REMOTE SENSING AND GIS APPLICATIONS FOR MAPPING AND SPATIAL MODELLING OF INVASIVE SPECIES

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ABSTRACT:

Biological invasions form a major threat to the sustainable provision of ecosystem products and services, both in man-made and natural ecosystems. Increasingly, efforts are made to avoid invasions or eradicate or control established invaders. It has long been recognized that remote sensing (RS) and geographical information system (GIS) could contribute to this, for instance through mapping actual invader distribution or areas at risk of invasion. Potentially GIS could also be used as a synthesising tool for management of interventions aiming at invasive species control. This paper reviews the application of remote sensing and GIS in mapping the actual and predicting the potential distribution of invasive species. Distinction is made into four categories of invasive species based on whether they appear in and dominate the ecosystem canopy or not. We argue that the possibility to apply RS to map invaders differs between these categories. Our review summarizes RS techniques applied in here and outlines the potential of new RS techniques. It also demonstrates that RS has so far been applied predominantly to canopy dominant species. This contrasts with ecological databases revealing that the large majority of invasive species do not dominate the canopy. The mapping of these invaders received little attention so far. In this paper we will review various possibilities to map non-canopy invader species. The paper also reviews techniques used to map the risk of invasion for areas not invaded so far.

1. INTRODUCTION

Invasive species are a current focus of interest of ecologists, biological conservationists and natural resources managers due to their rapid spread, threat to biodiversity and damage to ecosystems. Invasions may alter hydrology, nutrient accumulation and cycling, and carbon sequestration on grasslands (Polley et al., 1997). The global extent and rapid increase in invasive species is homogenising the world's flora and fauna (Mooney & Hobbs, 2000) and is recognized as a primary cause of global biodiversity loss (Czech & Krausman, 1997; Wilcove & Chen, 1998). Bio-invasion may be considered as a significant component on global change and one of the major causes of species extinction (Drake et al., 1989).

This article attempts to provide a review of several studies that assess the utility of remote sensing (RS), or remote sensing coupled with geographical information system (GIS), in mapping and modelling the distribution of invasive species. The term invasive species is also more or less synonymously referred to as aliens, barriers, naturalized species, invaders, pests, colonisers, weeds, immigrants, exotics, advantives, neophytes, xenophytes, introduced species or transformers (Heywood, 1989; Richardson et al., 2000). These terms come from studies having different view points on the problem but in the context of this paper they should be considered as similar.

1.1 Application of RS and GIS techniques in mapping biological invasions

Remote sensing technology has received considerable interest in the field of biological invasion in the recent years. It is a tool offering well-documented advantages including a synoptic view, multispectral data, multitemporal coverage and cost effectiveness (Stoms & Estes, 1993; Soule & Kohm, 1989; Van der Meer et al., 2002). It is now widely applied on collecting and processing data. It has proved to be a practical approach to study complex geographic terrain types and diverse inaccessible ecosystems. It provides a wide range of sensor systems including aerial photographs, airborne multi-spectral scanners, satellite imagery, low and high spatial and spectral resolution and ground based spectrometer measurements.

Remote sensing technology has many attributes that would be beneficial to detecting, mapping and monitoring invaders. Spatial heterogeneity complicates the study of seasonal and long-term trends of biological invasion. Remote sensing, however, with its broad view has the potential to deliver the relevant information. Satellite imagery is available for most of the world since 1972. The multidate nature of satellite imagery permits monitoring dynamic features of landscape and thus provides a means to detect major land cover changes and quantify the rates of change.

Integrated GIS and remote sensing have already successfully been applied to map the distribution of several plant and animal species, their ecosystems, landscapes, bio-climatic conditions and factors facilitating invasions ((Stow et al., 1989, 2000; Los et al., 2002; Haltuch et al., 2000; McCormick, 1999; Rowlinson et al., 1999). An increasing number of publications (Graph 1) is dealing with the application of remote sensing and GIS in the data collection and analysis of invasive animal and plant species, their abundance, distribution, mapping, modelling and factors influencing their distribution.

