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MAPPING *PROSOPIS JULIFLORA* IN WEST SOMALILAND WITH LANDSAT 8 SATELLITE IMAGERY AND GROUND INFORMATION

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ABSTRACT

Prosopis juliflora is a drought-tolerant fast-growing tree species originating from South and Central America with a high invasion potential in arid and semi-arid areas in Africa. It was introduced in Somaliland in the 1980s and is reported to have spread vigorously since. Despite being recognized as a serious issue in the country, the actual scale of the problem is unknown. In this study, we mapped the species in a study area that includes the capital, Hargeisa, using Landsat 8 satellite imagery. During a field campaign in 2015, we collected canopy-level spectral signatures of *P. juliflora* and native trees to analyse the potential use of spectral data in discriminating the invasive species. *P. juliflora* was found to be generally distinguishable because of its greater vigour during the dry season. We tested the accuracy of the random forest classifier and different classification set-ups, varying the spatial resolution (original 30 m vs pan-sharpened 15 m) and image acquisition dates (during the wet season, the dry season and a combination of the two). Best overall accuracy (84%) was achieved by using pan-sharpened data from the two seasons. About 30 years since its introduction, the invasive species was detected in 9% of the total investigated area with highest occurrence in the proximity of human settlements and along seasonal water courses. © 2016 The Authors. Land Degradation and Development published by John Wiley & Sons, Ltd.

KEY WORDS: invasive alien species; *Prosopis juliflora*; mapping; remote sensing; Landsat 8; Somaliland

INTRODUCTION

Land use change, non-sustainable agriculture and forest management, excessive grazing, forest fires and mining activities are among the most studied causes leading to land degradation (e.g. D'Odorico *et al*., 2013; Xu & Zhang, 2014; Rodrigo-Comino *et al*., 2015; Vieira *et al*., 2015). Biological invasion received much less attention, although it can be considered as a land degradation process as well, leading to a reduction in the capacity of ecosystems to supply services. Invasive alien species (IAS) are defined as non-native species that threaten ecosystems, habitats or species (United Nations, 1992). IAS are considered one of the most critical threats to natural ecosystems worldwide (for a review, see Pejchar & Mooney, 2009). When focussing on plant species, the term 'invasive' refers to the fact that such plants produce large numbers of offspring and are widely dispersed over long distances, which leads to their rapid spread over large areas. Among the many IAS, *Prosopis juliflora* is a drought-tolerant fast-growing tree species that originates from south and central America and has a high invasion potential in arid and semi-arid areas around the globe. Several taxa of *Prosopis* are among the world's worst woody invasive plants (Shackleton *et al*., 2014). *P. juliflora* is a perennial tree or shrub that grows up to 12 m in height. The plant is a nitrogen-fixing, drought- and salt-tolerant species (Singh *et al*., 1994). With its thorniness and shrub habit, it quickly invades open areas and paths, forming impenetrable dense bushes.

Prosopis juliflora typically initiates its invasion through the transportation of seeds along water courses and through animal dispersal, replacing endemic riverine plant communities (Pasiecznik, 2001). After the initial establishment, and with increased distance from deep soils with water availability, thorny thickets invade drier native grasslands and rangelands. Abandoned and poorly productive farms are also highly susceptible to invasion, as *P. juliflora* has competitive advantages on nutrient-limited soils and is extremely drought-tolerant, thanks to its articulated root system. For these reasons, *P. juliflora* is also considered a threat to food security (Steele *et al*., 2008). Fast invasion is facilitated by the role of livestock and natural fauna in dispersing the seeds, whose germination rate is increased by animal ingestion (Berhanu & Tesfaye, 2006). As the plant is often found to colonize ephemeral water courses in arid areas, riverine dispersal during flooding or water flow during the rainy season enables the long-distance transportation of the seeds.

The ecological advantages of *P. juliflora* in East Africa represent a threat to biodiversity. Being a drought-tolerant plant, it threatens the desert and semi-desert shrubland

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ecosystems (Tessema, 2012) that harbour valuable animal and plant species, many of which are endemic. On the other hand, the plant has been successfully used to fight desertification, as it can reduce soil erosion (Steele *et al*., 2008).

The socio-economic impacts are varied and controversial. Agro-pastoralists are the most affected, as *P. juliflora* can quickly invade their land and prohibit grazing and farming activities. The palatable seed pods offer fodder that is high in nutritive value for livestock and wild animals and can be used for human consumption, but the leaves and pods have some toxicological effects (William & Jafri, 2015). The sweet pods can cause tooth decay in cattle and goats when used as the main fodder over long periods (Obiri, 2011). *P. juliflora* wood can be used to produce charcoal of a quality that is comparable to the *Acacia* species (Oduor & Githiomi, 2013). However, the almost impenetrable dense thickets do not produce much timber or fuel wood and are considered to be a breeding ground for malaria-transmitting mosquitoes (Mwangi & Swallow, 2005). Other reported uses of *P. juliflora* refer to the provision of shade to humans and livestock, building, fencing and windbreakers (Berhanu & Tesfaye, 2006). Reports suggest that *P. juliflora* alters the groundwater table (Fourie *et al*., 2007) and rapidly invades communal pastoral areas, while its thorns can cause injuries to humans and cattle (van de Giessen, 2011) and are known to puncture tires (Mwangi & Swallow, 2005). It is therefore necessary to carefully balance the advantages of *P. juliflora* use against the negative side effects and the risk of the plant expansion becoming out of control. This risk is generally high in East Africa in all situations in which *P. juliflora* is not carefully managed (Ayanu *et al*., 2014). Management practices to control the invasion include mechanical eradication, sustainable control by utilization, prescribed burning and chemical and biological control (Berhanu & Tesfaye, 2006; Zachariades *et al*., 2011). Management strategies for addressing large-scale invasions of *Prosopis* spp. differ from country to country (Shackleton *et al*., 2014). For instance, mechanical eradication and chemical and biological control have been extensively used in Australia and South Africa. On the other hand, Kenya's government opted for a control-by-utilization strategy, which mainly involves milling pods into flour. Blended with other inputs, the flour can be used as animal feed.

Knowledge regarding the actual coverage and historical expansion of the species is incomplete. In East Africa, *P. juliflora* was introduced in the past century as an ecosystem engineer for the stabilization of dune systems, the rehabilitation of degraded land (Pasiecznik, 2001) and the provision of fuel wood (Ayensu, 1980; Von Maydell, 1986). The species has rapidly expanded ever since, aggressively outcompeting native shrub and tree vegetation (Pasiecznik, 2001).

