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A New Method for Post-introduction Risk Assessment of Biological Invasions Among Introduced Shrubs in Developing Countries

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Abstract Risk-assessment methods are useful in collecting data that can help decision making to prevent the introduction of new species that have the potential of invading as well as in management of established taxa. Not only the complexity and unaffordability of available pre-introduction risk-assessment models make them rarely or inconsistently applied in the least-developed countries, but also there is lack of tools to assess the status of already introduced plant species. In this study, an affordable and rapid method of assessment of invasiveness among introduced plant species was developed and tested in Rwanda. This method defines three invasion stages (potential, effective, and suppressive invaders) and four levels of risk assessment: post-introduction assessment of species inherent invasive potential (*Level 1*), post-establishment assessment of species capacity of regeneration (*Level 2*), post-naturalization assessment of species range of occurrence and ability for long-distance dispersal (*Level 3*), and post-naturalization assessment of species ability to outcompete other plants in the community and transform the landscape (*Level 4*). A review of invasive species in Rwanda was developed through desk review, examination of herbarium records, and vegetation surveys. This method should be applicable in other countries that lack the means for a more conventional scientific investigation or under any circumstance where a quick and inexpensive assessment is needed. The method could be useful to environmental managers for timely intervention with strategies specific to different stages of invasion (post-introduction, post-establishment, or post-naturalization) and allocate resources accordingly.

Keywords Alien · Shrubs · Invasive · Suppressive · Risk · Assessment

Introduction

Invasive plants are the world's second most serious threat to biodiversity conservation (Yates et al. 2004). In the United States alone, the estimated annual damage from displacement of native taxa by invasive species amounts to more than US$120 billion (Pimentel et al. 2005; Pimentel 2009), equivalent to 65–70 times the 2012 annual government expenditure budget of the Republic of Rwanda (CIA 2013). According to Pysek (2004), there are about 450 invasive plant species worldwide, nearly half of which are woody and up to 80 % having some commercial use such that they can be assumed to have been introduced intentionally. Approximately 1 % of introduced plant species become invasive (Fowler et al. 2000). Ideally, all plant species considered for introduction should be screened to identify and ban those whose likelihood to become invaders is high (Barbier et al. 2013). If such a taxa still manages to enter a region, the next best scenario is early detection and eradication (Fowler et al. 2000). Early

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detection and control of an invasive species is costly but more effective compared with the cost of implementation of counter-measures after the invasive plant has established (Pierre et al. 2006).

Risk-assessment systems are useful in collecting data that help decision making to prevent the introduction of new species that have the potential of invading as well as in management of established taxa (Andersen et al. 2004). However, the complexity and expense of available risk-assessment models contributes to the problem of data scarcity or poor quality data endemic to all developing countries (Nunez and Pauchard 2010). According to Gichua et al. (2013) there is limited interest among scientists and policy makers in East Africa to take appropriate measures to address issues relating to invasive species. As a result, despite the existence of pre-introduction risk-assessment methods that would work properly in the region like the WRA system (the Australia's weed risk assessment) (Dawson et al. 2009), uncontrolled plant introductions are still common. For instance, the Rwanda Environment Management Authority, the institution entrusted to prevent environmental hazards that may result from invasive plants in Rwanda, suggests that a number of recent introductions of alien plants in Rwanda took place without proper screening. These include macadamia, moringa, neem, mulberry, and jatropha (REMA 2009).

The situation is more worrying because in many developing countries including Rwanda little or no measures are taken to [re-]assess the invasiveness of species in the host range, after the introductions have taken place. For instance, between 1998 and 2014, Rwanda submitted five national-level reports to the Convention on Biological Diversity (CBD) Secretariat, with no single shrubby species mentioned as an alien invader in Rwanda due to lack of data until 2009 when the fourth report was compiled (Table 1). Also a source of concern is the fact that current predictions and reports regarding biological invasions in East Africa, apart from containing incomplete or fragmented information, may be of little help because they are inherently ineffective because of heavy reliance on studies conducted elsewhere (Gichua et al. 2013).

There are signs that policy makers in developing countries understand that monitoring is an important component in the management of invasive alien species. For, instance, law n° 70/2013 of 02/09/2013 governing biodiversity in Rwanda, in its article 20, makes compulsory the establishment of a list of species invasive in Rwanda and requires that it be reviewed every 2 years. However, for such an objective to be attained there is a need for a standardized and scientifically sound method of assessment if the results are to sufficiently reflect real world facts. We present a new cost-effective and robust post-introduction sampling and classification system for invasive shrubs, hereafter referred to as PISCI (Post-Introduction Sampling and Classification of Invasiveness), tested across a small and generally accessible country.

