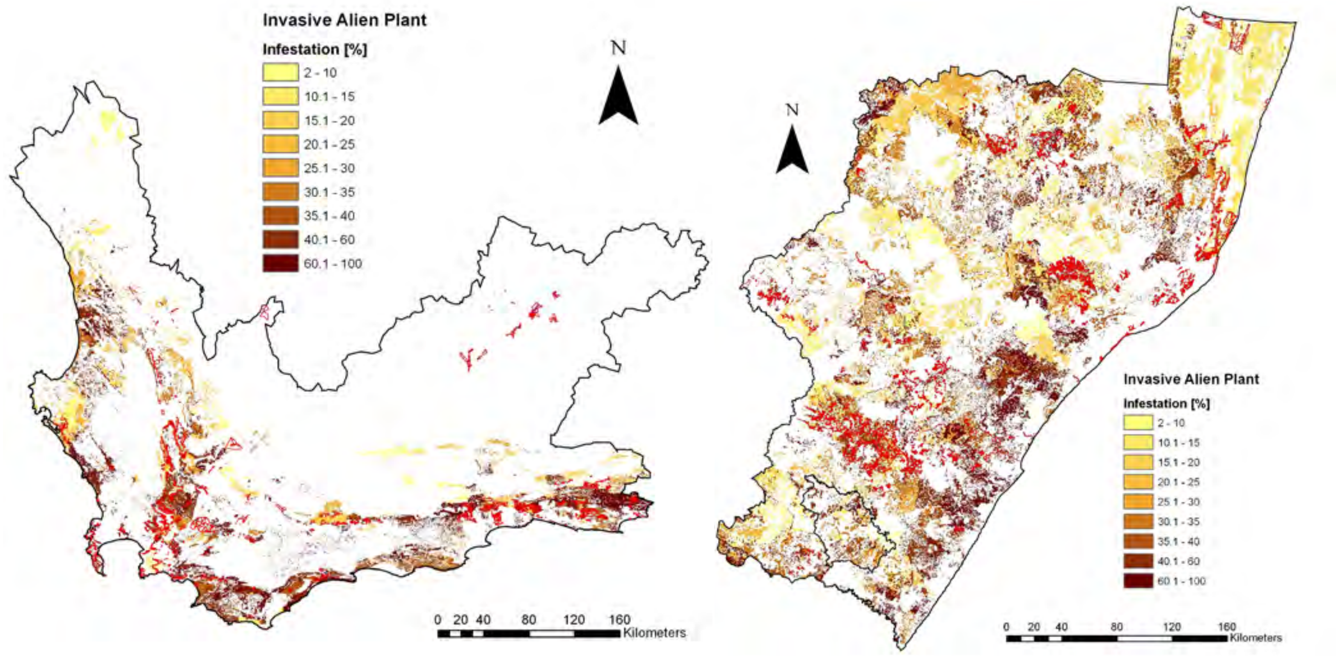

Figure 1

Invasive alien plant spread and infestation (%) in the Western Cape (left) and KwaZulu-Natal provinces (right) (according to Kotzé et al. (2010)) and the control areas (red polygons) by the Working for Water Programme over the period 1999–2006 (Source: WIMS).

TABLE 1
Top 10 invasive alien plant species found in South Africa according to the habitat, density of invasion and extent of their invasion (Source: Le Maitre et al., 2000)

Species	Common name	Habitat
Melia azedarach	Syringa / Persian lilac	Riparian, landscape
Pinus spp.	Pine	Landscape
Acacia mearnsii	Black wattle	Riparian, landscape
Lantana camara	Lantana	Riparian
Acacia cyclops	Rooikrans	Landscape
Acacia saligna	Port Jackson	Landscape, riparian
Opuntia sp.	Small round leaved prickly pear	Landscape
Prosopis spp.	Mesquite	Alluvial plains
Solanum mauritanium	Bugweed	Riparian, landscape
Hakea spp.	Hakea	Landscape

models (Le Maitre et al., 1996; 2000) were developed to predict the impact of IAPs on streamflow, both on a regional and national scale. The impact is expressed as the additional water used by exotic plantation trees compared with the native vegetation it has replaced. At field scale, studies showed that clearing woody IAPs (e.g. *Acacia*, *Eucalyptus* and *Pinus* spp.) increased streamflow (Prinsloo and Scott, 1999; Dye and Poulter, 1995). Other studies showed that, e.g., a riparian thicket of *Acacia mearnsii* used significantly more water than native fynbos and grassland it often replaces (Dye et al., 2001; Dye and Jarmain, 2004). A few other short-term studies also measured the ET of *Chromoleana* spp. (scrambler) (Jarmain et al., 2008), *Hakea* spp. (Dye et al., 2008) and *Pinus* spp. (Dye et al., 2008).

All of these past studies have contributed to our understanding of the impact of IAPs on streamflow and ET in SA, but have shortcomings (Görgens and Van Wilgen, 2004) as follows:

- The original predictions of the impact of IAPs on streamflow reduction are based on afforestation experiments conducted in high rainfall regions (annual rainfall > 1 100 mm), which raises the question as to whether these data can be extrapolated to drier regions
- In the past, no known methods existed to upscale-site specific field measurements of ET in space and time.
- Knowledge of the impact of IAPs on water resources is limited to a few IAP species found in SA, mainly woody IAPs grown in commercial forestry plantations. The impact of shrub-like species remains poorly understood. Similarly, knowledge on the ET of native plants is also limited to few species and therefore direct comparison of ET (IAPs vs. native vegetation) is not always possible.
- Finally, the impact of IAPs on groundwater resources is also poorly understood. Current knowledge on IAPs and native vegetation ET is too limited to provide an adequate foundation for the countrywide estimation of ET in invaded regions.

Recent developments in the use of surface energy balance models that use satellite remote-sensing data (visible, near-infrared and thermal infrared imagery) now make it possible to quantify actual ET of various land uses (e.g. various IAPs, native vegetation, exotic plantation forestry species and areas where IAPs have been removed) simultaneously over space and time, thus addressing the information gaps. In this study, remote-sensing data and the Surface Energy Balance Algorithm for Land (SEBAL) model were used to assess actual ET across the Western Cape and KwaZulu-Natal provinces, both densely invaded (Fig. 1) (Le Maitre et al., 2000). The annual ET prior to and following IAP clearing was estimated, and contrasted against the ET of other land uses (forestry, biomes and biotopes). In contrast to previous studies (Le Maitre et al., 2000; Cullis et al., 2007) where the invasion data from Versfeld et al. (1998) were used, this study used data from the Working for Water Information Management System (WIMS). WIMS is a geographical information system (GIS) database from the WFW programme that contains information on IAP species and densities of the invaded areas that have been controlled (i.e. cleared) by WFW (Fig. 1) (Marais and Wannenburgh, 2009). To account for climatic variability, we compared the ET calculated using SEBAL from 3 climatically different years (wet, dry and average rainfall).The results are described in this paper.

Definitions

SEBAL provides estimates of actual total evaporation (ET) for each pixel within a satellite image. Total evaporation refers to the sum of water lost from a surface, whether through transpiration by vegetation (T), soil evaporation or evaporation of intercepted water (E).