Significant *P. juliflora* infestations have been reported in the Horn of Africa (e.g. Ethiopia, Kenya and Somalia). In Ethiopia, it was planted in many arid and semi-arid regions, mainly for soil and water conservation purposes (Tegegn, 2008). It has subsequently become highly invasive, as for example in the Baduu area of the Awash Basin (Ayanu *et al*., 2014). In Kenya, it is present in the counties of Turkana and Garissa, along the Tana River and in the Lake Baringo area (Andersson, 2005; Mwangi & Swallow, 2005; Dubow, 2011). In the Garissa County, the expansion is reported to have rapidly increased, especially in communal grazing areas (Dubow, 2011).

In Somalia, *P. juliflora* was used from the 1970s for sand dune fixation in central regions and close to Mogadishu (Zollner, 1986). During the civil conflict since 1991 in central and southern Somalia, its uncontrolled dissemination has been favoured by war-driven degradation factors such as the deforestation of native tree species for charcoal production, sand extraction for building purposes and for the rehabilitation of canals with scarce irrigation (Adam-Bradford, 2014).

Prosopis juliflora was introduced in Somaliland in the 1980s by the Food and Agriculture Organization of the United Nations (FAO) and by several non-governmental organizations as a fast-growing tree species in areas that had been deforested by refugees (Awale & Sugule, 2006). It is increasingly difficult to properly manage its expansion in this region. Despite being recognized as a serious problem at the national level by Somaliland institutions that have planned extensive mechanical eradication in the National Development Plan 2012–2016 (MNDP, 2011), the actual scale of the problem is unknown. A recent policy workshop organized by the Ministry of Environment of Somaliland, the Pastoral and Environmental Network in the Horn of Africa and the International Fund for Agricultural Development (Livingstone *et al*., 2014) recommended that the extension of the invasion should be mapped as a first and essential step in order to elaborate different management options.

The use of satellite imagery is probably the only cost-efficient means of mapping IAS over large areas, as field observations would be prohibitively costly and largely impractical beyond very local scales. However, despite increasing data availability and decreasing data costs, it is still difficult to map *P. juliflora* from space, as the plant can be easily confused with other species, mostly as a result of its highly variable morphology. For example, *P. juliflora* can form multiple-branched shrubs as well as relatively tall trees.

Various approaches have been used to map *P. juliflora* by using remote sensing data that employ different methods, sensors and data recorded at various spatial resolutions. Several studies have been carried out based on the reported observation that the plant has a distinct spectral response compared with surrounding native vegetation. For example, in the semi-arid riverine environments in Sudan, Hoshino *et al*. (2012) mapped *P. juliflora* by using a single threshold of the Normalized Difference Infrared Index (NDII, using near- and short-wave infrared bands) on Landsat 5 imagery acquired during the dry period. Van de Berg *et al*. (2013) used a combination of terrain analysis and remote sensing techniques to map and monitor a *P. juliflora* invasion of the Northern Province in South Africa. They used a simple thresholding of Landsat near infrared/red band ratio during the greenest period of the year to discriminate the plant, based on the assumption that *P. juliflora* is more vigorous than other types of vegetation. As a result, *P. juliflora* was often confused with other bush and tree species. Classification by using spectral information was made by Mohamed *et al*. (2011), who used maximum likelihood supervised classification on QuickBird high spatial resolution satellite imagery. The same classification algorithm was applied by Ayanu *et al*. (2014) to a multi-temporal dataset composed of Landsat and Aster images. Mirik & Ansley (2012a) evaluated the impact of different spatial resolutions to map the invasion. The classification of *Prosopis glandulosa* by using aerial imagery at 1-m resolution was found to yield higher accuracy than 30-m Landsat data in Mexican rangelands. WorldView-2 multispectral imagery at 2-m spatial resolution has been used in Australia (Robinson *et al*., 2016). Time series of moderate-resolution data (250-m MODIS vegetation indexes) have also been used to map the current and potential distribution of *P. juliflora* in Ethiopia (Wakie *et al*., 2014), but the coarse resolution appeared to be suited only to very extended infestations.

In a preliminary study of *P. juliflora* mapping over the whole of Somaliland (Rembold *et al*., 2015), the authors used multispectral Landsat 8 imagery and probability thresholds of the maximum likelihood classifier to detect the presence of the invasive species. Unfortunately, the ground truths regarding the presence of *P. juliflora* were quantitatively insufficient and qualitatively poor, as derived from the *ex post* visual analysis of field photographs taken during different field campaigns carried out by the FAO—Somalia Water and Land Management Information System (FAO-SWALIM).

In this study, we address the need for a baseline map for evaluating the *P. juliflora* invasion in Somaliland, by mapping its distribution in an area of about 5,000 km^2, including the capital of Somaliland, where infestation was repeatedly reported and preliminarily mapped by Rembold *et al*. (2015).

This paper presents the methodology developed for mapping *P. juliflora* across relatively large areas by using freely available Landsat 8 imagery. Leveraging on the database of ground truths and spectral measurements collected during the field campaign, we specifically address the following research questions: Is the spectral signature of *P. juliflora* different compared with other native tree species? What level of classification accuracy is achievable by using Landsat 8 imagery at 30- and 15-m pan-sharpened resolution? Is the use of bi-temporal datasets useful for *P. juliflora* classification? And, of more ecological nature, what is the percentage of the total land area being invaded by the species so far? Is there any prevailing spatial pattern of such invasion?

MATERIALS AND METHODS

Study Area

The study area (Figure 1) is located in the west of Somaliland (a self-declared state that is internationally recognized as an autonomous region of Somalia) and covers an area of 5, 167 km^2 (between 9°27′ and 9°58′N and 43°33′ and 44°24′E), including the state capital, Hargeisa. Elevation ranges from 700 (in the North) to 1,600 m (in the South-West) asl.

The climate is arid to semi-arid (BSh and BW according to Köppen–Geiger climate classification; Peel *et al*., 2007), with annual rainfall of about 410 mm and a mean temperature of 21·7 °C in Hargeisa (Muchiri, 2007). Rains are mostly concentrated in the two rainy seasons (Figure 1C), namely the Gu season (between April and June) and the Deyr season (between September and November).