Materials and Methods

Study Area

The study was conducted in Rwanda, a landlocked country situated at 2°00 south of the Equator and 30°00 east of the Greenwich Meridian Line. Rwanda's elevation ranges from 950 m in the Rusizi valley to 4507 m on Mount Karisimbi. Rainfall varies with altitude and can range from 750 mm a^{-1} in Kagitumba and 1000 mm a^{-1} in Kigali to above 1400 mm a^{-1} in Kigeme and Ruhengeri and from 15 mm in July to 160 mm in April. Four seasons are

Table 1 Evolution of risk assessment of the eight invasive plants identified in this study with a reference to the country's 1998–2014 national reports to Convention on Biological Diversity

Species name	Year				
	1998	2005	2006	2009	2014
Agave americana L.					✔
Agave sisalana Perrine					✔
Caesalpinia decapetala (Roth) Alston					
Kalanchoe prolifera (B. ex Hook.) R.-H.					
Lantana camara L.				✔	✔
Mimosa pigra L.					
Opuntia ficus-indica (L.) Mill.[a]					
Opuntia monacantha Haw.[a]					
Tithonia diversifolia (Hemsl.) A. Gray					

Ticks indicate what species was reported in each of the five reports

[a] Rwanda's fifth national report to CBD indicates that cacti are spreading in the natural environments adjacent to cattle farmland where they are used as hedges. Unfortunately, these invasive plants were identified only to the genus level (Opuntia), which does not aid in comparison with the findings of this study

present: two rainy seasons (78 % of annual rainfall) and two dry seasons (22 % of annual rainfall). Average temperature varies with both altitude and land topography: 21.8 °C in Butare, 20.95 °C in Kigali and 17.6 °C in Kigeme and Ruhengeri. Land use profile includes 45.56 % arable land, 10.25 % permanent crops, and 44.19 % other types of land cover. The country has three national parks and is divided into 18 agro-ecological zones as illustrated in Fig. 1. Vitousek et al. (1997) estimated the number of vascular plant species that had naturalized in Rwanda by the late 1980s (93 species), but did not indicate how many shrub species had become naturalized or invasive.

Data Collection

Species with known invasive potential, regeneration capacity, range of occurrence, and ability to outcompete other plant species were investigated using an integrated methodology that combines desk review, grid-based survey, plot method and meander transect sampling, and Braun-Blanquet plant cover scaling. Four levels of assessment were considered, three of which concerned only species already established outside cultivation. The first level involved a review of literature to evaluate status of nonnative species in the study region. Level two and three included vegetation surveys to sample invasive species presentce in the study region. Level four assessed the probability of those invasive species found to out-compete neighboring plant species.

Assessment Levels

Level 1 Assessment: Species Inherent Potential of Invading

A desk-based review was conducted to collect data on each species' native range, records as invasive elsewhere, and purpose and date of introduction. Reference to establishment in the past outside cultivation was also noted.

Level 2 and 3 Assessment: The Presence of Alien Shrub Species

Vegetation surveys were conducted from August 2011 to July 2013 to record the presence–absence of wildly growing alien shrubby species across Rwanda. We used a 10 × 10 km^2 grid overlaid over Rwanda's elevation map. A total of 26 grid cells were randomly chosen for sampling, representing approximately 10 % of the country's total land cover. Each selected grid cell was walked and searched at a regular speed of 5 km/h, using the meander transect method and noting the presence or absence of alien shrubs every 1 km (the estimated routine maximum dispersal range of most plant species in the tropics (Corlett 2009). The meander method is the best method to document invasive species richness (Huebner 2007), which aligns well with Maxwell et al. (2012) who suggested that the ability to detect the presence of an invasive species with straight transects was relatively low. The randomly selected plot sampling is difficult to apply within the

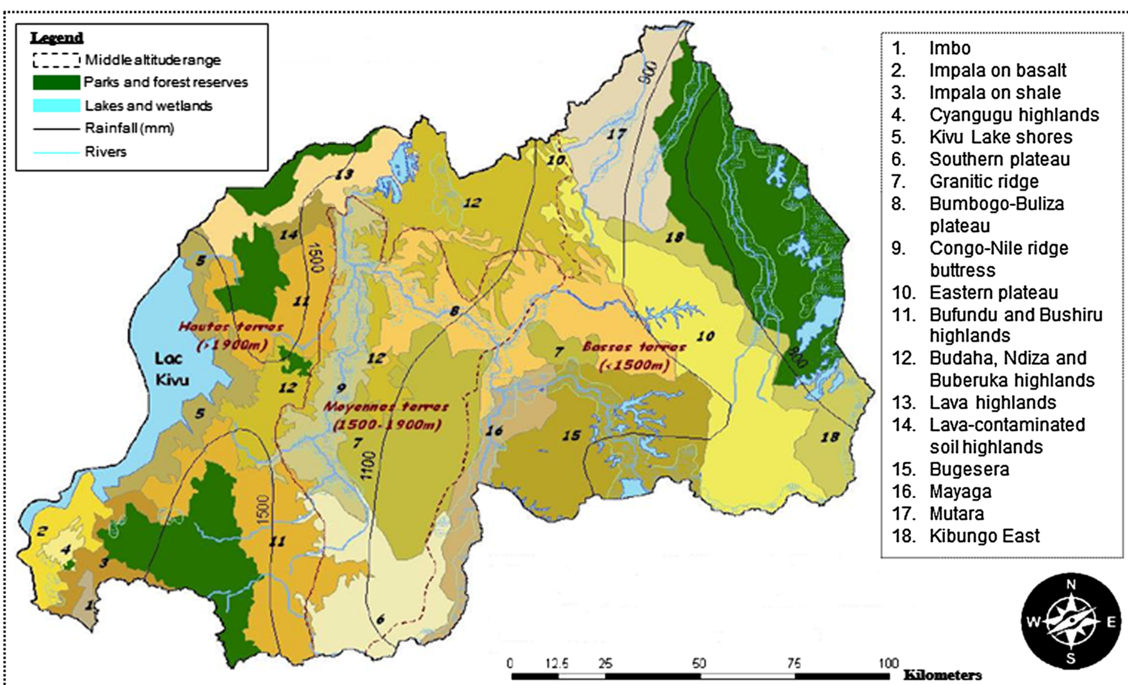

Fig. 1 Natural forests and agro-bioclimatic zones distribution in Rwanda [Adapted from NAFA (2013)]