ET estimates for IAPs refer to the water use of an area (i.e. a satellite pixel) invaded by a specific IAP species with a density exceeding 35% (see section on WIMS IAPs data). The ET of native vegetation was estimated for biomes and biotopes as classified by Low and Rebelo (1996). Cultivated areas (agriculture and forestry) were identified using the National Land Cover (NLC) classification of 2000 (Van den Berg et al., 2008). We will only discuss the ET estimates for exotic plantations from the NLC classification. Finally, the ET estimates of control (treated) areas refer to the water use of areas where the dominant IAPs have been cleared by WFW (according to WIMS). The ET estimates of these treated areas represent the water use of native vegetation, and eventually re-growing (and/or secondary) invaders, or a combination thereof.

METHODS

Satellite data

The size of the Western Cape and KwaZulu-Natal provinces compelled us to use Moderate Resolution Imaging Spectroradiometer (MODIS, http://modis.gsfc.nasa.gov/index.php) imagery in the SEBAL ET modelling. Total evaporation was estimated for 3 climatically different years (in this study a year extends from 1 July to 30 June), representing average, above-average and below-average rainfall conditions. The Tropical Rainfall Measurement Mission (TRMM) rainfall data (daily precipitation product 3B42, http://trmm.gsfc.nasa.gov) were used in the selection of the three years. For the Western Cape the following years were selected: 2000–2001 (dry), 2002–2003 (average) and 2006–2007 (wet). And for KwaZulu-Natal: 2000–2001 (average), 2003–2004 (dry) and 2006–2007 (wet).

A total of 70 MODIS images (Level 1B calibrated radiances – MODIS products) per province were used to estimate annual ET for each year. Generally, MODIS images are captured twice a day (by the Terra and Aqua sensors). To limit processing time and costs, one predominantly cloudfree image per 2-week period was selected and used. This approach might lead to biased ET results (in particular non-riparian areas) as ET changes from precipitation events are missed between consecutive images. However, this error should tend to decrease as more images are used per year. The following criteria were used for selecting good images: low to no cloud cover and low satellite viewing angles. Cloudy areas (as well as fog and fires) were masked out and filled at a later stage (gap filling was done at the stage at which the ET was derived, by interpolating ET using previous and following ET maps). Data from Aqua (mid-day satellite overpass) were preferred over Terra (early morning overpass) as the midday-based evaporative fraction (EF) is closer to the daily EF (Peng et al., 2013) (see next section). The spatial resolution of the 36 spectral bands of MODIS varies. Band 1 (red) and 2 (near-infrared) have a resolution of 250 m, while the other required MODIS bands have lower resolutions (500 m to 1 km). In order to estimate the ET at a 250 m resolution, all necessary spectral bands were downscaled to 250 m (i.e. the 500 m shortwave bands 3 to 7 were re-sampled to 250 m using cubic convolution). The 1 km thermal bands (band 31 and 32) were re-sampled to 250 m surface temperature maps using a broadband surface thermal emissivity relationship based on the 250 m NDVI (Normalised Difference Vegetation Index) (Van der Griend and Owe, 1992).

Surface Energy Balance Algorithm for Land (SEBAL) model

SEBAL is a surface energy balance model (based on physical and empirical parameterisation) that provides spatial estimates of actual ET at pixel scale (in this study at 250 m). Since the model has been discussed in detail by Bastiaanssen et al. (1998a, b; 2005) and Wang et al. (2009), only the basic steps are discussed here.

SEBAL combines the broadband surface albedo, NDVI and surface temperature with spatially gridded weather data (air temperature (T), relative humidity (RH), wind speed (u) and solar radiation ($K^{\downarrow}$)), a digital elevation map (DEM) and a land cover map to determine ET for each 250 m pixel. The weather data were provided by the South African Weather Service and the Agricultural Research Council. The spatial gridding of the weather data was done using Meteolook (a physically-based distribution model for T, RH and u (Voogt, 2006)). Solar radiation ($K^{\downarrow}$) was estimated using the DEM, the solar radiation model of Tasumi et al. (2006) in combination with atmospheric transmissivity (τ) data taken from either ground stations or the remote-sensing products of the Land Surface Analysis Satellite Applications Facility (http://landsaf.meteo.pt, available since 2005). The surface roughness (z_o) and zero-displacement height (d) were derived from the land cover map and NDVI (which is related to the leaf area index, LAI) data to incorporate seasonal changes in z_o and d (Raupach, 1994; Verhoef, et al., 1997) (as the LAI increases the canopy closes and the surface becomes aerodynamically smoother).

Each satellite image, which contains instantaneous information of the earth's surface, is processed in 3 steps. First, the instantaneous ($_i$) energy balance (EB_i) is solved at the time of the satellite overpass. Once the net radiation (R_{ni}) and soil heat flux (G_i) are estimated, the sensible heat flux (H_i) is derived using special 'anchor' pixels within the thermal image. These carefully selected 'anchor' pixels consist of a 'wet' pixel (mostly a water pixel) and a 'dry' pixel representing areas where the ET is considered maximum and zero respectively. Once H_i is estimated, the latent heat flux (λE_i, evaporation expressed as energy flux) is derived as the closure term of the EB, and the evaporative fraction (EF_i), in turn. Secondly, the daily ($_{24}$) energy balance is solved. Assuming the evaporative fraction remains reasonably stable during the day, the daily evaporative fraction (EF_{24}) is derived from EF_i. Here, EF_{24} is allowed to change slightly due to advection processes, using an empirical advection model (which describes advection as the ratio of the instantaneous ($EF_{i,ref\text{-}grass}$) and daily evaporative fraction ($EF_{24,ref\text{-}grass}$) for a standard grass reference crop, derived from standard hourly weather data; in case no advection occurs the ratio equals 1, i.e. $EF_i = EF_{24}$). Advection is defined here as the horizontal exchange of energy due to horizontal heterogeneity at the earth's surface which can alter the ET. Once the daily net radiation (R_{n24}) and soil heat flux (G_{24}) are known, together with daily mean weather data, the daily ET can be derived (ET_{24}) (Bastiaanssen, 2000). By applying the Penman-Monteith equation (Allen et al., 1998) 'in reverse', it is then possible to derive the daily average surface resistance or crop resistance (rs_{24}). The latter term is used in the third step to estimate the ET_{per} for a period of roughly 2 weeks using the Penman-Monteith equation and the corresponding period mean net radiation, soil heat flux and weather data. During this 2-week period it is assumed that rs_{24} remains fairly constant, i.e. rs_{24} is not adjusted after a rain event, except for advection processes similar to the advection correction in the second (daily) step. The ratio of the daily ($EF_{24,ref\text{-}grass}$) and the period evaporative fraction ($EF_{period,ref\text{-}grass}$), both derived from standard weather data, is used as a measure of advection. In each of the steps, spatially gridded meteorological data are used (e.g. T, RH, u and $K^{\downarrow}$ data). Finally, the biomass growth is estimated where the light use efficiency (assuming c_3 - vegetation) is coupled to the stomata aperture, i.e. the surface resistance (rs_{24}) (Zwart and Bastiaanssen, 2007).

WIMS IAPS DATA

Classification of invaded and treated areas

The clearing information (i.e. treatments) of the WFW programme is extracted from the WFW management database, WIMS. WIMS is a GIS database and contains information on each treatment, including the type of IAP species, IAP densities, costs of treatment, person days planned and worked on a specific area (polygon), and contract end dates (Marais and Wannenburgh, 2008), for the period 1999 to the end of 2006 (see Fig. 1, the red polygons). In general a contract lasts ~6 weeks (Wannenburgh, 2009). Using the contract end date, each polygon (and later on the SEBAL-ET pixels) was either classified as an invaded area or as treated area with respect to a SEBAL year. For example, a polygon (in KwaZulu-Natal) that was treated in August 2005 is classified as an invaded area for the SEBAL year 2003–2004 and as a control (treated) area for the SEBAL year 2006–2007. However, since the WIMS database (used in this study) extended until 2006, the SEBAL-ET data for 2006–2007 could not be used to investigate the ET of invaded areas, but only for the assessment of ET for the treated areas.