According to a recent study carried out by FAO-SWALIM in 2007 (Monaci *et al*., 2007), the main land use in the area is nomadic or semi-nomadic pastoralism and the main land-cover classes are rangeland (mainly Savanna,

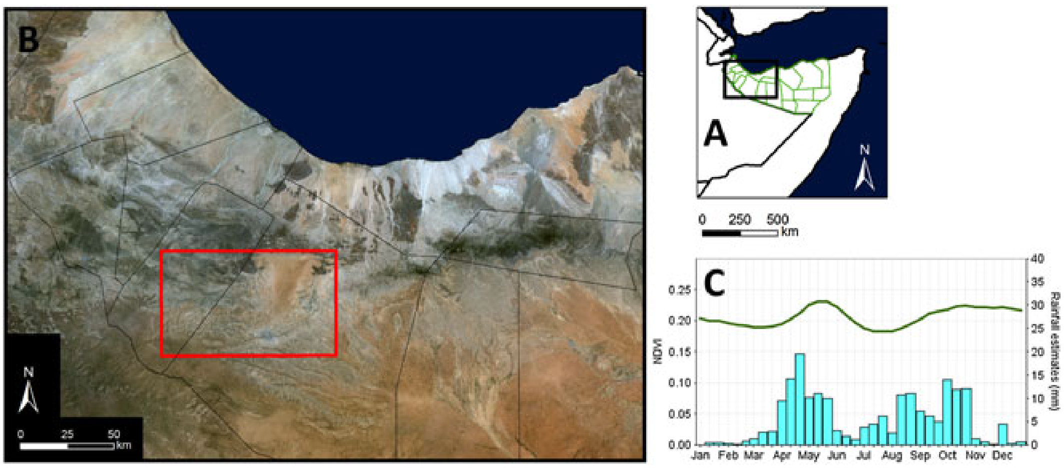

Figure 1. (A) Location Somaliland (green). (B) Location of the study area (red box), background imagery is a Landsat 8 true-colour composite mosaic. (C) Mean monthly rainfall (average for the period of 1983–2014, rainfall estimates from TAMSAT; Tarnavsky *et al*., 2014) and vegetation activity (average normalized difference vegetation index for the period of 1999–2014, NDVI, from SPOT-VEGETATION) for the Hargeisa district. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

49%), wooded vegetation (34%), agriculture (10%) and non-vegetated areas (including urban area, bare soils and water bodies, 7%).

The principal grain crop grown under rain-fed conditions is sorghum, followed by maize. Both crops are grown primarily for subsistence by small-scale farmers. Fruit and vegetable crops, which occupy relatively small areas, are grown mainly for commercial purposes. The sector is dominated by smallholder farmers with average farm sizes of approximately 4 ha (Balint *et al*., 2009). Irrigated agriculture (9% of total agriculture) is either located next to wadis (in Somaliland, these are ephemeral water courses, which are usually dry except during the rainy season) or canals or makes use of groundwater.

Prosopis juliflora expansion adds pressure to an environment in which many pastoral areas are threatened by land degradation due to overgrazing and soil erosion caused by vegetation cover loss (Oroda *et al*., 2007). Charcoal burning, which is carried out as an economic activity, severely affects very fragile ecosystems (such as tiger-bush vegetation) by reducing biomass and further accelerating land degradation (Oduori *et al*., 2011).

Reference Data

A total of 332 reference sites (polygons) were used in the classification of the area (Table I), 53 of which were visited during a field campaign that took place in February 2015. Sites to be visited were carefully chosen by using very high resolution (VHR) Worldview-2 and Quickbird panchromatic and true-colour composites that were made available to FAO-SWALIM under the NextView license. Most of the ground observations are of areas with different degrees of *P. juliflora* infestation, while the others are of agriculture and natural woody and shrub vegetation. Field observations confirmed that *P. juliflora* can have very diverse morphology, both in terms of stem and canopy structure, ranging from the well-developed large tree habit, to the multi-stemmed small trees, to a shrubby habit, as shown in Figures 2A to 2C respectively. The multi-stemmed form generally leads to the most dense canopy structure, while the shrubby form can range from dense green thicket on deeper soils to sparse dry cover on slopes and stony soils. The remaining 279 reference polygons were photointerpreted and delineated on VHR imagery. It was necessary to complement field data with photointerpretation, as access to the area is difficult for logistic and security reasons. Where possible, image interpretation was aided by the use of GPS-geolocated photographs taken from the car at regular time intervals during car trips.

Table I summarizes the ground truth information collected and the 16 land-use and land-cover classes observed during the field campaign. These 16 classes include pure *P. juliflora* stands (classes 1 and 2) and *P. juliflora* mixed with other endemic species (*P. juliflora* is dominant in class 3 and subdominant in classes 4–5). The other classes refer to natural vegetation (classes 6–8), agriculture (classes 9–10), built-up areas (class 11) and different bare soils (classes 12–16). No distinction is made within the ‘natural vegetation’ class, which includes all other tree/shrub species found (mainly *Acacia tortilis*, *Acacia bussei*, *Acacia mellifera*, *Eucaliptus* spp., *Ziziphus* spp. and succulent *Aloe* spp.). Despite being a non-native and invasive species, *Opuntia* spp.

Table I. Description of the reference dataset

		Number of polygons		Area (ha)	
		Field campaign	Photointerpreted	Field campaign	Photointerpreted
1	*P. j.*, FC > 50%	15	11	9	6
2	*P. j.*, FC ≤ 50%	6	14	4	14
3	Mixed cover with *P. j.* dominant, FC > 50%	6	15	4	11
4	Mixed cover with *P. j.* subdominant, FC = 25–50%	6	14	6	20
5	Mixed cover with *P. j.* subdominant, FC < 25%	1	10	1	16
6	Natural vegetation, FC > 50%	5	15	1	25
7	Natural vegetation, FC = 25–50%	6	14	19	90
8	Natural vegetation, FC < 25%	5	17	5	256
9	Irrigated agriculture	3	25	2	13
10	Rain-fed agriculture	–	20	–	105
11	Urban	–	24	–	94
12	Light sandy soil (river beds)	–	20	–	101
13	Light rocky soil	–	20	–	120
14	Dark rocky soil	–	20	–	135
15	Dark sandy soil	–	20	–	49
16	Reddish soil (Gabiley area)	–	20	–	35
	Total	53	279	50	1,091

P. j. stands for *Prosopis juliflora*. Fractional cover (FC) percentage refers to total tree and shrub cover of soil. When *P. juliflora* is mixed with other tree species, we use the terms ‘dominant’ or ‘subdominant’ to indicate whether *P. juliflora* represents more or less than half of the total tree cover. The different bare soils were grouped according to their brightness and surface stoniness. According to the soil map of Vargas & Alim (2007), the following soils can be associated with our simplified groups: Haplic Fluvisols (light sandy soils); Lithic Leptosols and Skeletic Haplic Regosols (light rocky soils); Hyperskeletic and Hyperskeletic Lithic Leptosols (dark rocky soils); Hyperskeletic Leptosols, Haplic Calcisols and Skeletic Haplic Fluvisols (dark sandy soils); and Haplic Fluvisols and Haplic Regosols (reddish soils found in the agricultural area of Gabiley).