cultural landscape and was considered not practical for this study (Shuster et al. 2005). For the purpose of this study, the meander transect method was combined with a grid-cell survey design (McCaffrey et al. 2014). We walked one meandering transect per grid. The transect length varied with land use: 20–25 km. The start point was located at mid-distance of the grid's side and covered a width 0.5 km on both sides of the perpendicular line segment that divides the grid into two equal-sized rectangles. To be practical, the meander transect pattern was kept as close to a maximum meander width (or amplitude) of 0.5 km on either side of the meander axis and an average meander arc length of 2.18 km per km of the meander axis. The time budget was 7–8 h per transect, excluding break time and depending on land use, topography, and alien species richness.

Alien shrub species, defined, for the purpose of this study, as plant species with erect or rambling stems not exceeding 6 m of height at mature stage and native range of which does not include Rwanda, were noted to a distance of 5 m on either side of the meander transect, equivalent to a search effort (the meander sweep per surveyed unit area) of 220 m^2 ha^{-1}. Species occurrence was recorded using a binary coding system in which "1" stands for species presence and "0" for the species absence. Each new alien shrub species was recorded, and altitude was noted. The same coding system was used to note whether a species had ("1") or not ("0") one or more populations comprising two or more generations of adult plants. Coordinates of locations of exceptionally high occurrence (continuous occurrence over 50–100 m or more) were also taken. Long distances were measured virtually, using Google Earth program through its incorporated ruler tool.

The evidence for minimum time length of occurrence in the wild not less than 25 years (threshold for an established species to be assigned the status of a "naturalized") was primarily drawn from our personal observations. Alternatively, Records at the National Herbarium of Rwanda or in the BGM (Botanical Garden Meise) online databases and reference in Troupin (1971 and 1982) were considered. Where these two approaches were not effective, we relied on relatively recent literature and expert judgment.

Level 4 Assessment: The Ability to Out-Compete Other Plants

For each naturalized alien shrub species recorded, areas of continuous occurrence over 50–100 m as identified opportunistically, during the species occurrence data collection phase were ranked by relative likelihood to constitute evidence that the species has reached the status of a "suppressive invader plant" or by revisiting sites of past surveys. Five highest-ranking sites were then selected per candidate "suppressive invader" species for assessment of distribution grain [=percent cover or frequency of occurrence in the ecotope (smallest ecologically distinct landscape feature)]. In each site, one 50 × 10 m plot was defined. Abundance of the alien shrub species was estimated using the Braun-Blanquet scales (Westhoff and van der Maarel 1978). To convert these scales (which are categories with a continuum of points representing each category range) into percent cover, the midpoint was used. The exercise was done for each "suppressive invader" species present and each plot in each site, and was stopped when abundance scale in any *n*th plot was greater than 3 (50–100 % cover, Table 2), with a mean distance between individuals or groups of plants less than one time the average canopy range of an individual plant. Otherwise, sampling continued until the fifth site. Short distances were estimated with bare eye or with a calibrated stick. Otherwise, a measuring tape was used. If the species completely covered the plot, no measurements were made.

Table 2 Braun-Blanquet cover-abundance (CA) scales (Wikum and Shanholtzer 1978)

Scales[a]	Range of cover (%)	Midpoint of cover (%) range
5	75–100	87.5
4	50–75	62.5
3	25–50	37.5
2	5–25	15.0
1	<5; numerous individuals	2.5
0	<5; few individuals	0.1

[a] CA is midpoint value of the corresponding range of cover (%), except for the last scale

Invasion Stages and Species Classification

According to Richardson et al. (2000), an invasive species is a naturalized plant that produces offspring in large numbers at considerable distances from parent plants in relatively short period of time. However, there is no unequivocal threshold [in terms of extent and duration of occurrence] above which a species can be said to be invasive (Simberloff 2010). The invasion stage for each species was defined as the highest level it has reached of the following invasive statuses: [1] potential invader plant (PIP), [2] effective invader plant (EIP), or [3] suppressive invader plant (SIP) based on the following descriptors:

(I) The species is a potential invader plant (PIP) = noxious (*Level 1*), regenerating (*Level 2a*), or naturalizing (*Level 2b*) (Dawson et al. 2009):

- *Level 1* (post-introduction assessment of species ability for self-establishment: does the taxon have inherent potential of invading?): This condition was fulfilled if a species [1] proved to be native to a geographic range with similar climatic regime as Rwanda's (Richardson et al. 2000), [2] it was introduced for a purpose other than food cropping, indoor gardening, or alike (=seed dispersal limiting) (Weber and Gut 2004), and [3] was found to be invasive elsewhere in the region (Kumschick and Richardson 2013);

- *Levels 2a and b* (post-establishment assessment of species regeneration potential: is the taxon characterized by a persistent occurrence?): two scenarios were recognized. Either [a] the taxon was self-established and considered as heading to naturalization, which was measured against its ability to form self-sustained populations over at least two lifecycles [in practice—this condition was considered fulfilled if the species was represented in at least three wild populations that each comprised at least two generations of seedlings (Seburanga et al. 2013)] or [b] was effectively naturalized in Rwanda, if, in addition to self-establishment and regeneration potential, the species was believed to have been occurring in the wild for at least 25 years (Tutin et al. 1964).