Selecting IAPs pixels for inclusion in data analysis

The size of the Western Cape and KwaZulu-Natal provinces compelled us to use MODIS imagery (which has a large swath width), as a MODIS-satellite image covers an entire province and therefore all the invaded areas (Fig. 1) that have been treated by WFW. However, the spatial resolution is limited to 250 m, i.e., an area of 6.25 ha. Compared to the size of most polygons in the WIMS GIS-database, 6.25 ha is relatively coarse. Therefore, when superimposed, only certain MODIS pixels are fully contained in the WIMS polygons. Valid SEBAL-ET pixels were selected using the following criteria: (i) more than 70% of a 250 m MODIS-pixel must be in a polygon that represents a WFW treated area; (ii) the recorded species density must be more than 35% (according to WIMS). The ideal situation would be to use polygons (and pixels) with a species density of 100%. Unfortunately, most polygons with a 100% species density are small (mostly riparian areas along narrow streams) and do not cover a 250 m pixel sufficiently and were excluded from further analysis. Therefore, as a compromise between a sufficient amount of sampled pixels and a sufficient species density, a minimum invasion density of 35% was chosen. As a result the number of pixels that could be assessed in this study was: 2 400 sampled pixels for the Western Cape and 400 sampled pixels for KwaZulu-Natal. Most of these pixels represent non-riparian areas, and have a mean invasion density of 57%. This implies that the SEBAL-ET results for IAPs likely also contain information (43%) from other (native) vegetation. The amount of IAP pixels that could be sampled for KwaZulu-Natal was very limited and this fact should be taken into account when interpreting the results.

RESULTS

Annual ET at provincial scale

Annual ET, rainfall (Schulze, 2007), biomass production and NDVI vary spatially across the Western Cape and KwaZulu-Natal provinces (Figs. 2 and 3). The total NDVI (NDVI-sum) is derived from the NDVI-SPOT archive data (http://free.vgt.vito.be). The annual NDVI-sum shows high (low) annual cumulative NDVI values for areas that have abundant (little) active vegetation during the year, which are likely the result of high (low) rainfall amounts and/or unlimited water resources (Figs. 2 and 3). Missing data (white areas in the ET and biomass panels) are the result of frequent cloud cover in the images. The TRMM rainfall data, due to its limited spatial resolution (25 km), in combination with the mountainous terrain of the Western Cape and KwaZulu-Natal province, could not be used to assess the SEBAL-ET results. Instead, long-term average rainfall data from the South African Atlas of Agro-Hydrology and Climatology (Schulze, 2007) were used.

The provincial average ET for the Western Cape was estimated to be 325 mm for the average rainfall year (2002–2003). This is significantly lower than the average ET estimate of 570 mm (2000–2001) for KwaZulu-Natal. Note that the 2000–2001 results for KwaZulu-Natal are susceptible to errors (underestimation of ET) due to limited solar radiation data. The higher ET estimates for KwaZulu-Natal for all three years are consistent with the higher rainfall estimates for this province, with more than twice the rainfall of the Western Cape (Table 2). This is also reflected in the higher biomass production and NDVI values. The annual biomass production in KwaZulu-Natal varied between 22 and 25 ton·ha^{-1} and in the Western Cape was, on average, 9 ton·ha^{-1}.

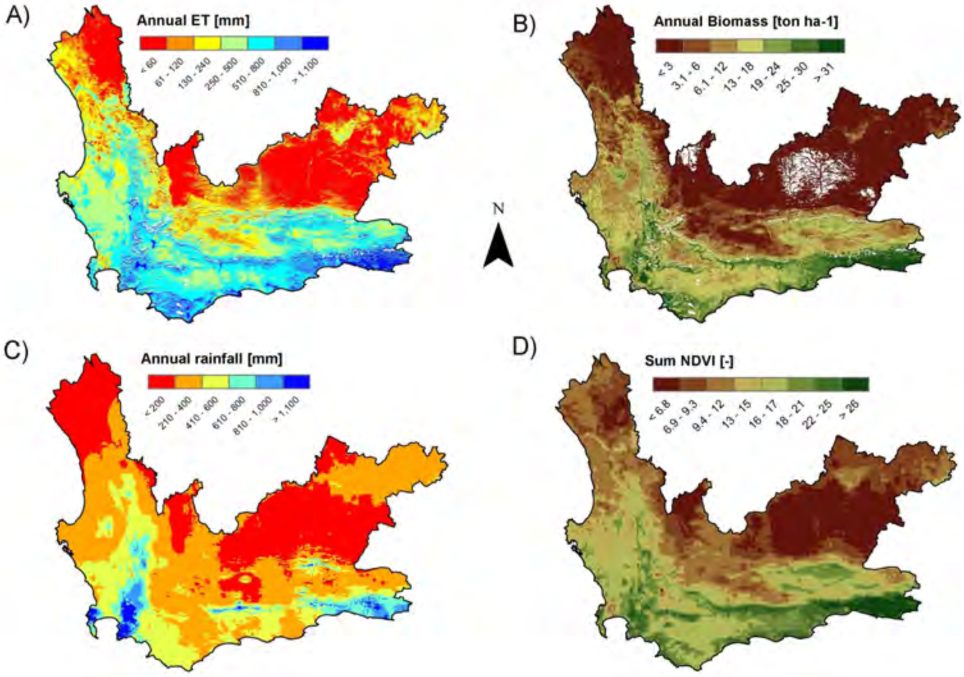

Figure 2
Annual ET (mm), annual biomass production (ton·ha^{-1}), annual climatic rainfall (mm) (Schulze, 2007) and sum of NDVI-SPOT over the period July 2002 – June 2003 (average rainfall year) for the Western Cape.

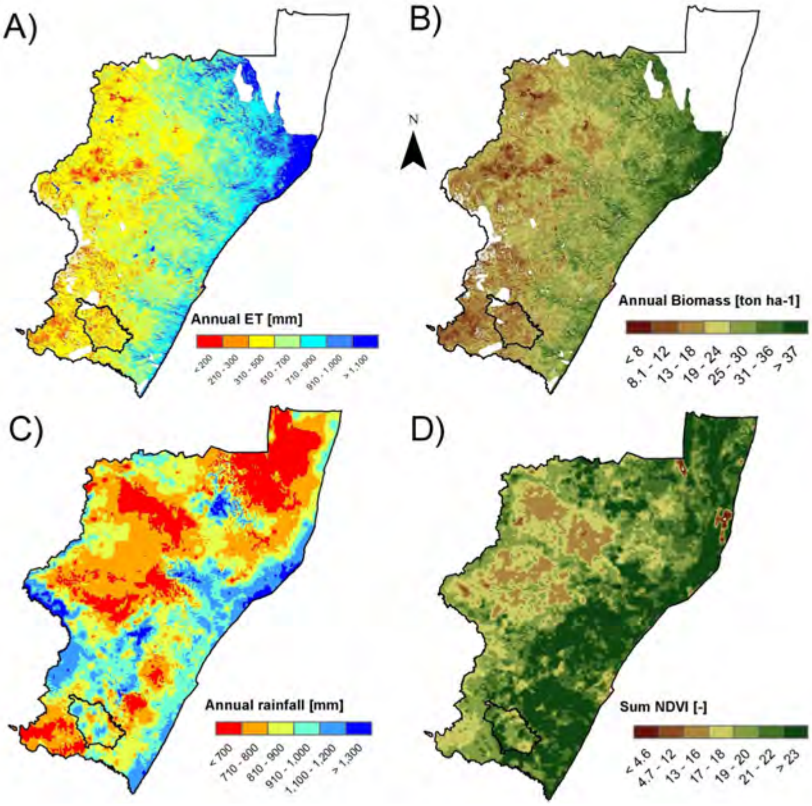

Figure 3
Annual ET (mm), annual biomass production (ton·ha^{-1}), annual rainfall (mm) (Schulze, 2007) and sum of NDVI-SPOT over the period July 2000 – June 2001 (average rainfall year) for KwaZulu-Natal.