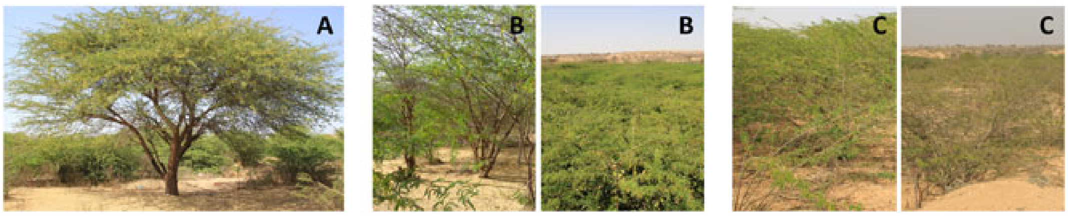

Figure 2. Examples of *Prosopis juliflora* stands encountered in the field campaign. (A) Tree form with large main stem; (B) multi-stemmed trees (left) forming a closed canopy (right); (C) shrub habit of the plant (more dense and green on the left and sparse and dry on the right). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

is also grouped within the 'natural vegetation' class because it was sparse and mixed with other species in the few locations where it was spotted. This prevented its mapping as a unique class in the present study.

To simplify the final map and to increase its accuracy, the 16 classes mentioned in the preceding text were regrouped into seven broader classes (Table II). The simplification was only made after the classification stage and was also used for accuracy assessment (see the Results – Classification and Mapping section).

Field Spectroscopic Measurements

Prosopis juliflora trees and shrubs use water very efficiently due to their deep and articulated root system, which includes both a tap root that grows deeply downward in search of the water table and a system of shallow lateral roots capable of exploiting infrequent rainfall events (Pasiecznik, 2001). Consequently, *P. juliflora* outperforms most other natural tree species in terms of canopy water content and general plant vigour during dry periods (Hoshino *et al*., 2012). To verify this trait, we collected a set ($n = 27$) of field spectroscopy measurements of *P. juliflora* and the most representative natural vegetation species (*Acacia* spp.). The appearance of the majority of the sampled trees was typical for the dry season, with *P. juliflora* being green, while the natural vegetation was already dry. However, we also sampled the less frequent situation represented by yellowing *P. juliflora* and green *Acacia*.

Table II. Post-classification merging of observed field classes

	Field-observed classes		Post-classification merged classes
1	*P. j.*, FC > 50%	1	*P. j.*, FC > 50%
2	*P. j.*, FC ≤ 50%	2	*P. j.*, FC ≤ 50%
3	Mixed cover with *P. j.* dominant, FC > 50%	3	Mixed cover with *P. j* dominant, FC > 50%
4	Mixed cover with *P. j.* subdominant, FC = 25–50%	4	Mixed cover with *P.j.* subdominant, FC ≤ 50%
5	Mixed cover with *P. j.* subdominant, FC < 25%		
6	Natural vegetation, FC > 50%	5	Natural vegetation
7	Natural vegetation, FC 25–50%		
8	Natural vegetation, FC < 25%		
9	Irrigated agriculture	6	Agriculture
10	Rain-fed agriculture		
11	Urban	7	Non-vegetated areas
12	Light sandy soil (river beds)		
13	Light rocky soil		
14	Dark rocky soil		
15	Dark sandy soil		
16	Reddish soil (Gabiley area)		

Original classes subjected to merging are in grey.

Spectral measurements were acquired with an FS HH Pro spectrometer (Analytical Spectral Devices, Boulder, CO, USA) covering the range of 325–1075 nm with a sampling interval of 1 nm. Ten canopy measurements (each the result of ten consecutive samples, internally averaged) per target were collected from near-nadir (using existing elevated points and a ladder) at a distance ranging from 1 to a few metres above the canopy by using the spectrometer fiber (25° field of view).

Satellite Imagery and Ancillary Data

Satellite images recorded during the dry and wet seasons were acquired. The classification of the dry-season imagery should benefit from the fact that the drought-tolerant *P. juliflora* remains greener than endemic vegetation. In addition, it can be expected that *P. juliflora* shows a reduced variability between the wet and dry periods, as compared with natural vegetation. To exploit this information and to better discriminate other land-use classes (such as rain-fed agriculture and irrigated agriculture), we selected and tested one Landsat 8 satellite image acquired during the driest period (January to the end of March, Figure 1) and one in the previous wet period (September to November).

The two cloud-free Landsat 8 L1T top-of-atmosphere radiance scenes (path/row 165/53, acquisition dates 28/10/2014 and 17/02/2015, corresponding to the wet and dry seasons respectively) were downloaded from the USGS portal (http://earthexplorer.usgs.gov/). Radiance values were compensated for the different illumination conditions (assumed here to be controlled by the sun–terrain geometry) by using a 30-m resolution digital elevation model (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map) and the C correction method (Teillet *et al*., 1982), employing a nine-pixel kernel for the extraction of morphological characteristics. Images were fully cloud-free for the area of interest, and no atmospheric correction was applied.

We used the six 30-m resolution bands (OLI bands 2 to 7), corresponding to the following spectral regions: blue, green, red, near infrared and shortwave infrared 1 and 2. To create a 15-m multispectral dataset, these six bands were then pan-sharpened by using the Gram–Schmidt method (implemented in ENVI 5·3) and the panchromatic band. The normalized difference vegetation index (NDVI, Rouse *et al*., 1974) was then computed by using both the original and pan-sharpened data. After these steps, all layers were stacked into a single raster containing a total of seven bands for two acquisition times: six bands in the reflected domain plus the NDVI.

Finally, settlements and drainage network vector layers provided by United Nations Office for the Coordination of Humanitarian Affairs Somalia (place code release VII updated in 2011) and FAO-SWALIM respectively, were used in the analysis.

Classification Method

In this study, we used the non-parametric random forest classification method (Breiman, 2001). Random forest is a state-of-the-art non-parametric classifier based on an ensemble of decision trees that is relatively insensitive to noise, number and multi-collinearity of input data (Gislason *et al*., 2006; Hastie *et al*., 2009; Rodriguez-Galiano *et al*., 2012).