(II) The species is an effective invader plant (EIP) = spreading (Dawson et al. 2009):

- *Level 3* (post-naturalization assessment of species long-range dispersal and range of occurrence (Claridge and Franklin 2002): does the taxon have widespread occurrence?): the taxon was considered to have started invading in Rwanda if, in addition to effective naturalization, it was found to occur through self-sustained populations in at least three localities separated by at least 1000 m, the estimated routine maximum dispersal range of most plant species in the tropics (Corlett 2009).

(III) The species is a hyper-effective or suppressive invader plant (SIP) = transformer (Richardson et al. 2000):

- *Level 4* (post-spread assessment of species competitiveness: does the taxon have a dominant occurrence?): the taxon was considered as having the ability to suppress the growth of other plants, dominate in ecosystems, and transform landscapes if, in addition to naturalization, range of occurrence, and long distance dispersal, it was found to have spread over a continuous area of more than 500 m^2 [an average-sized ecotope or smallest ecologically distinct landscape feature (Ellis et al. 2006)]. To be assigned such a status, the mean distance between individuals or groups of plants had to be less than one time the average canopy range of an individual plant; equivalent to a canopy cover of more than 50 % (Bernez et al. 2006; Westhoff and van der Maarel 1978).

To put an emphasis on levels of threat to nature conservation, upon satisfying the criteria to be assigned the status of 'effective invader plant' as described above, a species was classified as an 'environmental weed' or a 'true invasive plant' if it showed the ability to invade natural areas, adversely affecting native communities (Williams and West, 2000). Alternatively, it was assigned the status of 'agricultural weed.' Inspired by Khan et al. (2013), the expressions "suppressive invader plant" and "hyper-effective invader plant" were coined to refer to those invasive plants that are competitive enough to achieve prominent occurrence, transform landscapes, and position themselves as the drivers of ecological processes within communities they have invaded. Richardson et al. (2000) call these kinds of plants "transformers." The approach adopted in this study was meant to simplify the terminology for invasion risk assessment from the time species are introduced to any later time. Similarly, Theoharides and Dukes (2007) indicated that after the first three stages of invasion (transport, colonization, and establishment), the plant species spends time spreading across landscapes or, in other words, dispersing within the region. A later stage involves gap filling and increase of density of distribution grain (Seburanga et al. 2013), culminating in suppression of the growth of other plants and landscape transformation.

System Validation

The list of invasive species established using the PISCI system was compared with lists from other scientific reports, including REMA (2009) and GoR (2014). The results were also compared with studies conducted outside Rwanda, including Vitousek et al. (1997), Kedera and Kuria (2005), IUCN (2012), Bigirimana et al. (2012), and Dawson et al. (2008).

Results

Sixteen potential invasive alien shrub species (=noxious species) were identified among which 12 species were effectively naturalized. Of these, 9 species were classified as effective invader plants (=invasive species). Four species were assigned the status of transformers (=suppressive invader plants) (Fig. 2). Two species were categorized as environmental weeds.

A total of 178 alien shrubby species were identified, the bulk of which were composed of Tropical American native plants (42.70 %). They were followed by Asian (25.84 %) and African-continent native (16.29 %) species, representing approximately 85 % of the total of alien shrubby flora in Rwanda. A great majority of these alien shrubs were first introduced for ornamental purposes (91.57 %). Of these, 16 species were previously reported to be invasive elsewhere (Table 3).

Twelve species were found to be naturalized with self-established populations sustained over 25 years or more (Table 4). The evidence was drawn from our personal observations for five out of twelve species (*Agave americana* L., *Agave sisalana* Perrine, *Lantana camara* L., *Opuntia ficus-indica* (L.) Mill., and *Tithonia diversifolia* (Hemsley) A. Gray) that were assigned the status of "naturalized." For *Brugmansia suaveolens* (Willd.) Bercht. & Presl, *Caesalpinia decapetala* (Roth) Alston, *Mimosa pigra* L., *Lonicera japonica* Thunb. ex Murray, and *Mimosa invisa* Mart. ex Colla, this status of "naturalized" was assigned based on records at the National Herbarium of Rwanda or in the BGM (Botanical Garden Meise) online databases or reference in Troupin (1971 and 1982). *Kalanchoe prolifera* (Bowie ex Hook.) R.-H and *Opuntia monacantha* Haw. were categorized as "naturalized" based on relatively recent literature and expert judgment (Table 4). Of these, 9 species had naturalized (*Level* 2b assessment) in more than 3 agro-ecological zones with an average residence time of 50 years (Table 4) and were classified as effective invaders (Table 5), amounting to 3(1.75) times the number of invasive shrub species (genera) listed in the latest government report to CBD (Table 1). Four species (*Lantana camara* L., *Agave sisalana* Perrine, *Tithonia diversifolia* (Hemsley) A. Gray, and *Mimosa pigra* L.) fell in the category of suppressive invaders (Fig. 2; Table 6). *Lantana camara* L. and *Mimosa pigra* L. occurred both within and outside protected areas and should be classified as "environmental weeds" in Rwanda.