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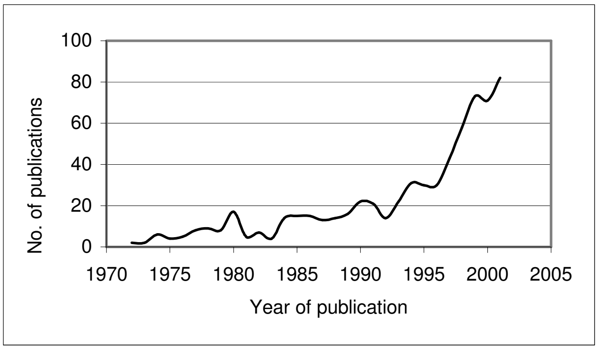


Graph 1. Publications on application of remote sensing and GIS techniques in mapping invasive species

Mapping the type and extent of bio-invasions, the impact of invasions or potential risks of invasions requires accurate assessment and modelling species distributions. So far no synoptic literature review has been published in the field of mapping invasive species. To sketch the possibilities, limitations and challenges of remote sensing techniques in mitigation of invasive species, this paper provides an overview of the application of remote sensing and GIS technologies in mapping biological invasions. We addressed the following questions.

1. What mapping techniques have been used to map and predict the potential distribution of invasive species?
2. What sensors and what image processing and classification techniques have been used to map the actual distribution of invasive species?
3. For what species groups (canopy versus non canopy members, plant versus animal species) has successful mapping been reported? Is there any evidence that the reported successful applications tend to be biased towards any particular species groups?
4. To what extent has sensitivity to scale and the reliability of the mapping product been addressed?
5. Which available mapping techniques so far not applied to invaders could be used to improve the mapping of invasive species?

We searched for articles on biological invasions using several electronic databases (AgECONCD, GEOBASE and SOILCD), covering international agricultural, economical and rural development literature, Journals, monographs, conferences, books and annual reports. We also searched other sources such as scientific abstracts, worldwide web, CD ROMs and libraries within the Netherlands. Several experts were contacted who provided additional references.

2. MAPPING ACTUAL AND POTENTIAL DISTRIBUTION

2.1 From global to local scale

At national or continental level, maps of invasive species distribution are mainly interpolations from recorded observations compiled and stored in herbaria, zoological collections and research institutes. Maps are often generated by manually drawing polygons (boundaries) around areas where the species is known to occur or alternatively using some automated interpolation procedures. For example the distribution map of *Chromolaena odorata*, one of the world's worst invaders is displayed in Figure 1. The map displays the distribution as a continuous surface. This suggests that the species occurs throughout the area represented by the map polygons. In reality, species are not homogeneously distributed across their distribution range. Instead they prevail in certain environments while they are absent from others. Maps showing discontinuous patches would more realistically represent such a distribution pattern. However, at small scale (typically < 1 to a million) we prefer to use interpolations, while realizing that they are generalizations, displaying the broad geographic range within which the species is known to occur.

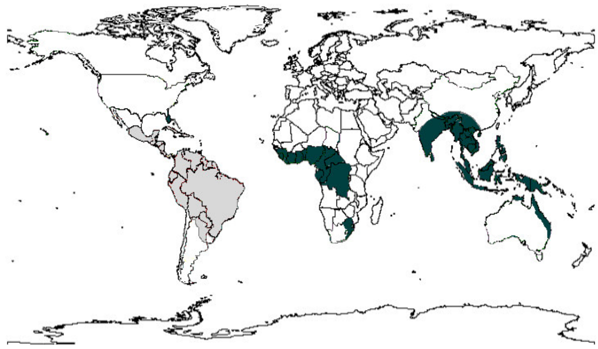
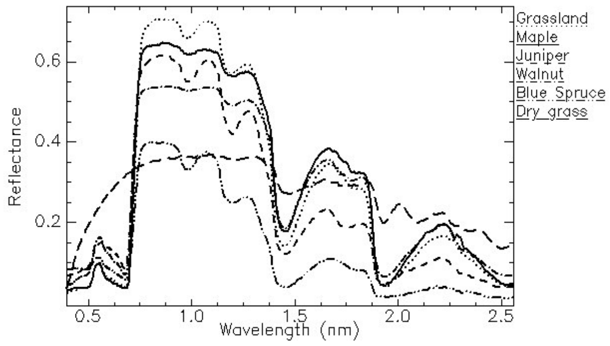


Figure 1. The world distribution of *Chromolaena odorata:* area under infestation (Black) and native range (Grey). Source: map drown by the author based on global invasive species database (ISSG, 2004)

The need to display the discontinuity and patchiness in distribution patterns emerges while moving towards larger scales. Here, it would be impractical to derive maps through interpolation, because it would require sampling every patch, a costly operation particularly when larger areas are to be mapped.