With the Landsat 8 data described in the preceding text, we tested different input configurations for a total of six classification outputs originating from the combination of three different acquisition times (wet season, dry season and the combination of the two) and two different spatial resolutions (the original 30m and the pan-sharpened 15m data).

An object-based analysis was also attempted by using the pan-sharpened data but did not increase the overall accuracy (OAA; data not shown). Details of the object-based analysis can be found in Ng *et al*. (2016).

The open source statistical software R version 3·2·3 (R Development Core Team, 2015) was used to develop a script to automatize the various tests. All the classifications were performed with the R package ‘randomForest’ (Liaw & Wiener, 2002).

Classification Evaluation

We opted for a tenfold cross-validation procedure (Kohavi, 1995) to validate the classification results and make optimal use of the relatively small sample size of our reference dataset (Brovelli *et al*., 2008; Friedl *et al*., 2010; Mannel *et al*., 2011). We thus performed ten classifications for each method/dataset tested. For each individual run, 10% of the polygons per class were excluded from the training polygons and left aside for the subsequent validation. The validation polygons were drawn without replacement, resulting in ten unique combinations of training-validation polygons (i.e. with no repetition of validation polygons). We kept this set of combinations constant for all classifications. Classification results over the validation polygons were stored and combined to generate the final confusion matrices (Foody, 2002). After the evaluation of the accuracy and selection of the best-performing method, we ran a final classification by using the full dataset for training purposes.

RESULTS

Spectral Measurements

The spectral reflectance (hemispherical conical reflectance factor) data collected in the field survey are shown in Figure 3. Samples have been grouped into three sets for clarity: (i) bare soils and the succulent *Opuntia* spp.; (ii) healthy *P. juliflora* and dry *Acacia* spp.; and (iii) dry *P. juliflora* and healthy *Acacia* spp.

Bare soils and succulent plant spectral signatures (Figure 3 A) are obviously different from all other tree samples. Panel B depicts the spectral signatures of *P. juliflora* and *Acacia* spp. encountered in the majority of the visited sites: green and healthy *P. juliflora* (green lines) showing large differences in absorption in the visible range and reflection in the near infrared as compared with dry *Acacia* spp. (blue lines).

This analysis shows that in the dry season, when *P. juliflora* is typically much greener and healthier than native tree species, the invasive species has a distinct spectral response. Nevertheless, this observation cannot be generalized. Although less frequently encountered in the field,

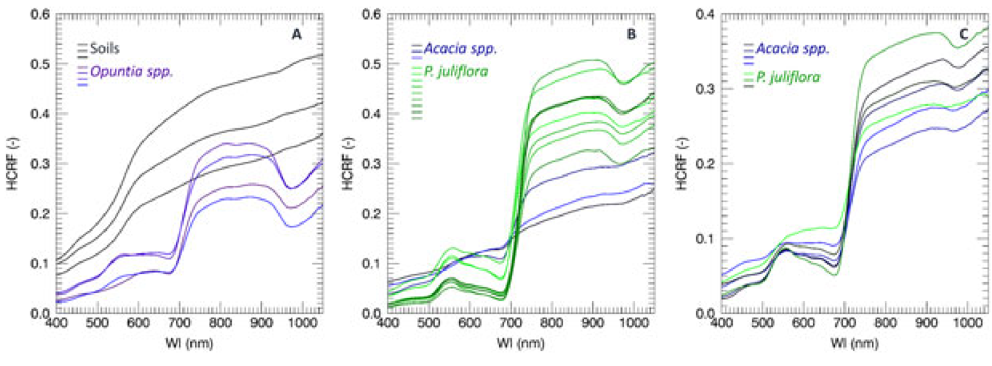

Figure 3. Hemispherical conical reflectance factor collected in the field survey. (A) Black: bare soils; purple: *Opuntia* spp. (B) Blue: *Acacia* spp.; green: *P. juliflora*. (C) As B but with the greenest *Acacia* and driest *P. juliflora*. Reflectances have been smoothed with the Savitzky–Golay filter (Savitzky & Golay, 1964). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

panel C depicts the opposite situation, with dry *P. juliflora* and healthy *Acacia* spp. growing in locations characterized by different water availability and showing fairly similar spectral reflectances. The results of the classification will be likely impacted by this similarity in spectral response, especially for the classes where *P. juliflora* is mixed with native trees.

Classification and Mapping

Preliminary tests indicated that some of the original 16 classes were prone to classification confusion among similar classes (e.g. the two mixed cover with *P. juliflora* subdominant classes, some soil classes). As the objective of this classification is the detection of *P. juliflora* spread, we tested the possibility of merging some of the more challenging classes. However, merging the training polygons to reduce the number of thematic classes resulted in reduction of OAA. Conversely, post-classification merging of selected classes was implemented to improve the OAA and simplify the legend (Table II). This process resulted in a final legend with seven classes.

The accuracy achieved with the various methods and datasets is presented in Table III. The table lists the user's accuracy, producer's accuracy and OAA for the various classification set-ups, characterized by the spatial resolution (original 30- or 15-m pan-sharpened) and the 'timing' (images from the wet, dry or wet and dry seasons).

The OAA of the various classifications ranges from 81 to 84%, depending on the dataset used. The acquisition period of the imagery (during the wet or dry season) used in the classification has an effect on accuracy. The use of wet-season imagery results in the lowest OAA (81–82%). This confirms the initial hypothesis that during the wet season, when rainfall allows the growth of all types of vegetation, the contrast between drought-tolerant *P. juliflora* and the other species and between natural vegetation and agriculture is reduced. The contrast between the spectral response of different classes increases during the dry season and the results in increased accuracy (83%). The simultaneous use of both seasons provides the best OAA results (84%), although by only a small margin compared with the use of the dry season only.

The use of pan-sharpened data only marginally increases the OAA by less than 1% when the dry period is used. Conversely, it has a minor negative impact when used with the single wet period.

Focussing on individual class accuracy (producer's and user's accuracies), fairly good results are achieved for the pure *P. juliflora* with high fractional cover (FC; 66–79%), natural vegetation (76–84%), agriculture (78–92%) and non-vegetated areas (88–93%). By contrast, poor discrimination is achieved for the classes that have *P. juliflora* with low FC (FC ≤ 50% *P. juliflora* dominant, 24–40%) or mixed with endemic natural vegetation (FC > 50% *P. juliflora* dominant and FC ≤ 50% *P. juliflora* subdominant, 24–47%).