In Ruliba site (Nyarugenge District), a 50 × 10 m plot was delimited where *Lantana camara* L. had a canopy cover of almost 100 % (cover scale: 5) and was the dominant species across many hectares either under eucalypts or in old fallows (Fig. 3), with infestation levels decreasing from east to west and the absence on top of the Congo-Nile ridge and surrounding areas. This species increased again

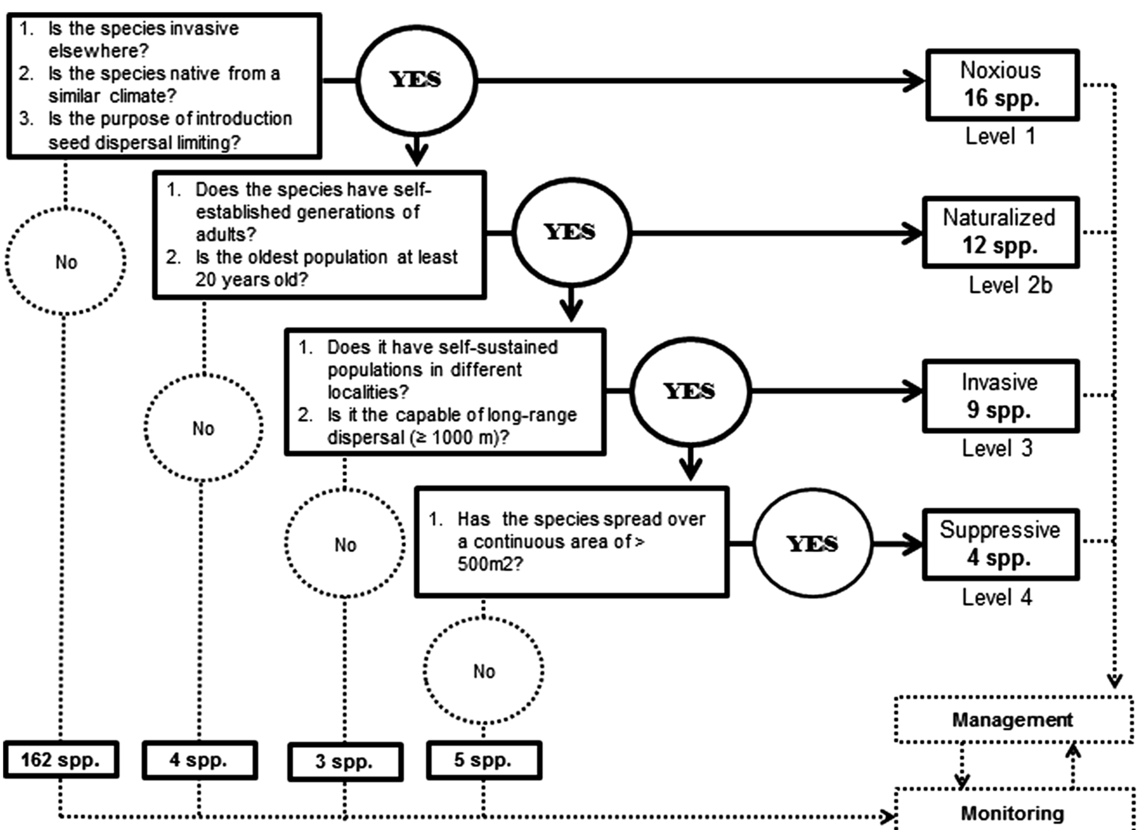

Fig. 2 Post-introduction plant invasion risk assessment and suggested stages of intervention for management and monitoring

Table 3 Noxious alien shrub species in Rwanda: nonnative shrub species from native range with similar climate, known as invasive elsewhere and introduced in Rwanda for nondispersal purposes

Species name	Place of origin	Purpose of introduction	Invaded countries	References
Agave americana L.	Tropical America	Ornamental	Tanzania	Henderson (2002)
Agave sisalana Perrine	Tropical America	Fiber source	Tanzania	Henderson (2002)
Brugmansia suaveolens (Willd.) Bercht. & Presl	Tropical America	Ornamental	Pacific	Burkill and Crosby (1901)
Buddleja davidii Franch.	East Asia	Ornamental	New Zealand	Kriticos et al. (2011)
Caesalpinia decapetala (Roth) Alston	Tropical Asia	Ornamental	Tanzania	Dawson et al. (2008)
Duranta erecta L.	Tropical America	Ornamental	China	Xu et al. (2012)
Jatropha curcas L.	Tropical America	Bio-fuel	United States	Gordon et al. (2011)
Kalanchoe prolifera (Bowie ex Hook.) R.-H.	Madagascar	Ornamental	South Africa	Crouch and Smith (2007)
Lantana camara L	Tropical America	Ornamental	Tanzania; Uganda	Dawson et al. (2008), Safari and Byarugaba (2008)
Lonicera japonica Thunb. ex Murray	East Asia	Ornamental	Tanzania	Foxcroft et al. (2006)
Mimosa invisa Mart. ex Colla	Tropical Asia	Live fence	Burundi, Nigeria	Ekhator et al. (2013)
Mimosa pigra L.	Tropical America	Live fence	Uganda	Byenkya et al. (2004)
Opuntia ficus-indica (L.) Mill.	Tropical America	Live fence	Tanzania; Kenya	Obiri (2011)
Opuntia monacantha Haw.	Tropical America	Live fence	D R Congo; Tanzania	Foxcroft et al. (2006), IUCN (2010)
Solanum mauritianum Scop.	Tropical America	Ornamental	South Africa	Olckers (1999)
Tithonia diversifolia (Hemsley) A. Gray	Tropical America	Ornamental	Burundi; Uganda	Eilu et al. (2007), Bigirimana et al. (2012)

from the crest down to Lake Kivu shores and islands. *Tithonia diversifolia* (Hemsl.) A. Gray was frequently recorded in agro-systems and young fallows. *Agave sisalana* Perrine readily established under Eucalyptus plantations (Fig. 4). *Mimosa pigra* L. was particularly abundant in riparian communities of the central and eastern floodplains. Unlike the three others, its occurrence was restricted to the central and eastern part of the country.