2.2 Remote sensing techniques

Remote sensing gives a synoptic view of the surface of the earth. Aerial photography is the oldest remote sensing technique (Sabins, 1987; Lillesand & Kiefer, 1994). There is a wide choice of films and spectral sensitivity (visible part of the spectrum versus those that include the infrared). Aerial photography has been used to assess vegetation and plant species attributes such as canopy architecture, vegetative density, leaf pubescence and phenological stage (Everitt et al., 2001a). Digital camera photography and videography are recently introduced as cheap, easily available and flexible alternatives to standard photography, particularly when the data are to be transferred onto a computer system. There are systems available that cover the near infrared (NIR) and infrared (IR) as well. Multispectral scanners register reflectance in a number of spectral bands throughout the visible, near- to far-infrared portions of the electromagnetic spectrum. Broad-band scanners have few spectral bands of one hundred or more nm wide. Hyperspectral scanners have more (tens up to several hundreds) but narrower (from tens to a few nm wide) spectral bands. Broad-band scanners have been successfully applied to discriminate between broad land cover types such as forest versus bare soil and built up area. The higher spectral resolution of hyperspectral scanners allows discrimination of more subtle differences such as those between individual species (Graph 2).



Graph 2. Electromagnetic spectrum and spectral reflectance profiles for different species (adopted from the spectral library of the Environment for Visualizing Images software (ENVI, 2003)

The signal noise (s/n) ratio of scanners depends on the photon flux received from the earth surface. This is influenced by atmospheric conditions. Also reductions in spectral (band width) and spatial (pixel size) resolution negatively influence this ratio. Today's SPOT HRIV and Landsat TM scanners maintain acceptable s/n ratios with pixel sizes in the range of 10 - 20 m for spectral resolutions in the order of 50 - 100 nm. A 1m resolution is obtained for panchromatic satellite imagery such as IKONOS. In order to maintain acceptable signal noise ratios for hyperspectral scanners one has the choice to either reduce flying height (airborne instead of spaceborne) or increase pixel size. Airborne hyperspectral scanners, therefore, combine high spectral and spatial resolution. Spaceborne hyperspectral scanners such as the MODIS, record high spectral resolution information at pixel sizes of 250 meters.

2.3 Classification of invasive species

The data captured by remote sensing devices will be most directly related to the properties of that canopy. We introduced a classification of species based on their remotely sensed canopy reflectance response (Figure 2). It is the canopy of an ecosystem (be it vegetation or fauna) that reflects the electro-magnetic radiation that is captured by remote sensing devices.

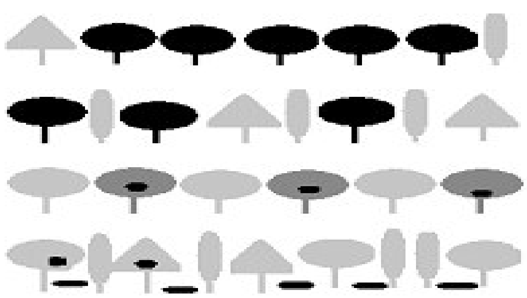


Figure 2. Application of remote sensing in detecting individual invasive species (may be an animal or plant) as represented in black colour. Class I: Canopy dominating species (top row), class II: Mixed canopy dominant species (second row), class III: Invaders influencing canopy dominant species (third row) and class IV: Understory species (bottom row)

Class I includes species dominating the canopy and forming homogeneous single species stands. Class II includes species that are members of a multi species canopy and directly reflects electro-magnetic radiation. Class III includes species not reflecting, but influencing the reflective properties of canopy members belonging in class II and I. Class IV finally includes all species that neither reflect light nor influence the reflective properties of other species in class I and II.