Finally, Table IV presents the full error matrix of the set-up that provides the highest OAA (wet and dry season images, pan-sharpened data), which is used in the following

Table III. Classification results for the different combination of datasets

Spatial resolution (m)	Timing (seasons)	Producer's and user's accuracies (%): *P. juliflora* FC > 50% PA	UA	*P. juliflora* FC ≤ 50% PA	UA	Mixed cover FC > 50%, *P. j.* dominant PA	UA	Mixed cover FC ≤ 50%, *P. j.* subdominant PA	UA	Natural vegetation PA	UA	Agriculture PA	UA	Non-vegetated PA	UA	Overall Accuracy (%)	OAA rank
30	Wet	66	68	22	43	24	25	28	31	78	80	82	78	92	89	81·64	5
30	Dry	72	72	34	52	31	35	42	38	79	81	88	90	91	88	82·94	4
30	Wet and dry	68	79	31	56	40	35	46	40	80	83	87	91	92	89	83·99	2
15	Wet	68	72	23	36	25	27	33	33	76	80	82	79	92	88	81·01	6
15	Dry	71	70	31	48	28	31	46	40	78	82	88	89	92	88	83·16	3
15	Wet and dry	71	74	32	51	31	30	47	40	80	84	88	92	93	89	84·12	1

OAA, PA and UA stand for overall, producer's and user's accuracies respectively.

Table IV. Confusion matrix of the classification using 15-m pan-sharpened spatial resolution and both dry- and wet-season imagery

Overall accuracy = 84%, KHAT = 0·75	Reference data							User's accuracy
	P. juliflora		Mixed cover		Natural vegetation	Agriculture	Non-vegetated	
	FC > 50%	FC ≤ 50%	FC > 50%, *P. j.* dominant	FC ≤ 50%, *P. j.* subdominant				
Classification data								
P. j., FC > 50%	**336**	4	102	3	2	5	0	74%
P. j., FC ≤ 50%	15	**250**	33	83	16	8	89	51%
Mixed cover with *P. j.* dominant, FC > 50%	79	102	**177**	79	47	68	43	30%
Mixed cover with *P. j.* subdominant, FC ≤ 50%	6	187	126	**851**	735	36	165	40%
Natural vegetation	28	30	38	662	**12,941**	444	1,328	84%
Agriculture	8	28	35	40	259	**4,382**	16	92%
Non-vegetated	0	183	52	77	2,226	34	**20,917**	89%
Producer's accuracy	71%	32%	31%	47%	80%	88%	93%	

analysis. The classification output by using this set-up is presented in Figure 4.

DISCUSSION

Spectral Signatures

Field-measured spectra acquired during the dry season show that drought-tolerant *P. juliflora* exhibits different spectral signatures as compared with endemic trees that suffer severe water stress. This confirms that timing of imagery acquisition is important and imagery should be acquired during the driest period of the year (Mirik & Ansley, 2012b; Van de Berg *et al.*, 2013; Wakie *et al.*, 2014) when plant vigour differences are likely enhanced. Such acquisitions will yield the highest spectral discrimination between *P. juliflora* and the native trees. Nevertheless, in contrast with Hoshino *et al.* (2012), we observed no spectral differences between some healthy *Acacia* spp. (less frequently spotted in our

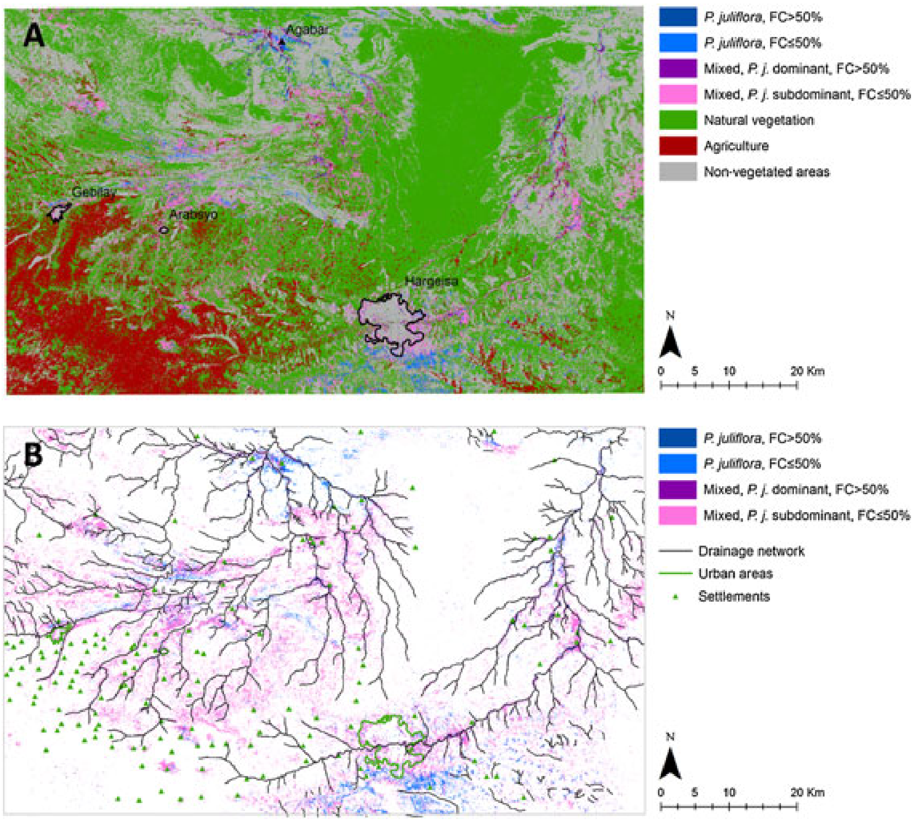

Figure 4. (A) Classifications of the study area using pan-sharpened imagery of the wet and dry seasons, urban areas (Hargeisa, Gabilay and Arabsyo) and the settlement of Agabar are in black; (B) drainage network (black lines), urban areas (green polygons) and settlements (green triangles) overlaid on the classification (as in A, but displaying only the classes in which *P. juliflora* is present). Higher elevations are found in the South of the area, water in seasonal water courses flows approximately from south to north. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

field campaign and mainly located in the proximity of water sources) and the driest samples of *P. juliflora*. This finding suggests that some confusion between species is likely to occur, negatively affecting the classification results, even during the dry season.