Discussion

The robustness of the PISCI model proceeds from the fact that it builds upon findings from a variety of studies, whose pieces are put together to form a single evaluation system. In accordance with Kumschick and Richardson (2013), suggesting that invasion risk-assessment studies should indicate the stages considered, the PISCI system defines three invasion stages (potential, effective, and suppressive invaders) and four levels of risk assessment: post-introduction assessment of species inherent invasive potential (*Level 1*), post-establishment assessment of species capacity of regeneration (*Level 2*), Post-naturalization assessment of species range of occurrence and ability for long-distance dispersal (*Level 3*), and post-naturalization assessment of species' ability to outcompete other plants in the community, and transform the landscape (*Level 4*).

All the species identified as invasive shrubs in Rwanda met at least two of the three criteria considered at *Level 1* (Tables 3, 5). All invasive species identified are native to the tropics, with the great majority (7/9) coming from Tropical America. All but one (8/9) were introduced in Rwanda mainly for ornamental and amenity purposes. All have been reported as invasive elsewhere, including an overwhelming majority (8/9) invading in at least one of Rwanda's neighboring countries. These findings confirm that native range, invasive status elsewhere, and purpose of introduction can be used as predictors of a species' potential invasiveness and align well with previous studies, including those discussed in Richardson et al. (2000), Kumschick and Richardson (2013), and Dehnen-Schmutz and Touza (2008).

The selection of PISCI criteria at *Level 1* aligns well with the "biogeographic history" section of the Galapagos weed risk-assessment model (Rogg et al. 2005) as well as Ou et al.'s (2008) ranking system in its second, fourth and fifth primary indices. However, one aspect of the originality of the classification system described here lies in the inclusion of the purpose of introduction as a predictor of an alien species' probability to become invasive in the introduced range. The rationale behind this proposal stems from the findings of Nairn et al. (1996), suggesting that more than 70 % of the naturalized flora of Australia had been intentionally introduced for agricultural purposes,

Table 4 Estimated minimum residence time of naturalized alien shrub species in Rwanda

Species	DFR[a]	POR	MRT	References[e]
Agave americana L.	Before 1970	–	45	Troupin (1971)
Agave sisalana Perrine	Before 1970	–	45	Troupin (1971)
Brugmansia suaveolens (Willd.) Bercht. & Presl	Before 1970	–	45	Troupin (1971)
Caesalpinia decapetala (Roth) Alston	Before 1955	Gisagara	60	Bazarusanga (1957)
Kalanchoe prolifera (Bowie ex Hook.) R.-H	Before 1990	–	35	–[b]
Lantana camara L.	Before 1955	Huye	60	Michel (1958)
Mimosa pigra L.	Before 1930	Masaka	85	Becquet (1932)
Lonicera japonica Thunb. ex Murray	Before 1975	Nyungwe	40	Auquier (1974)[c]
Mimosa invisa Mart. ex Colla	Before 1980	–	35	Troupin (1982)
Opuntia ficus-indica (L.) Mill.	Before 1960	–	45	Troupin (1971)
Opuntia monacantha Haw.	Before 1990	–	25	Rwangabo (1993)[d]
Tithonia diversifolia (Hemsley) A. Gray	Before 1970	–	45	Troupin (1971)

[a] *DFR* date of first record in Rwanda by a qualified botanist, *POR* place of specimen record, *MRT* estimated minimum residence time (years)

[b] No reference to an earlier record of *K. prolifera* was retrieved. However, the pattern of its current distribution and its presence in the natural environment in the region (Rembold 2011) allows believing that its introduction date can be situated between 1970s and 1990s, with a minimum residence time between 25 and 45 years

[c] The residence time of *L. japonica* was based on a specimen recorded at Botanical Garden Meise (Beligium): specimen no 3551 by P. Auquier, collected from Nyungwe forest on 31/07/1974

[d] Based on Foxcroft et al. (2003), *Opuntia monacantha* Haw. was considered as a synonym of *O. vulgaris* misapplied

[e] Bazarusanga (1957), Michel (1958), Becquet (1932) and Auquier (1974) are references to the earliest herbarium records of the corresponding plant species as mentioned on specimen labels

Table 5 Effective invader plants (PIP) in Rwanda: Naturalized shrub species with self-sustained populations in at least three noncontiguous administrative districts (Minimum distance between self-sustained populations from any pair districts is obviously greater than 1000 m)

Species	District
Agave americana L.	Gatsibo, Kamonyi, Ruhango
Agave sisalana Perrine	Huye, Musanze, Rusizi
Caesalpinia decapetala (Roth) Alston	Gicumbi, Gisagara, Karongi
Kalanchoe prolifera (Bowie ex Hook.) R.-H	Huye, Musanze, Rubavu
Lantana camara L.	Huye, Kayonza, Nyarugenge
Mimosa pigra L.	Kicukiro, Nyagatare, Rulindo
Opuntia ficus-indica (L.) Mill.	Bugesera, Nyagatare, Ruhango
Opuntia monacantha Haw.	Kamonyi, Rwamagana, Nyagatare
Tithonia diversifolia (Hemsley) A. Gray	Gasabo, Ngoma, Ngororero

Table 6 Transformer alien shrub species in Rwanda: invasive shrub species having spread over a 50 × 10 m strip or more with a canopy cover of more than 50 %

Species name	Location name	Latitude	Longitude	Date of record
Agave sisalana Perrine	Rwaza	1°32′49″S	29°41′29″E	10/07/2012
Lantana camara L.	Ruliba	1°57′03″S	30°00′16″E	27/07/2012
Mimosa pigra L.	Gahanga	2°03′28″S	30°05′14″E	25/07/2012
Tithonia diversifolia (Hemsley) A. Gray	Mamba	2°37′12″S	29°44′05″E	07/06/2012

corroborated by Hulme (2007) and Dehnen-Schmutz and Touza (2008) who estimated that more than 80 and 50 % of European and world invasive plant species (respectively) were intentionally introduced firstly as ornamentals.