2.3.1 Canopy dominating species: Several invasive species dominate the canopy of the earth surface forming homogeneous single species stands that extend over larger areas. Included are a large number of tree species such as *Melaleuca quinquenervia, Miconia calvescens, Tamarix ramosissima, Acacia mearnsii*, *Ardisia elliptica, Cecropia peltata, Leucaena leucocephala, Spathodea campanulata, Ligustrum robustum, Morella faya, Pinus pinaster* and *Prosopis glandulosa*. Canopy dominance among invaders is not restricted to tree species, it also occurs in grasses (e.g. *Arundo donax*, *Spartina anglica*), floating water hyacinth (*Eichhornia crassipes*) and submerged aquatic vegetation (*Caulerpa taxifolia, Undaria pinnatifida, Oscillatoria sp.*) and among colonial animals such as zebra mussels (*Dreissena polymorpha*). Detection of invasive *Prosopis glandulosa* var. *torreyana* and *P. velutina* using TM images (Harding & Bate, 1991), *Gutierrezia sarothrae* with NOAA-10 low resolution spectral image (Peters et al., 1992), *Kalmia angustifolia (*Franklin et al., 1994), *Imperata cylindrica* with multispectral high-resolution visible (HRV) images (Thenkabail, 1999), *Carpobrotus edulis*, *Cordateria jubata*, *Foeniculum vulgare* and *Arundo donax* using high spatial resolution (~4m) AVIRIS data (Ustin et al., 2002), *Cynodon dactylon* with aerial video and colour-IR photographs (Everitt & Nixon, 1985a), *Populus tremuloides* clones using hand-held video (Stohlgren et al., 2000) are some of the examples of mapping canopy dominating species.

Several of those studies have used aerial photography, videography and multispectral scanners for identifying and mapping invasive species. Everitt et al. (2001a), who used aerial photographs to discriminate *Acacia smallii, Tamarix chinensis*, *Gutierrezia sarothrae* and *Astragalus wootonii,* noted the importance of differences in canopy architecture, vegetative density and leaf pubescence for the mapping of invasive species. Venugopal (1998) used SPOT multitemporal data to monitor the infestation of *Eichhornia crassipes (*water hyacinth) using Normalised Difference Vegetation Index (NDVI). Shepherd & Dymond (2000) presented a method for correcting AVHRR visible and near-infrared imagery which can be used in detecting indigenous forest, exotic forest, scrub, pasture and grassland. Anderson et al. (1993) mapped *Ericameria austrote*xana infestation in a large homogenous area using Landsat TM imagery. Anderson et al. (1996) found GIS and remote sensing to be a powerful combination tools that provided information about the extent and spatial dynamics of significant association of leafy spurge with drainage channels. Everitt & Nixon (1985a) applied airborne video and colour-IR photographs to detect infestation by *Acacia smallii* and *Prosopis glandulosa.* Everitt et al. (1992) applied airborne video imagery, for distinguishing *Tamarix chinensis, Ericameria austrotexana* and *Aster spinosus*. Everitt & Nixon (1985b) used a multi-video system to assess ground conditions infested with *Stemodia tomentosa, Paspalum lividum and Cynodon dactylon*.

Some of the reported invasive species dominate submerged aquatic ecosystems. For those ecosystems, remote sensing methods described so far, are limited, because little light is reflected back by submerged organisms. Budd et al. (2001) used Advanced Very High Resolution Radiometer (AVHRR) remote sensing reflectance imagery and found a significant relationship between reflectance before and after *Dreissena polymorpha* invasion. Hill et al. (1998) modeled the propagation of the green alga *Caulerpa taxifolia* and predicted the local pattern of expansion, increase of biomass and covered surfaces, and invasive behaviour. Gross et al. (1988) estimated biomass of the *Spartina alterniflora* using a hand-held fixed band radiometer configured to collect data in Landsat TM. Welch *et al.* (1988) related 13 invasive macrophytes distributions (including *Hydrilla verticillata, Potamogeton, Lemna perpusilla)* to environmental factors influencing aquatic plant growth using bathymetry and herbicide applications maps and statistical data on nutrients, dissolved oxygen, biological oxygen demand, and turbidity into a PC-based GIS. A significant change was found in the ratio of emergents to subemergents as well as the total area of aquatic macrophyts.