The spatial variation in SEBAL-ET and biomass reflected the spatial variation in rainfall (Schulze, 2007) and NDVI (SPOT) reasonably well for the Western Cape. Areas that received high rainfall amounts also showed high ET, biomass production and NDVI values. In low rainfall areas, lower ET, biomass and NDVI were estimated. In general the spatial variation in ET in the Western Cape (σ_{ET} ranges from 303 to 328 mm for the three years, where σ_{ET} represents the standard deviation in space of the annual ET for the entire province) is much higher than in KwaZulu-Natal (σ_{ET} ranges from 215 to 239 mm). In KwaZulu-Natal (for 2000– 2001), the western part of the province received the lowest amount of rainfall and this is visible in the NDVI-SPOT observations, ET and biomass production estimates.

In the Western Cape, the lowest ET values were found in the central Karoo. The annual average ET for Karoo vegetation (succulent Karoo and Nama Karoo combined) was 115 mm, with the lowest ET estimates (50 mm) for the Upper, Great and Central Nama Karoo vegetation. These ET estimates are much lower than the long-term average rainfall estimates (according

TABLE 2
Annual rainfall (TRMM, FEWS, rain gauge data and climatic rainfall data from Schulze (2007)), annual (provincial) mean ET and its standard deviation, and precipitation excess for the Western Cape and KwaZulu-Natal provinces (*: uncertain value)

Province	Year	Rainfall (mm)		ET (mm)	σ_{ET} (mm)	Precipitation excess (mm)
Western Cape	2000–2001	290–320	'dry'	317	328	
	2002–2003	320–400	'average'	326	303	
	2006–2007	410–480	'wet'	362	304	
	3^{yr} average	370		335		~35
	climatic rainfall	348				
	10^{yr} TRMM	360				
KwaZulu-Natal	2000–2001	640–870	'average'	572^{*}	239	
	2003–2004	630–700	'dry'	695	238	
	2006–2007	770–1 100	'wet'	734	215	
	2^{yr} average	785		714		~70
	climatic rainfall	845				
	10^{yr} TRMM	880				

TABLE 3
Dominant invasive alien plant species in the Western Cape that have been treated by the WFW programme (Source: WIMS)

Species	Western Cape	
	(ha)	(%)
All IAPs (total)	203 292	100
Acacia mearnsii	23 801	11.7
Acacia saligna	6 923	3.4
Eucalyptus spp.	5 116	2.5
Hakea spp.	43 459	21.4
Pinus spp.	67 839	33.4
Remaining IAPs	40 842	27.6

to the Climate Atlas (Schulze, 2007)) for these biomes, which were in the order of 190 mm (both Karoo classes combined). Although it was expected that (Nama) Karoo would reveal some of the lowest ET values in the Western Cape, the ET estimates seem very low (50 mm). Unfortunately, no field observations of ET are available for this area to confirm these low ET-values. Since the Karoo region of the Western Cape is not heavily invaded by IAPs (Fig. 1), it was decided to discard this region from further discussions.

On a provincial scale the annual rainfall exceeded the annual ET (Table 2). For the Western Cape the average precipitation excess (i.e. rainfall minus ET) was estimated to be 35 mm·yr^{-1} and for KwaZulu-Natal, 70 mm·yr^{-1}. The annual rainfall for the Western Cape and KwaZulu-Natal provinces presented in Table 2 are taken from 3 data sources: (i) TRMM (3B42, 25 km resolution), (ii) Famine Early Warning Systems (FEWS) (8 km resolution), and (iii) spatially interpolated rain gauge data. The range of these data sources compares reasonably well with the long-term average annual rainfall estimates from the South African Atlas of Agro-hydrology and Climatology (Schulze, 2007) for both provinces. The 10-year (1998–2007) average rainfall estimates based on TRMM are also presented in Table 2.

Annual ET of invasive alien plants in the Western Cape

The five dominant IAPs (according to aerial cover) found in the Western Cape cover roughly 72% of the areas that are treated by WFW (Table 3; source: WIMS). These species are woody IAPs and include *A. mearnsii*, *A. saligna*, *Eucalyptus* spp., *Hakea* spp. and *Pinus* spp. Note that the total area treated in WIMS (203 292 ha) accounts for 5.5% of the total area estimated to be invaded in the Western Cape according to Le Maitre et al. (2000). The estimated annual average ET of these IAPs is listed in Table 4, together with annual rainfall estimates based on Schulze (2007).

The average annual ET of the IAPs for the three years ranges between 600 and 945 mm, with an average ET of 895 mm (σ_{ET} = 295 mm·yr^{-1}) (Table 4). The lowest ET estimates are for *A. saligna* and the highest values for *A. mearnsii* and *Eucalyptus* spp. The ET for areas invaded by *Pinus* and *Hakea* spp. are slightly lower and on average 915 and 830 mm, respectively. The variation in ET between the different IAPs corresponds well with the rainfall. The overall range of IAP ET agrees well with the ET of forest plantations (735 to 990 mm, Table 4), since many of the IAPs are plantation tree species.

The annual ET of the native vegetation (forest, thicket and fynbos biomes) ranged between 95 and 1 000 mm (Table 4). The highest ET estimates are for afromontane forest in the south-east of the Western Cape (Fig. 2, annual ET), which also receives the highest amount of rainfall.

The extent of invasion (assuming it can be related to the amount of treatments done by WFW, taken from WIMS) within the listed biomes is also shown in Table 4. The most invaded biome is fynbos (primarily mountain fynbos), where more than 70% of the WFW control activities take place. The annual ET for fynbos is estimated to range between 95 mm (escarpment mountain Renosterveld) and 775 mm (limestone fynbos), with an average ET of 520 mm. For thicket (combination of dune and spekboom thicket) the average ET is 575 mm. In general the ET estimates for all biomes were lower than the ET of the invaded areas. The ET of IAPs taken as one group exceeds the annual ET estimates of these biomes by between 36% (thicket) and 42% (fynbos).

The annual ET of treated areas averages 780 mm (Table 4). This is roughly 13% lower than the ET of invaded areas, but generally higher than most biomes. Note that the variation in annual ET (σ_{ET}) for the IAPs and the various biomes can be significant (Table 4). This is demonstrated in Fig. 4, which shows the frequency distributions of ET for IAPs, forest plantations, fynbos and thicket. It can be seen that the ET distribution in the histogram for IAPs and plantations is similar, but very different from fynbos. The large spread in ET, which is visible in all graphs, is expected to be the result of various factors: climatic conditions, soil characteristic and slope, water availability, density of species or native vegetation, species characteristics and physiology. The small peak in the histogram of thicket at 80 mm corresponds to an area of spekboom succulent thicket, an area located just east of Prince Albert.