Classification Set-up

The results show that the highest OAAs are obtained by using pan-sharpened wet- and dry-season data. The difference between the dry and the combination of wet and dry is minimal. We therefore consider the dry season data to be equally adequate for *P. juliflora* detection. Field observations during the dry period indicate that *P. juliflora* remains relatively green throughout the year, thanks to its deep rooting system (Yoda *et al*., 2012) and metabolic and ecophysiological coping mechanisms (Sen & Mehta, 1998), whereas the endemic trees dry out, turn yellow and eventually shed their foliage. During wet season, *P. juliflora* and the natural vegetation are likely to be spectrally similar, resulting in the reduced classification accuracy we observed when using solely the wet season imagery. This finding is in agreement with Wakie *et al*. (2014), who analysed MODIS 250-m NDVI and Enhanced Vegetation Index (EVI) time series imagery of the Afar region of Ethiopia. They found that imagery acquired during the dry season allowed for better discrimination between *Prosopis* spp. and other woody vegetations. The observed small improvement gained by the use of both seasons may be the result of additional information regarding the plant phenology. For instance, sparse natural vegetation or rain-fed agriculture could be confused with bare soils when only the dry season data are used.

Our results demonstrate that the use of 15-m pan-sharpened data only marginally increased the accuracy with respect to the original 30-m data. The moderate improvement may be due to the fact that the spectral information content is not increased with the employed pan-sharpening technique. Actual multispectral information at higher spatial resolution, such as the 10-m resolution imagery provided by the Sentinel-2 ESA mission (e.g. Immitzer *et al*., 2016), may improve the classification accuracy as for instance found by Mirik & Ansley (2012a) comparing 1- with 30-m spatial resolution data. With this freely available data to hand, the object-based analysis (Ng *et al*., 2016) that failed to improve the classification accuracy with the Landsat 8 pan-sharpened data used in this study should be re-evaluated. Given that Sentinel-2 will map any pixel on Earth every 5 days, the utility of multi-temporal data should also be re-assessed, as only bi-temporal data were used in this study.

The poor classification results for the *P. juliflora* classes with FC that is less than 50% or for *P. juliflora* mixed with natural vegetation are related to two sources of confusion: (i) *P. juliflora* and the endemic trees have a similar spectral signature when the former is rather dry and the latter is green, as shown in the Results - Spectral Measurements section; (ii) the overall FC of vegetation plays a similar role to the fractional presence of *P. juliflora* as compared with total vegetation. Hence, the spectral signature of a pure *P. juliflora* pixel with a low FC is likely to be similar to that of a mixed pixel with a higher overall FC but have a smaller fraction of *P. juliflora*.

The confusion between the three classes in which *P. juliflora* is present with low FC or mixed with endemic vegetation is evident from the full error matrix of Table IV. The producer's and user's accuracies of these classes are low (31–47% and 40–51% respectively). However, with the exception of the class subdominant *P. juliflora* with FC < 50%, which is severely confused with natural vegetation, the misclassifications appear to occur mostly within the *P. juliflora* classes. In fact, by grouping these classes within a single class ('sparse or mixed *P. juliflora*'), the producer's and user's accuracies increase to 85 and 59% respectively. Therefore, even if the accuracy achieved is suboptimal for discriminating the dominance of the invasive species, it appears to be suitable for providing an overview of the *P. juliflora* invasion and allows for the mapping of where it is well established (dense and pure) and where it is in its initial stages of colonization (sparse or mixed with natural vegetation).

P. juliflora Distribution

Prosopis juliflora is detected mainly along wadis and peri-urban areas (Figure 4B). The major expansion routes are the wadis that cross the city of Hargeisa in the South and the wadi network in the area of Agabar in the North. In both areas, extensive planting of *P. juliflora* was promoted by non-governmental organizations (Awale & Sugule, 2006) in the late 1980s. During our field campaign, local representatives of the Agabar village reported that the *P. juliflora* was planted to restore the areas deforested by the Ethiopian refugees who were displaced in the area as a consequence of the Ethio-Somali war (in 1977–1978). In this way, the acacia forest that predated the deforestation was quickly replaced by a dense and tall formation of *P. juliflora*.

Along the wadis, the invasive species competes with natural vegetation and small-scale irrigated agriculture. During the dry season, near-surface groundwater in or in the proximity of the wadis is pumped to irrigate nearby fields, often orchards. The reduced availability of groundwater was attributed by local people in Agabar to the increasing presence of *P. juliflora*. As *P. juliflora* is very difficult to eradicate without mechanical or chemical aid, it is contained only in the managed agricultural fields and not in the common land along the wadis.

The presence of *P. juliflora* is minimal in the agricultural area in the south-west of the study area, likely due to the absence of a dense drainage network, its distance from infested areas and possibly the higher density of farmers with an interest in controlling the expansion as found by Ayanu *et al*. (2014) in Ethiopia. Similarly, the sparsely inhabited large dry area located far from the drainage network (north of Hargeisa) is currently not affected.

The area covered by various LC classes is summarized in Table V and is derived from the map shown in Figure 4. The percentage of the total area covered by pure *P. juliflora* is

Table V. Area covered by the various classes according to the classification of Figure 4

	Area (ha)	Area (% of total)	Area (% buffered area)				
			Drainage network buffer			Settlement buffer	
			1,000 m	500 m	200 m	3,000 m	1,000 m
P. juliflora							
FC > 50%	450	0·09	0·15	0·24	0·44	0·16	0·19
FC ≤ 50%	8,137	1·57	1·89	2·07	2·72	2·01	1·98
FC > 50%, *P. j.* dominant	2,107	0·41	0·56	0·73	1·18	0·59	0·62
FC ≤ 50%, *P. j.* subdominant	35,754	6·92	9·05	10·17	11·87	10·85	10·25
Total of classes with *P. j.* presence	46,448	8·99	11·6	13·2	16·2	13·6	13·0
Natural vegetation	270,643	52·38	49·76	47·53	44·42	47·40	38·65
Agriculture	62,415	12·08	6·41	5·88	5·73	16·22	33·56
Non-vegetated	137,201	26·55	32·17	33·39	33·64	22·77	14·76

The percentage cover is computed for the total area, for the area obtained buffering the drainage network of Figure 4B with a buffer distance of 1,000, 500 and 200 m and finally for the area obtained buffering the settlements of Figure 4B (the towns of Hargeisa, Gabilay and Arabsyo are excluded) with a buffer radius of 3,000 and 1,000 m.

relatively small (1·7%) but becomes significant when all classes with *P. juliflora* are considered (8·99%). There is some uncertainty in this figure because the producer's and user's accuracies of the *P. juliflora* class with the largest cover (*P. juliflora* subdominant and FC < 50%) were rather poor (Table IV). Nevertheless, considering that the class is affected by similar commission and omission errors, the estimated area cover should reflect the actual one fairly accurately.