2.3.2 Mixed canopy dominant species: Plant characteristics such as life form, leaves, flowers etc determine reflectance. If a species is dominant enough in the canopy and characteristics can be distinguished from other species, than it is possible to detect such individual species based on spectral reflectance. The ability of high spectral and spatial resolution sensors to discriminate between invasive and native species depends on intra-specific variability in spectral reflectance. Everitt & Nixon (1985c) demonstrated that a family of spectra can represent a particular species, and invasive species are easily separated using low altitude aerial photographs or field spectrographs. They quantitatively distinguished *Heterotheca subaxillaris* from other rangeland vegetation using spectroradiometric plant canopy measurements. Everitt et al. (2001a) detected *Helianthus argophyllus,* and *Astragalus mollissimus var. earlei* using aerial photography. Menges et al. (1985) found colour IR (CIR) aerial photography to be useful for detecting *Sarcostemma cyanchoides; Parthenium hysterophorus; Sorghum halepense; Sisymbrium irio* and *Amaranthus palmeri* in different crops. Young et al. (1976) detected growth timing of *Chrysothamnus viscidiflorus* using colour photography. Abdon et al. (1998) discriminated areas with predominance of *Salvinia auriculata* and *Scirpus cubensis* using Landsat TM and HRV-SPOT digital images. Feyaerts & van Gool (2001) proposed an online system that distinguishes crop from weeds based on multispectal reflectance gathered with an imaging spectrograph.

2.3.3 Invaders influencing canopy dominant species: Numerous investigators have worked on developing techniques for using multispectral data in invasive species mapping and detection (Eav et al., 1984; Zhang et al., 2002; Medlin et al., 2000; Vrindts et al., 2002). Analysis of hyperspectral data has produced encouraging results in the discrimination of healthy and infected canopy dominant species infected by various fungus such as *Batrachochytrium dendrobatidis*, *Cryphonectria parasitica*, *Ophiostoma ulmi*, *Phytophthora cinnamomi* and *Pentalonia nigronervosa* (Banana bunchy top virus). Using habitat type, condition and soil type as the delineating parameters, Bryceson (1991) located *Chortoicetes terminifera* (Australian plague locust) by using Landsat-5 multispectral scanner data. Kharuk et al. (2001) analysed large-scale outbreak of the *Dendrolimus sibiricus* (Siberian moth) in the forests using NOAA/AVHRR imagery and found that the imagery could be used for detecting dying and dead trees. Rencz & Nemeth (1985) detected the red stage of *Dendroctonus ponderosae* (pine beetle) infestation using different ratio of multispectral scanner bands. Epp et al. (1986) were able to detect white spruce stands damaged by *Choristoneura fumiferana* infestation using an airborne pushbroom scanner and Thematic Mapper data. Using principal component and cluster analyses Zhang et al. (2002) used spectral ratio analysis based on principle component analysis and clustered analysis. They observed that the sensitive spectral wavelengths and reflectance values enabled them to discriminate *Phytophthora infestants* infection on tomatoes. Fouche (1995) identified rootrot-infested cashew nut trees, *Phytophthora cinnamomi* infestation in avocado orchards and infected citrus trees. They could be differentiated from their healthy neighbours, using low-altitude aerial colour infrared (CIR) imagery. Gebhardt (1986) used IR measurements of crop canopy temperature to detect differences in water supply and nematode infestation. Smirnov & Kotova (1994) monitored the infection by *Heterobasidion annosum* in areas with pollution levels exceeding 15 Ci/km^2 after the Chernobyl nuclear disaster in Russia. Lee (1989) applied aerial photography to detect soil-borne disease such as nematode *Rotylenchulus reniformis* on cotton, *Phymatotrichum* of cotton, *Phymatotrichum omnivorum*, and *Phymatotrichopsis omnivora* (root rot of Lucerne), *Armillaria tabescens (*root rot of pecans), *Radopholus similis* (burrowing nematode damage on citrus orchards) and citrus tree root rot infestation.