Annual ET of invasive alien plants in KwaZulu-Natal

The five dominant IAPs found in KwaZulu-Natal include *Chromoleana*, *Lantana camara*, *A. mearnsii*, *Solanum* spp. and

TABLE 4
Annual average evaporation (ET) and rainfall (plus median and standard deviation) of IAP-invaded and controlled areas, forest plantations and native vegetation (thicket and fynbos) in the Western Cape. Area-% represents the fraction of the total province. IAP-% represents the fractional area of that biome invaded by IAPs (based on WIMS)

		ET$^{00-01, 02-03}$ (mm)[1]		σ_{ET} (mm)[1]	Rainfall (mm)		σ_{Rain} (mm)	
All IAPs (species density > 35%)		**895**		**295**	**675**		**255**	
Acacia mearnsii		925		225	650		140	
Acacia saligna		600		195	525		200	
Eucalyptus spp.		945		230	860		250	
Hakea spp.		830		240	685		160	
Pinus spp.		915		265	700		245	
		ET$^{02-03,06-07}$ (mm)		**σ_{ET} (mm)**	**Rainfall (mm)**		**σ_{Rain} (mm)**	
Controlled areas		**780**		**215**	**675**		**255**	
	Area (%)	**ET^{3yr} (mm)[1]**	**Median ET (mm)[1]**	**σ_{ET} (mm)[1]**	**Rainfall (mm)**	**Median rain (mm)**	**σ_{Rain} (mm)**	**IAPs (%)**
Forest plantations	**0.65**	**805**	**840**	**235**	**810**	**790**	**200**	
Pinus plantations	0.37	735	760	215	790	780	205	
Mixed plantations	0.17	990	1000	170	845	825	130	
Indigenous Forest	**0.49**	**1 000**	**1 015**	**170**	**875**	**865**	**115**	
Thicket	**3.2**	**575**	**560**	**240**	**325**	**290**	**125**	**3.2**
Dune thicket	1.34	660	640	250	410	400	135	3.2
Spekboom succulent thicket	1.88	515	510	210	260	260	65	0.0
Karoo	**44.1**				**190**	**175**	**60**	**11**
Fynbos	**30.2**	**520**	**510**	**280**	**430**	**385**	**220**	**71.5**
Escarpment mountain Renosterveld	1.43	95	85	65	210	210	40	0.0
Central mountain Renosterveld	4.90	385	355	225	315	290	120	4.8
South and south-west coast Renosterveld	3.67	635	630	200	405	395	140	3.4
Mountain fynbos	16.3	555	545	280	495	440	250	60
Limestone fynbos	1.47	775	805	145	410	400	60	1.6
Sand plain fynbos	1.46	360	345	155	340	305	135	0.7

[1] *For all biotopes and land cover classes the average annual ET and corresponding median and σ_{ET} values are based on 3 years. For all IAPs it is based on 2000–2001 and 2002–2003 and for all treated areas on 2002–2003 and 2006–2007. The WIMS database used in this study did not extend past 2006.*

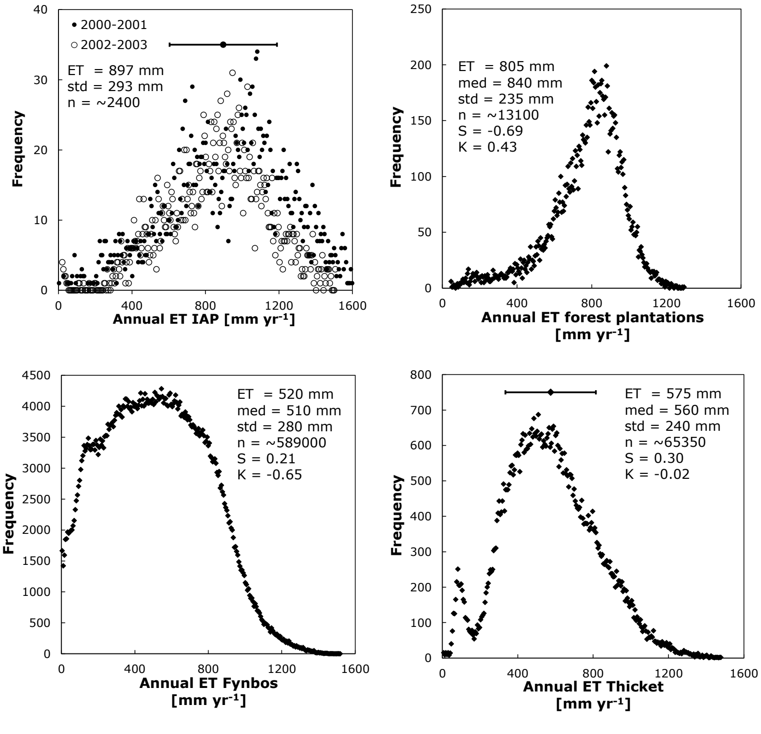

Figure 4
Frequency distribution of annual ET for IAPs, forest plantations, fynbos and thicket based on 3 years (for IAPs it is based on 2000–2001 and 2002–2003). The average ET, and corresponding median (med), standard deviation (std), number of pixels (n), skewness (S) and kurtosis (K) are also shown.

TABLE 5
Dominant invasive alien plant species in KwaZulu-Natal that have been treated by the WFW programme (Source: WIMS)

Species	KwaZulu-Natal	
	(ha)	(%)
All IAPs (total)	151 352	100
Acacia mearnsii	35 306	23.3
Chromoleana odorata	66 296	43.8
Eucalyptus spp.	4 548	3.0
Lantana camara	13 596	9.0
Solanum mauritanium	10 187	6.7
Remaining IAPs	21 419	14.2

Eucalyptus spp. (Table 5). Together these species cover 86% of the invaded areas that have been treated by WFW (151 352 ha). Again it must be emphasised that this is a mere 16.4% of the total area presumed to be invaded in KwaZulu-Natal according to Le Maitre et al. (2000). The annual average ET of these IAP-species, of which three are (scrambly) shrub-like (*Chromoleana*, *Lantana* and *Solanum*) and two woody, are listed in Table 6. Again, the rainfall estimates present long-term means and are from the South African Atlas of Agro-hydrology and Climatology (Schulze, 2007).

The average annual ET (2003–2004) for the five IAPs ranges between 575 and 1 020 mm with an average ET of 875 mm (Table 6). The annual ET for *Chromoleana* was the highest and for *Eucalyptus* the lowest. Note, since ET for 2000–2001 are probably underestimated because of the limited availability of solar radiation data (in total 8 stations for the entire province were available, while for the other years more than 22 stations could be used), these data are excluded from the analysis, and the focus is on the two remaining years (2003–2004 and 2006–2007).

The annual ET estimates for the IAPs show that the ET of woody species (*A. mearnsii* and *Eucalyptus*) is lower than for the shrub-like species (*Chromoleana*, *Lantana* and *Solanum*) (Table 6). This corresponded with the higher annual NDVI values for the shrub-like vegetation (not shown here), compared with the woody types. Note that the IAP-ET results are based on a small amount of sampled pixels. This likely explains the difference in ET between the same IAP and forest plantation species (Table 6, *A. mearnsii*: 740 mm versus 615 mm, and *Eucalyptus*: 575 mm versus 690 mm). For shrub-like IAPs the obstruction by tall vegetation may affect the results, as the AIP-understory might be missed by the satellite.