By computing the cover percentage within a decreasing distance from the drainage network (1,000, 500 and 200 m), an increase in the presence of *P. juliflora* classes can be observed. This can be explained by the increasing availability of water in the proximity of the seasonal water courses and by the fact that the transportation of seeds along watercourses is a major dispersal route (Pasiecznik, 2001). Within a distance of 200 m from the drainage network, the percentage of *P. juliflora* classes (16·2%) nearly doubles as compared with the overall percentage (8·99%). The denser infestations along the river beds of the wadis are observable in the greater increase of the pure and dense *P. juliflora* class (*P. juliflora* FC > 50%) compared with the other *P. juliflora* classes when considering areas closer to the drainage network. In fact, the percentage cover of this class triples in the 200-m compared with the 1,000-m buffer zone.

Similarly, the percentage of *P. juliflora* classes increases in the proximity of settlements to about 13%, while that of the dense *P. juliflora* class (*P. juliflora* FC > 50%, 0·19%) doubles within a 1,000-m radius compared with the overall fraction. This greater presence close to settlements is likely caused by seed dispersal by pastoralists' animals.

Finally, it should be noted that statistics in Table V refer to the entire number of settlements and seasonal water courses present in the study area. The infestation can be locally much heavier near specific settlements or along specific wadis, as depicted in Figure 5.

Figure 5A shows the dense infestation in the area of Hargeisa, where the classes with *P. juliflora* mixed with natural vegetation are widespread in the peri-urban area and along the wadi leaving the city to the west. Pure *P. juliflora* stands are also present in such areas and dominate large patches in the south of the city. The classification in the area of Agabar village is shown in Figure 5B. The classification nicely depicts what was observed during the field campaign: pastoral areas around the settlement are nearly completely occupied by *P. juliflora* that grows dense and pure in more favourable conditions and is sparser in the drier zones. Large patches of *P. juliflora* encroachments replace the original native forest areas along the wadis north-east and north-west of the village. In addition, the invasive species often occurs and threatens nearby irrigated agricultural fields along the wadis and rapidly invades abandoned agricultural areas. Here, the plant was observed as thick impenetrable stands. In the same area, we observed agricultural fields where *P. juliflora* plants were clearcut and had regrown to a height of 2 m after only 2 years. Finally, Figure 5C shows the level of infestation of an area north-west and downstream of the capital, where *P. juliflora* is a constant presence close to irrigated agriculture along the drainage network. The dispersion of the plant is likely facilitated by the seasonal watercourses that can carry the invasive plant seeds over relatively large distances. This interpretation is sustained by the fact that *P. juliflora* is more abundant along the seasonal water courses downstream of Hargeisa (Figure 5C) compared with the agricultural region in the east, located in an area with a sparser drainage network upstream of the capital. Cropland weeding by farmers as a management practice to contain *P. juliflora* may also play a role in this latter area.

Initiatives to tackle the problem and prevent further invasion of native grasslands and rangelands are already underway in the area, including eradication by local stakeholders such as farmers and pastoralists, and utilization of the plant (Livingstone *et al.*, 2014). The produced map will be made available to assist the planning of new management activities. The effectiveness of initiated management steps could

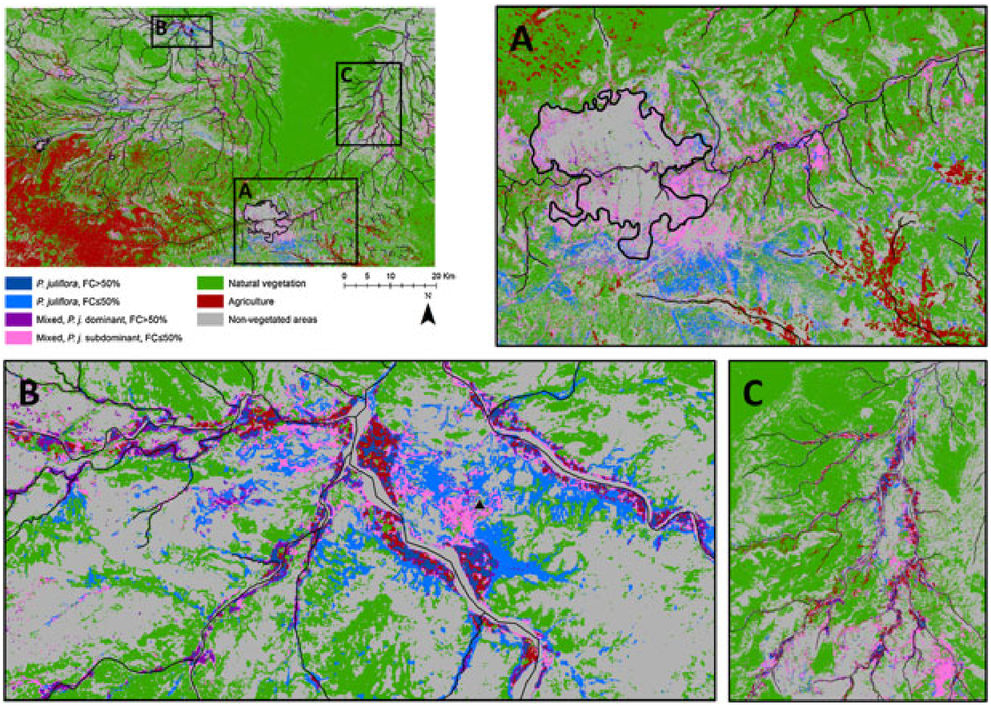

Figure 5. Spatial zoom of the classification for selected areas. (A) Hargeisa town (thick black polygon), (B) Agabar village (black triangle) and (C) a wadis system in the North-East. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

be then efficiently assessed by repeating the classification exercise after 5 to 10 years.

CONCLUSIONS

In this study, we investigated the potential of freely available Landsat 8 imagery to map *P. juliflora* in the arid environment of the Hargeisa area in Somaliland. The spatial extension of *P. juliflora* first depicted in this study shows that the plant is extensively spread across the whole study area, with the exception of the rain-fed agricultural area in the South-West and the large arid area occupied by natural vegetation in the North-East. The combined fraction occupied by all *P. juliflora* classes amounts to about 9% of the total area, a significant land-cover change considering that its introduction in the area is likely to have started in the mid-1980s.

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DISCLAIMER

The authors and their respective organizations do not assume any responsibility for the geographic borders and names used for the purpose of orientation and mapping in this publication.

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