Performing spatial correlations, GIS tools often does identification of invaders influencing canopy dominant species. For example, Kazmi & Usery (2001) monitored vector-borne diseases, Bell (1995) detected grape phylloxera spread and Terry & Edwards (1989) analysed the effect of insecticides and parasites released for invasive species control.

2.3.4 Understory species: Few researchers have pointed out the possibilities of application of remote sensing in studying understory invasives. Plant species such as *Chromolaena odorata, Ulex europaeus, Clidemia hirta, Lantana camara, Mimosa pigra, Psidium cattleianum, Rubus ellipticus, Schinus terebinthifolius* and most of the invasive animal species are examples of this category. May et al. (2000) quantified remotely sensed airborne data into physical and ecological variables, obtaining an improved spatial and temporal representation of the dynamics of native and exotic plant communities.

Most of the invasive animals, lower flora, herbs, shrubs and fauna are found to be understory vegetation, making detection using direct remote sensing techniques almost impossible. Nevertheless a combination of remote sensing techniques, GIS and expert knowledge still offer potential to detect understory invasion through development of models and risk maps. These can help predicting the probability of actual and potential sites and areas where environmental conditions are susceptible to infestation.

3. MONITORING AND PREDICTION OF INVASION RISK

Predicting the probability of biological invasion and probable invaders has been a long-standing goal of ecologists. A major challenge of invasion biology lies in the development of pre and post predictive models and understanding of the invasion processes. Introduced species vary in their invasive behaviour in different regions (Krueger *et al.,* 1998). Prediction is more difficult than finding an explanation. Predicting the ecological behaviour of a species in a new environment may be effectively impossible (Williamson, 1999). The consequence of a given disturbance depends on the properties of the ecosystem or community. There is a need to evaluate disturbances not in terms of the elements of a given regime, but rather in terms of ecological effects.

Estimating animal species numbers, population size and related features is rather difficult in comparison to plants. However, Kolar & Lodge (2001) indicated clear relationships between the characteristics of releases and the species involved, and the successful establishment and spread of invaders. Allen & Kupfer (2000) developed a modified change vector analysis (CVA) using normalized multidate data from Landsat TM and examined *Adelges piceae* infestation. Mineter et al. (2000) showed that parallel software frameworks could speed up both the development and the execution of new applications. Luther et al. (1997) pointed out the importance of logistic regression techniques to develop models for predicting forest susceptibility and vulnerability and to assess the accuracy of the susceptibility and vulnerability forecasts. Using an integrated multimedia approach in the vegetation database for invasive species provides a unique way to represent geographic features and associated information on interrelationships between flora, fauna, and human activities (Hu et al., 1999). Predictions of malaria risk mapping (Kleinschmidt et al., 2000) and microbiological risk assessment for drinking water (Gale, 2001) are some examples of risk mapping and prediction that have been done in the field of biological invasions. Applications of these promising quantitative approaches in an Integrated GIS environment may allow us to predict patterns of invading species more successfully. For the monitoring and control of insect pests such as screw-worm (cattle pest), desert locust (rainfall-dependent agricultural pest) and armyworm, satellite facilities and the simultaneous use of their data could be used for a wide variety of purposes (Barrett, 1980). Crops can be regularly monitored to predict their economic yields, regional early warning for famine or pest infestation and phenological mapping of natural vegetation (Steven et al., 1992). The cost of monitoring with colour aerial photography is within the affordable range of most control programmes (Benton & Newnam, 1976).

4. ISSUES OF SPATIAL AND TEMPORAL SCALE AND ACCURACY

Scale is one of the central issues in invasion ecology. All observations depend upon the spatial scale, size of the study area investigated and resolution of the remote sensor. Habitat evaluation of a species is influenced strongly by spatial scale (Cogan 2002; Trani, 2002). There is no "correct" scale; it depends on survey purpose (Trani, 2002). The variations in the landscape patterns are scale-dependent (Rescia *et al.,* 1997). However, in most of the cases, landscape scale is used as an appropriate scale for modelling.