TABLE 6
Annual average evaporation (ET) and rainfall (plus median and standard deviation) of IAP-invaded and controlled areas, forest plantations and indigenous vegetation (thicket, savanna and grassland) in KwaZulu-Natal. Area-% represents the fraction of the total province. IAP-% represents the fractional area of that biome invaded by IAPs (based on WIMS).

		$\text{ET}^{03\text{-}04}$ (mm)[2]		σ_{ET} (mm)[2]	Rainfall (mm)		σ_{Rain} (mm)	
All IAPs (species density > 35%)		**875**		**210**	**930**		**155**	
Acacia mearnsii		740		145	870		135	
Chromoleana odorata	shrub	1 020		215	970		130	
Eucalyptus spp.		575		195	865		65	
Lantana camara	shrub	965		140	845		120	
Solanum mauritanium	shrub	945		125	1080		55	
		$\text{ET}^{03\text{-}04,06\text{-}07}$ (mm)		σ_{ET} (mm)	Rainfall (mm)		σ_{Rain} (mm)	
Controlled areas		**825**		**230**	**930**		**155**	
	Area (%)	$\text{ET}^{03\text{-}04,\,06\text{-}07}$ (mm)[2]	Median ET (mm)[2]	σ_{ET} (mm)[2]	Rainfall (mm)	Median rain (mm)	σ_{Rain} (mm)	IAPs (%)
Forest plantations	**7.12**	**710**	**690**	**190**	**950**	**915**	**150**	
Eucalyptus spp. plantations	4.26	690	675	190	935	905	130	
Pinus spp. plantations	1.18	650	655	155	935	915	130	
Acacia mearnsii plantations	0.60	615	630	140	900	895	125	
Indigenous forest	**1.56**	**680**	**655**	**230**	**1 020**	**985**	**190**	
Valley thicket	**7.12**	**755**	**760**	**170**	**800**	**760**	**130**	**6.4**
Savanna	**38.3**	**685**	**690**	**205**	**815**	**780**	**130**	**44**
Coastal bushveld / grassland	4.96	940	935	145	955	950	120	9.8
Coast-hinterland bushveld	8.06	780	935	150	885	875	120	6.7
Natal central bushveld	14.3	565	790	175	750	740	100	2.9
Natal lowveld bushveld	8.29	785	785	185	810	790	130	12.8
Grassland	**26.0**	**640**	**630**	**175**	**840**	**830**	**110**	**14**
Wet cold highveld grassland	2.73	600	585	115	840	850	100	1.8
Moist upland grassland	10.5	625	625	150	840	840	115	4.1
Afro mountain grassland	1.84	680	690	155	870	790	180	1.3
Alti mountain grassland	2.19	745	750	155	890	885	135	1.9

[2] For all biotopes, land cover classes and treated areas the average annual ET and corresponding median and σ_{ET} values are based on the years 2003–2004 and 2006–2007. For all IAPs it is based on 2003–2004 and for all treated areas 2003–2004 and 2006–2007. The WIMS database used in this study did not extend past 2006.

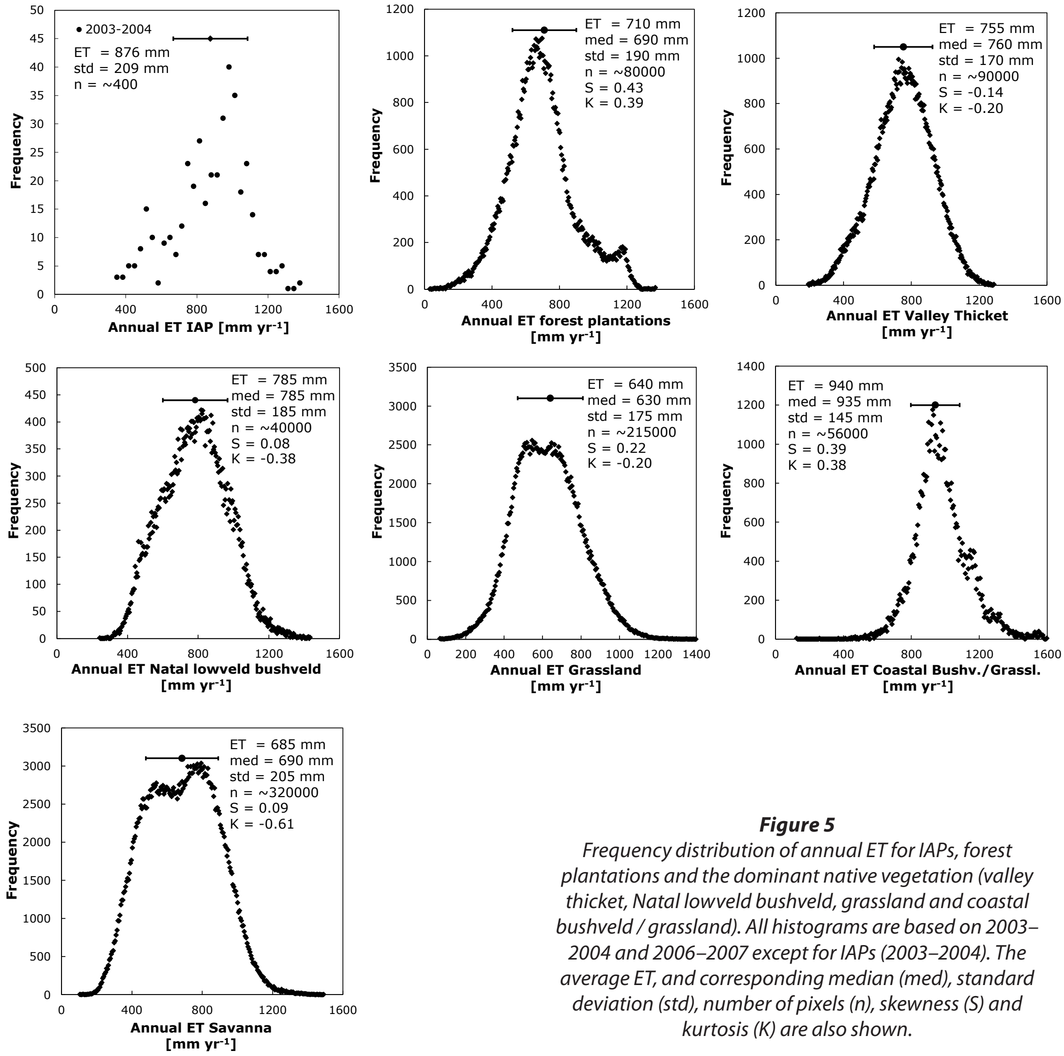

Figure 5

Frequency distribution of annual ET for IAPs, forest plantations and the dominant native vegetation (valley thicket, Natal lowveld bushveld, grassland and coastal bushveld / grassland). All histograms are based on 2003–2004 and 2006–2007 except for IAPs (2003–2004). The average ET, and corresponding median (med), standard deviation (std), number of pixels (n), skewness (S) and kurtosis (K) are also shown.

In Table 6, the average annual ET of the biomes found in KwaZulu-Natal (forest, thicket, savanna and grassland) are also presented. The average ET for these biomes ranges between 640 and 755 mm. Compared to the Western Cape the spread in ET between the biomes is much smaller and consistent with the rainfall data.