The post-naturalization investigation of a species invasiveness in the PISCI system (*Level 3 & 4* assessment) aligns with components of the weed risk-assessment system from Galapagos Islands, which itself is a modification of the Australia's weed risk assessment (WRA) model (Gordon et al. 2008). The WRA system has been credited to be effective in predicting alien plant species noxiousness in a variety of environments (Speek et al. 2013). However,

Fig. 3 *Lantana camara*-dominated landscape in Ruliba (Nyarugenge District) along Bujumbura–Kigali highway, Rwanda

the Galapagos model, much like the PISCI system, differs from the WRA model in that it includes a series of entries that make it suitable for the classification of alien species already present in the country under consideration (Rogg et al. 2005). The PISCI-based assessment was powerful enough not only to recognize the invasiveness of all well-established invasive shrubs in Rwanda (REMA 2009; GoR 2014), but also to identify invasive plants that were omitted in previous studies (Table 1). It further classified these invasive species into two subcategories: effective invaders (5 species) and suppressive invaders (4 species) (Table 6). In line with Sandvik et al.'s (2013) risk-assessment model, the PISCI system takes into account the importance of the species' population age, residence time, spread potential, and the ability to suppress the growth of other plants and transform landscapes. However, while Sandvik et al.'s (2013) model aims to predict future trends, the PISCI system can better be described as a real time "status" snapshot. The PISCI system can also be described as a simplistic, but reliable and more affordable version of Magee et al.'s (2010) innovative approach for alien impact indexing at individual species' level because it is not limited to measurement of species abundance, but also considers the species life history, capacity of regeneration, spread of occurrence and ability to outcompete other plants.

In accord with Vitousek et al. (1997) who suggested that 93 plant species had established by late 1980s, 18 shrub species passed the PISCI level 2b filter and were classified as naturalized in Rwanda. The number of invasive species identified using the PISCI system was comparable to regional records. For instance, Kedera and Kuria (2005) listed nine invasive plant species in Kenya (all groups of plants combined). In neighboring Burundi, IUCN (2012) identified 11 invasive shrubby and small tree species. Unexpectedly, Bigirimana et al. (2012) identified only two invasive alien shrubs in Burundi's capital city, Bujumbura. In particular, the association between species' invasive status in Rwanda and their records as invasive elsewhere highlighted in this study corroborates Dawson et al.'s (2008) findings suggesting that more than 90 % of species spreading into the Amani Botanical Garden (Tanzania) were recorded as naturalized or invasive elsewhere.

Application in Environmental Management

The sampling and classification system developed in this study could be useful to environmental managers in developing countries. At *Level 1*, the assessments help identify which among introduced crops should be monitored closely and intervention plan prepared so that as soon as the species escapes from cultivation action steps can be taken. If a species passes *Level 1* filters and manages to establish self-sustained populations outside cultivation, it has the likelihood to be caught up at a later date at *Level 2* screening and be eradicated through mechanical removal

Fig. 4 *Agave sisalana*-transformed landscape **a** in association with *L. camara* in Ruhande Arboretum and **b** in relatively pure stands within a roadside forest in Rwaza, Northern Province, Rwanda

before it becomes naturalized (Fig. 2). *Level 3* assessment aims to identify species that, upon passing *Level 2*, are likely to become effective invaders. *Level 4* assessments will separate invader plants whose impact on native species and communities requires a prompt response from those with a relatively low occurrence and thus may be regarded as having benign impact on the environment (Weber and Gut 2004) (Fig. 2).

The four levels of assessment are not inherently linked to each other and can be disjointed depending on the management objectives. For instance, one can go straight forward to level 4 if the aim is to investigate the status of a single species like *L. camara* already recognized as invasive in the study area but whose "transformer" status is yet to be attested, and the assessment could be conducted only in sites opportunistically identified as with high occurrence or by revisiting sites of past surveys. Similarly, *Level 1 & 2a* assessments would be sufficient for new comer species, yet to escape from cultivation or with casual occurrence in the wild (refer to Richardson et al.'s (2000) for the invasive plant species terminology). However, full assessment (*Level 1–4*) should be compulsory as a starting point to establish a baseline dataset and should be repeated at regular intervals (say every 10–20 years) to update the database or, eventually, to inform future policy adjustments. Within a country, environmental literacy and invasive plant species awareness among the general public, which is part of the information needed at *Levels 2–3* assessments, could be drawn from data collected from local communities (Dangles et al. 2010). The investigator could then schedule a ground-truth survey, targeting sites identified through the examination of informants' reports.