McCormick (1999) pointed out the importance of scale and colour infrared-photographs while mapping *Melaleuca quinquenervia*. Carson et al. (1995) found that the LANDSAT TM and SPOT data with ground resolution of 30 and 20 meters respectively, are not considered useful for mapping at species level, unless the stand of an invasive species is large enough. Multi-date imagery therefore appears to improve mapping and modelling the infestation pattern of canopy dominant species (Bren, 1992, Hessburg et al., 2000, Mast et al., 1997). Medd & Pratley (1998) assessed the relevance of precision systems for weed management. Bren (1992) examined the invasion of *Eucalyptus camaldulensis* into an extensive, natural grassland in a high flood frequency site using 45 years time series aerial photographs (taken in 1945, 1957, 1970, and 1985) extrapolated model showed the almost complete extinction of extensive grass plains. Hessburg et al. (2000) used aerial photo (from 1932 to 93) of interior northwest forests, USA and found emergent non-native herb lands. Mast et al. (1997) provided a quantitative description of the *Pinus ponderosa* tree invasion process at a landscape scale using historical aerial photography, image processing and GIS approaches. Welch *et al.* (1988) applied GIS to analyse aerial photo for monitoring the growth and distribution of 13 aquatic emergent, submergent and free-floating species. They produced vegetation maps using large scale (1:8000-1:12000 scale) color infrared aerial photographs of different years (1972, '76, '83, '84, '85).

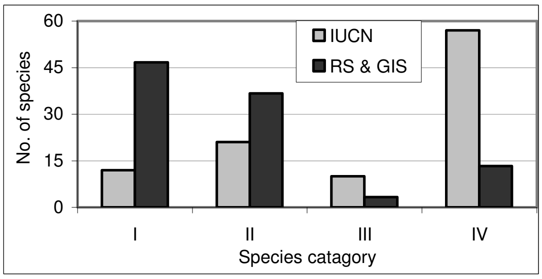
Current developments in sensor technology have the potential to enable improved accuracy in the mapping of vegetation and its productivity. Rowlinson et al. (1999) indicated that using manual techniques to identify infested riparian vegetation from 1:10,000 scale black and white aerial photographs yielded the most accurate and cost-effective results. The least accurate data sources for this purpose were aerial videography and Landsat thematic mapper (TM) satellite imagery. High spatial (less or equal to 1m) but low spectral resolution remote sensing data appeared to be useful in mapping invasive Chinese tallow trees with an accuracy of greater than 95 percent (Ramsey et al., 2002). Medlin et al. (2000) could detect infestations of *Senna obtusifolia, Ipomoea lacunosa,* and *Solanum carolinense* with at least 75% accuracy using multispectral digital images. Vrindts et al. (2002) distinguished seven weed species with a more than 97% correct classification using a limited number of wavelength band ratios. Everitt et al. (2001b) noted that *Juniperus pinchotii* had lower visible and higher near-infrared (NIR) reflectance than associated species and mixtures of species allowing a mapping accuracy of 100 percent. Lass et al. (2000) tested accuracy of detection of a homogenous population of *Centaurea solstitialis* at different spatial resolution. Their result showed a low commission and ommission errors with 0.5m spatial resolution than 4.0m. Very-high spatial resolution (0.5 m) colour infrared (CIR) digital image data from colour-infrared digital camera imagery showed potential for discriminating *Acacia* species from native fynbos vegetation, other alien vegetation and bare ground (Stow et al., 2000). In cases where different spatial resolutions resulted in equal detection accuracy, the larger spatial resolution was selected due to lower costs of acquiring and processing the data.

All these studies noted the importance of image resolution, spectral characteristics, superiority of lower scaled aerial photographs and images. It also shows clearly that for accurate mapping of invasive species it is important to take the phenological stage into account in aiming of taking the aerial photographs or images.