Table 6 also shows the extent of invasion (IAPs %) within the biomes. Most of the WFW treatments of IAPs took place in the savanna (44%), grassland (14%) and, to a small extent, thicket biomes (6.4%). The IAP-ET (taken as one group) exceeds the annual ET estimates of all biomes by 14% (valley thicket) to 28% (grassland). The average ET of treated areas in KwaZulu-Natal was 825 mm, approximately 6% lower than for the invaded areas. The smaller difference in IAP-ET and the ET of treated areas (compared to the results of the Western Cape) is likely related to the fact that the difference between IAP-ET and the ET of native vegetation is also smaller.

Finally, the frequency distributions of ET are shown in Fig. 5 for IAPs, a selection of biomes (grassland, thicket and savanna) and forest plantations. These histograms demonstrate that the variation in ET within one vegetation class can be large. Note that the histogram of IAP-ET is based on a limited amount of sampled pixels (Fig. 5). However, these histograms compare well in shape with those for the Western Cape (Fig. 4). Again it is expected that the large spread in ET (for most graphs) is likely the result of various factors linked to climatic conditions, soil characteristics and slope, water availability, density of species or vegetation, species characteristics and physiology. The small peak in the histogram of forest plantations at 1 160 mm corresponds with the plantations north of Richards Bay.

DISCUSSION

ET of IAPs and native vegetation using the SEBAL model

In this study, SEBAL using MODIS satellite images was used to estimate the ET of IAPs and native vegetation. Over the past decade, the SEBAL model has been applied extensively over various regions to compare ET of various land uses and land use change in space and time to address water resource and irrigation challenges (e.g. Goodrich et al., 2000; Bastiaanssen and Chandrapala, 2003; Bastiaanssen et al., 1998a,b, 2002, 2005; Immerzeel et al., 2008; Singh et al., 2008; Mohamed et al., 2011). However, to the authors' knowledge this study is the first example where remote sensing data was used to estimate the ET of IAPs in space and time. Using this approach, the limited database on water use of IAPs available in South Africa to the WFW programme was substantially expanded and represents some of the first sources of annual

IAP estimates for many of the top invaders listed in Table 1 and also for native vegetation.

IAP-ET vs. ET native vegetation and treated areas

The impact of IAPs on available water resources in an area can be assessed in terms of ET increases when compared to treated (cleared) areas or areas under native vegetation. When comparing IAP-ET and ET of treated areas, small differences in ET are expected, in view of the fact that the study comprised areas with low invasion densities and under water-limiting conditions (non-riparian). We found that the IAP-ET exceeded the ET from treated areas by conservative amounts of 13% and 6% for the Western Cape and KwaZulu-Natal provinces, respectively. However, comparing IAP-ET to ET of specific native vegetation classes much larger differences and variation in ET were found. In the Western Cape, considering the native vegetation where most clearing is taking place, the IAP-ET exceeds the annual ET estimates of these native vegetation types by between 36% (thicket) and 42% (fynbos). Similarly, in KwaZulu-Natal, IAP-ET exceeds the annual ET estimates of native vegetation by 14% (valley thicket) to 28% (grassland).

Cavaleri and Sack (2010) reviewed results from over 40 studies worldwide where the water use of IAPs and native vegetation were compared across various scales (leaf, plant and ecosystem). Important to note is that they focussed on IAPs and native vegetation with the same growth form and not specifically on, e.g., woody or herbaceous invasions which are common in SA. At each scale, Cavaleri and Sack (2010) found numerous differences in water use between specific paired invasive and native species. At leaf scale, IAPs had a greater potential to have stomatal conductance (and water use) exceeding that of native plants (related to higher overall metabolic rates of IAPs). At plant scale, they found that native and IAPs had a similar probability of displayingthe higher sap flow rate in the comparison. They suggest that the disconnect between leaf and plant scale is related to the wide variation in leaf surface properties (which are missed by the leaf scale measurements), and that whole-plant water use can increase and/or decrease with plant size and age. Also, interestingly, they found that at ecosystem scale the sap flow rates of IAP-dominated ecosystems were likely to be higher than those of native-dominated ecosystems, but that this pattern was not found for ET (although they mentioned the few data available at this scale). They also highlighted the strong dependence of differences in ET (IAPs vs. native species) on climate, where hotter and wetter climates at the coarser scales favoured higher IAP-ET.

Calder and Dye (2001) investigated potential causes for IAP-ET to exceed ET of native vegetation, specifically where the water use (ET) of IAP-trees vs. short native crops are concerned. Using the 'limits concept' they developed a methodology to assess under what conditions high water use by IAPs may occur. They concluded that the greatest increase in IAP-ET (in dry climates) may occur in water-limited rather than riparian (water-unlimited) conditions (deep-rooting behaviour of alien tree species compared to short native vegetation, such as grass, which in addition is also winter dormant).

Comparison of SEBAL-ET estimates with ground measurements

A number of studies have assessed the accuracy of the SEBAL energy balance and ET estimates, with differences in ET estimates ranging between 1 and 11% (Bastiaanssen et al., 2002; Bastiaanssen and Bandara, 2001; Bastiaanssen and Chandrapala, 2003; Mohamed et al., 2004; Tasumi et al., 2005; Singh et al, 2008; Wang et al., 2009). Bastiaanssen et al. (1998b; 2005) reviewed the accuracy of SEBAL under several climatic conditions at both field and catchment scale by validating data against field observations. Allen et al. (2007) found that at field scale the accuracy of SEBAL typically ranges between 85% (1 day) and 95% (seasonal basis), as some random errors are reduced in the aggregation of daily ET to seasonal ET. At larger scales (e.g. catchment level) an average accuracy of 96% was found (Bastiaanssen et al., 2005).

Table 7 lists (field) studies where the annual ET of IAPs (*A. mearnsii*, *Eucalyptus* and *Pinus*) and native vegetation (fynbos, grassland and thicket) were measured in the Western Cape and KwaZulu-Natal provinces. Most field measurements listed in Table 7 were done outside the SEBAL study years, making it impossible to validate the SEBAL-ET data generated in this study. Nevertheless it provides comparative data.

The IAP-ET data in Table 7 are generally much higher than the average values found in this study. In most cases the measured ET is also higher than the rainfall, indicating that no water deficitits occur in these riparian areas. Since these IAPs are evergreen they can transpire throughout the year, resulting in high ET-values. Isotope measurements suggested that at Seven-Oaks (*Acacia*, non-riparian site) during the dry months groundwater is the source of water (Clulow, 2013). As the field ET data mainly represent the wet range, they are difficult to compare with the SEBAL-ET results covering a wide range of conditions.

The annual ET of some native vegetation types is also listed in Table 7. For grassland (KwaZulu-Natal), the field (catchment) measurements range between 600 and 850 mm. This agrees well with the SEBAL results: 640 ± 175 mm (Table 6). Field measurements of fynbos show an ET between 600 and 900 mm (catchment-scale estimates) and up to 1 330 mm (Bowen-ratio technique) for a riparian zone. The high ET values of the latter site are likely the result of non-limiting water conditions and the evergreen nature of fynbos in this habitat. As for the IAP-ET measurements, the fynbos field measurements, representing relative wet circumstances (high rainfall), exceed the SEBAL-ET estimates of fynbos (520 ± 280 mm) (Table 4) covering a wide range of conditions.