Although the comparative study of the cost of the PISCI approach vis-à-vis other risk-assessment methods was beyond the scope of this paper, a look at the minimum budget required to conduct this study suggests that it could take between US\$0.5–1.0 per km^2 (about 0.2–0.5 % of the expected per square-km annual budget rate for invasive plant eradication calculated assuming Rwanda were allocating as much as South Africa would spend if it were applied Rwanda 2013 GDP per capita (Obiri 2011; data.worldbank.org, 19/11/2014)) and could be completed within 6–12 months. This makes the PISCI largely affordable.

Major Invasive Shrub Species in Rwanda

The four shrub species identified with the PISCI system as transformers in Rwanda have been previously reported in other studies and reports. If ranked by the date of first formal record as invasive, *Lantana camara* L. was the oldest invasive alien shrub in Rwanda (Troupin 1971). *Mimosa pigra* L. was first reported in 2013 (Seburanga et al. 2013). Two of the transformer species, *Agave sisalana* Perrine and *Tithonia diversifolia*, were most recently reported (Hemsley) A. Gray (GoR 2014; Seburanga 2014). In total, out of the nine invasive alien shrubs reported in this paper, eight were not known as such until 2012. Four species and one invasive genus were identified within the time frame of this study (*Mimosa pigra* L., *Agave sisalana* Perrine, *Tithonia diversifolia* (Hemsl.) A. Gray, *Caesalpinia decapetala* (Roth) Alston, and *Opuntia* spp.). Four species are reported fpr the first time: *Agave americana* L., *Kalanchoe prolifera* (B. ex Hook.) R.-H., *Opuntia ficus-indica* (L.) Mill. and *Opuntia monacantha* Haw. Although all the invasive and noxious species should be kept under scrutiny, the management of invasive alien plant species in Rwanda should put more attention on the following four species with the ability to out-compete native species and dominate in the landscapes they invade: *Lantana camara* L., *Mimosa pigra* L., *Tithonia diversifolia* (Hemsl.) A. Gray, and *Agave sisalana* Perrine.

Lantana camara L. In Rwanda, this species is a serious invasive species in natural and cultivated forests, pastures, and rangelands, at the expense of native understory species and palatable grasses (FAO 2013). In valleys, it behaves as evergreen, with flower and fruit production occurring all year along. In contrast, on hillsides, flowers, and fruits start developing shortly after the reconstitution of the leaf system and spans the rain seasons. As a result, it is common to observe an overlap of phenophases, with a single stem bearing flower buds, mature flowers, young fruits, and mature fruits at the same time. The flowers are showy which attracts horticulturists who in turn actively cultivated it and take it to areas beyond the reach of its own dispersal mechanism. Besides human cultivation of this species, seed dispersal is chiefly mediated by frugivorous birds.

Mimosa pigra L. This species is key invasive alien species in the region, from Burundi to Egypt, along the Nile River and associated floodplains. This species was first recorded in Rwanda in 1932. However, its status as an invasive alien species in Rwanda was first reported in 2013 (Seburanga et al. 2013). Its presence in the agricultural wetlands of Central and eastern Rwanda seems to be a serious threat to farming because of higher costs of production due to extra budget required for weed removal. However, the most concerning case is its widespread occurrence in the Akagera National Park and floodplains ecologically linked to it.

Tithonia diversifolia (Hemsley) A. Gray. Introduced into Rwanda during the colonial period as an ornamental crop, this species invades agro-systems, parklands, and fallows under situated 2000 m of altitude, with prominent occurrence in agricultural floodplains, fringes of undisturbed wetlands, and road and stream embankments. In the region, this species has a transboundary pattern of invasion and was classified as invasive in three of Rwanda's neighboring countries: in the Democratic Republic of Congo, in Burundi, and Uganda (Seburanga 2014).

Agave sisalana Perrine. Reported to be invasive in parts of neighboring Tanzania (Henderson 2002), Agave sisalana Perrine was introduced into Tanganyika (now part of the United Republic of Tanzania) by the German East Africa Company from Mexico in 1893 for fiber production (Kimaro et al. 1994). The exact date of introduction in Rwanda is obscure. However, it seems that it was introduced from Tanganyika shortly after Rwanda became a German colony in 1899. Since then, it has been used in Rwanda's cities and towns mainly as an ornamental crop. In rural areas, it was used both as a garden plant, boundary marker or source of fiber. The main point to learn from the invasive behavior of *Agave sisalana* Perrine in Rwanda is that, while in the past its populations could be effectively controlled by regular leaf harvest for fiber extraction, today the extraction of Agave fibers is practically absent in many parts of the country, and, as a result, the species establishes populations whose range quickly expands to cover vast areas. The use of sisal ropes in construction and bag making has declined tremendously with transition to concrete-based housing and use of plastics, evidence of how cultural change can result in the alteration of the distribution patterns of a potential invasive plant species.

Conclusion

This method of post-introduction assessment of plant invasiveness results in a reliable classification of plant species into categories relating to the respective invasion stages and risk assessment and could be applicable in other countries that lack the means to apply more sophisticated methods or in situations where a prompt response is needed (within 6–12 months). The method could be useful to environmental managers to intervene in a timely manner with strategies specific to different stages of invasion: post-introduction assessment of species inherent invasive potential, post-establishment assessment of species capacity of regeneration, post-naturalization assessment of species range of occurrence and ability for long-distance dispersal, and post-naturalization assessment of species' ability to outcompete other plants in the community and transform the landscape. This hierarchical sampling and classification system will allow environmental managers to envisage timely prevention measures and control strategies and allocate resources accordingly.

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