Although high spectral and spatial resolution provide the ability to classify canopy dominant species, precise classification of a species is still difficult. Several such studies of the spectral properties of invasive species have been derived, mostly from low altitude aerial photography or field spectrographs. However, the information reaching the remote observer will be minimum. Other factors like atmospheric noise, humidity, shadow, contribution from soil add to the confusion and the chance of discrimination of separate species low (Price 1994). Furthermore, variation in orientation of leaves, age of a leaf, variation in leaf area index, different slopes of the locations where the individuals are found could make the spectral signature of a species difficult to define. It is not however practically feasible to determine the ideal wavelengths for discrimination when large numbers of invasive species are present. Furthermore, if the presence of number of invasive species per pixel increases, the difficulty in identifying the individual components that contribute to the mixed spectrum also increases. These problems will be further aggravated if species variability in spectral signatures is high. For large scale direct remotely sensed monitoring of several invasive species, the possibility of correctly identifying all individuals through direct mapping thus appears doubtful.

5. SUMMARY AND CONCLUSIONS

In this article, we attempted to evaluate the potential of remote sensing and GIS techniques for the critical task of invasion mapping. Although the use of RS and GIS techniques for mapping invasive species and invaded ecosystems is increasing rapidly, the literature on means and methods for invasive species mapping remains scattered and often contradictory. Most of the IUCN's worst invasive species fall under our class IV species, in which straightforward application of remote sensing is almost impossible. Recent remote sensing and GIS applications on detecting invasive species were mainly dealing with species belonging to class I (Graph 3).



Graph 3. Classification of 100 world's worst invasive species included in the list of International Union for Conservation of Nature and Natural Resources (IUCN) and 100 world's invasive species addressed in GIS and RS literatures (RS & GIS)

For instance, most of the understory species that have been declared as the world's worst invaders by the ecologists have not caught the attention of remote sensing experts. In the same way species such as *Melaleuca quinquenervia* or *Tamarix ramosissima,* which dominate entire ecosystems forming a monotypic dense canopy, do not necessarily need the use of high spectral resolution imagery and vice versa. It is not clear whether RS and GIS techniques will prove equally strong for mapping mobile invasive species such as *Acridotheres tristis* (Bird), *Aedes albopictus* (mosquito) or *Boiga irregularis* (snake). This needs further testing in the near future.

The status of many exotic species with respects to their invasiveness is not well documented. Therefore the ability of remote sensing and GIS techniques to monitor changes in different ecosystems may be crucial if the effect as well as the cause of rarity are to be assessed. Cases of actual applications are still not much more than the traditional investigations. Rapidly shifting interest in remote sensing and IGIS of bio-invasion mapping has resulted in the development of a diverse range of mapping techniques. But, the technology needs further development in terms of real world applications in the mapping of invasive species. Moreover, mapping, modelling and predicting biological invasion will still be a major challenge for ecologists because the biological processes involved are very complex. This complexity makes it difficult to retrieve or delineate invasions which occur in diverse ecosystems. As Specter and Gayle (1990) pointed out the proliferation of new technologies does not guarantee their application to real world problems.

Although restricted to few taxa, studies revealed the potential of remote sensing and GIS application in mapping and modelling invasive species. Possibly, the greatest impacts of invaders are caused by plant species that come to dominate entire ecosystems as remarked by Simberloff et al. (1996). There are possibilities of generating in-depth information in detecting, mapping and analyzing the impact of invasion on an area or entire ecosystem and species level properties. To enhance the result of invasion mapping, there is a clear need of combined use of remote sensing, GIS and expert knowledge. Management dealing with invasive species requires accurate mapping and modelling techniques at relative low costs. Development of those will be a valuable step towards conservation of native biodiversity.

6. DIRECTIONS FOR FUTURE RESEARCH

The increasing number of sensors have provided spatial ecologists with tremendous opportunities to advance the application of RS and GIS techniques in mapping and modelling the distribution of invasive species. Yet progress has been slow. Application of remote sensing is strongly limited when dealing with world's worst understory plant species and most of the animal species. In our view, progress will be hastened if ecologists and remote sensing experts adopt integrated approaches to their studies of invasions, including GIS and RS techniques, modelling, meta-analysis exploration of existing concepts, and full utilization of available pre- and post invasion models to test emerging concepts. We argue that spatial, spectral and temporal image analysis holds particular promise since ecosystem boundaries can be delineated; species biometry, expert knowledge and environmental data often incorporate pre- and post-invasion phases.

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