Most SEBAL-ET validation studies are based on field measurements that were done in relatively homogeneous (agricultural) fields and areas. Validating the SEBAL-ET of landscapes populated by native vegetation and invaders is much more difficult. These areas are generally very complex due to spatial variations in species, species density, age, physiology, topography, micro-meteorological and -hydrological conditions, thereby limiting the representativeness of most in-situ measurement techniques. When the field data is representative of a larger area, such as for the catchment-scale studies listed in Table 7, the agreement with SEBAL-ET data appears to improve.

At a provincial scale the average precipitation excess for the Western Cape and KwaZulu-Natal provinces is roughly 35 and 70 mm yr^{-1}, respectively (~ 9% of the mean annual rainfall) (Table 2). Le Maitre et al. (2000), using a biomass-streamflow-model, estimated the mean annual runoff as 50 and 130 mm·yr^{-1} for the Western Cape and KwaZulu-Natal, respectively (14 to 15% of the mean annual rainfall). Basson et al. (1997) reported precipitation excess values for catchments in the Western Cape ranging between 1 and 8%, and for KwaZulu-Natal between 5 and 11%. At a provincial scale, our findings for the mean annual runoff (precipitation excess) suggest that the SEBAL-ET results are comparable to previous studies.

TABLE 7
List of annual evaporation (ET) estimates for various IAPs and vegetation biomes mostly estimated using micrometeorological measurement techniques (HPV: Heat Pulse Velocity; BR: Bowen-Ratio; SC: Scintillometry) and water balance models from various sites in the Western Cape (WC) and KwaZulu-Natal (KZN) provinces. Corresponding annual rainfall amounts are also presented. (T) refers to transpiration.

Vegetation	Province	ET (mm)	Rain (mm)	Site	Source
Acacia					
A. mearnsii stand – riparian	WC KZN	1 503^{HPV} 1 260^{HPV}	1 050 867	Jonkershoek Gilboa	Dye et al., 2001 Dye and Jarmain, 2004
A. mearnsii – non-riparian (plantation)	KZN	1 240^{BR} 1 364^{BR} 1 239^{BR} 1 048^{BR}	874 616 1 016 860	Seven-Oaks	Dye and Jarmain, 2004
A. mearnsii – non-riparian (plantation)	KZN	1 156^{SC} 1 171^{SC}	689 819	Seven-Oaks	Clulow et al., 2011 Clulow, 2008
Eucalyptus					
Eucalyptus stand	KZN	1 347(T)	1459	Sabie	Dye et al., 1997 Dye et al., 2008
Eucalyptus plantation	KZN	1 246 – 1 618^{BR}	616 – 1 016	Seven-Oaks	Jarmain and Everson, 2002
Pinus patula plantation	KZN	944^{HPV}	1 124	Usutu	Dye et al., 2008
Grassland					
Wet grassland	KZN	836^{BR}	867	Gilboa	Dye et al., 2001 Dye and Jarmain, 2004
Grassland – moist upland	KZN	651 – 752^{BR}	1 092 – 1 469	Cathedral peak	Everson et al., 1998
Grassland	KZN	651^{BR}		Midlands	Dye et al., 2008
Grassland	KZN	673^{SC}		Midlands	Savage et al., 2004
Grassland-dominated catchments	KZN	600 – 850	700 – 1 500	Drakensberg & Midlands	Schulze, 1979
Fynbos					
Fynbos – riparian	WC	1 332^{BR}	1 324	Jonkershoek	Dye et al., 2001 Dye and Jarmain, 2004
Fynbos – upland	WC	757	1 000 – 1 200	Helderberg	Dye et al., 2008
Fynbos shrubland	WC	600 – 900	1 100 – 1 300	Jonkershoek	Scott et al., 2000
Thicket (valley)	**KZN**	**668**	**843**	**Noodsberg**	**Dye et al., 2008**

IAP-ET differences between provinces

IAP-ET estimates for the same species in the Western Cape exceeded that in KwaZulu-Natal – by 185 mm for *A. mearnsii* and 370 mm for *Eucalyptus* (Tables 4 and 6). Although there is a substantial difference in the elevation at which *A. mearnsii* occurs (320 m for Western Cape versus 1 300 m for KwaZulu-Natal), the difference in ET is probably due to the limited amount of sampled pixels (associated with limited representation of species density, soil water availability, etc.) analysed for KwaZulu-Natal. Furthermore, the ET results for KwaZulu-Natal are based on 1 year, which limits the climatic representativeness of the dataset. Despite the limited data, it must be noted that the different spread of IAPs in the two provinces might explain the large difference in ET. In the Western Cape, *Acacia* and *Eucalyptus* tend to invade only relatively wet areas such as riparian zones, while in KwaZulu-Natal these species can be found across a wider range of conditions due to the generally wetter climate (see Fig. 1).

Validity of SEBAL-ET of KwaZulu-Natal for 2000–2001

One of the input requirements for the SEBAL model is surface solar (shortwave) radiation data. Sufficient (ground stations) and accurate radiation data are unfortunately not always available. This was particularly the case for KwaZulu-Natal for the year 2000–2001. A good alternative is the remote-sensing products provided by the Land Surface Analysis Satellite Applications Facility, which have also been used in this study. These products are however available only from 2005. As a result the first SEBAL year (2000–2001, average rainfall year) for KwaZulu-Natal had to be processed using limited radiation data and stations (8 instead of 22 stations). Since the ET results for this year were significantly lower than the other two years (Table 2), it was decided to discard this year from the analysis.

CONCLUSIONS

Methodology: In this study we showed that the SEBAL model using remote-sensing data can be used to determine ET over time and space. The results presented in this study represent the first estimates of large-scale annual evaporation from IAPs and native vegetation in the Western Cape and KwaZulu-Natal provinces of South Africa. Combining the ET data with information on land use we showed differences in ET between IAPs, native vegetation, commercial forestry species and IAP control areas. This spatial approach holds great potential for assessing the impact that WFW has on the water resources of South Africa. Although course resolution (at 250 m) remote-sensing data can be used to assess the impact of IAPs on ET, it respresents data largely from areas with lower invasion densities, often occurring in non-riparian, water-limited regions. We believe that higher resolution data is likely more suitable to assess the impact of IAPs on ET across a wider range of invasion densities and water regimes, including riparian zones.

Validation: Validation of the SEBAL-ET estimates for IAPs and native vegetation against ground measurements was not possible, but comparisons against measured data were done. In most cases the (limited available) ground measurements of ET were inconsistent with SEBAL-ET. In general, the complexity of landscapes populated by natural vegetation and invaders limits the area-representativeness of local field measurements and comparison with moderate resolution satellite pixels. Increasing the resolution of satellite imagery (e.g. Landsat-8 with 100 m resolution) and the using scintillometers, which can provide path-average surface fluxes on kilometre scales, might lead to a better validation of satellite-based ET data.

Impact of IAPs on ET and water availability: We confirmed what was found in previous studies – that invaded areas showed a higher ET than most native vegetation, with the differences in ET (IAPs vs. native vegetation) varying greatly. We found that treated areas had a lower ET than invaded areas. In both provinces we found that the clearing of IAPs by the WFW programme has a positive effect on the availability of water resources through a reduction in ET. Since the majority of invaded areas considered in this analysis represent non-riparian areas with moderate species densities (~57%), the impact of control of IAPs on ET is likely conservative but still important. The impact of WFW control of densely-invaded riparian areas is therefore likely more pronounced.

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