**Temporal analysis of biological invasion by Pinus spp. in humid area of Cerrado domain**

Dhemerson Conciani¹, Yuri Silva de Souza¹, Paulo Henrique Peira Ruffino², Denise Zanchetta²

¹ Ecologist, São Paulo State University, Biosciences Institute, Department of Ecology, Rio Claro, Brazil. E-mail: dh.conciani@gmail.com (autor correspondente) ² Researcher, São Paulo State Environmental Secretariat, Instituto Florestal, Itirapina, Brazil.

Artigo recebido em 31/05/2017 e aceite em 20/03/2018

**ABSTRACT**

The Cerrado domain in Brazil currently presents only 20% of its original coverage, 8.21% of which is in protected areas. Of this total, 1% is in the state of São Paulo, on private properties or protected in conservation units. In view of these environmental conditions and the richness of this system, the Cerrado is considered one of the 25 most important terrestrial sites for conservation. Despite conservation efforts, this domain is plagued by the invasion of exotic species such as the Pinus genus. Considering the importance of life history knowledge for the mitigation of exotic species, we sought to investigate the history of invasion by Pinus in wetlands at the Ecological Station of Itirapina, SP, using near infrared reflectance (NIR) and the Normalized Difference Vegetation Index (NDVI) for the period 1985–2011. Our results showed that areas with high occupation of Pinus spp. have a higher NIR reflectance value, and that such reflectance varied over the analyzed period, as well as between the areas occupied by Pinus spp. Despite this variation, the results from the NDVI showed a linear increase in the density and biomass of this vegetation for the same period, indicating that spatial limitations do not affect the development of Pinus spp. The use of NIR and NDVI measurements together proved to be a good tool for studies aiming to understand temporal patterns of invasion.

Key-words: Conservation Units; Itirapina; Normalized Difference Vegetation Index; Near Infrared Radiation; Hotspot.

**Introduction**

Known as the second largest vegetation domain in the Brazilian territory, the Cerrado is listed as one of the 25 most important terrestrial hotspots for biodiversity conservation (Myers et al., 2000). Currently, about 20% of its original coverage remains, 8.21% of which is in protected areas. These areas, according to Da Silva and Bates (2002) and Myers et al. (2000), are responsible for preserving 1.5% of plants and 0.4% of vertebrate species.

The Cerrado’s phytophysiognomic diversity creates a mosaic of three distinct biomes and is often compared to African savannas (Durigan et al., 2007; Batalha, 2011). The ecoregion comprises tropical fields formed by a continuous herbaceous stratum and "campos limpos" (Coutinho, 1978; Woodward, 2009; Batalha, 2011); savanna formations, with predominant herbaceous vegetation and interspersed trees (Woodward, 2009; Batalha, 2011); and seasonal forests (or "cerradão") composed of large canopy trees (Woodward, 2009; Batalha, 2011). Ferreira (2003) has another understanding of the Brazilian Cerrado formation, attributing its typical landscape and phytogeographic characteristics to the diverse regional soil and to climatic relationships. In other areas, the lower or more open forms are considered a consequence of anthropogenic degradation, either by cutting, annual burning, pasture, monocultures or a combination of these activities (Eiten, 1972; Dinkel et al., 2007; Klink and Machado, 2015). Durigan et al. (2007) and Kronka et al. (2007) state that these physiognomies originally covered 14% of the state of São Paulo, but have diminished to approximately 1%. At
present, this remainder is divided into small fragments surrounded by a variety of agricultural matrices and urban land uses. These fragments suffer continuous deterioration of biodiversity due in particular to inadequate fire management and the facilitation of biological invasion by alien species (Durigan et al., 2007; Kronka et al., 2007; Klink and Machado, 2015).

The last remnants of these phytophysiognomies are found in the central region of São Paulo State, on private properties or protected in Conservation Units. The savanna physiognomies, considered the most scarce in the cerrado of São Paulo, are situated within the 2,300 hectares of the Itirapina Ecological Station, located between the municipalities of Itirapina and Brotas (PROBIO-SMA/SP, 1997; Zanchetta et al., 2006). Although it belongs to one of the more restrictive integral protection categories, this fragment is under severe pressure from the buffer zone, principally the Itirapina Experimental Station, which is undergoing extensive reforestation with exotic species of the genus Pinus, the reproductive characteristics of which confer a high potential for invasion.

The Pinus genus is considered one of the most aggressive invaders in many natural ecosystems in several countries, such as New Zealand, Australia, South Africa, Argentina and Chile, where the species establish themselves preferentially in open and humid areas (Ziller et al., 2006; Zalba et al., 2008). Invasive dispersal of Pinus, as well as that of other alien species, has a broad impact on ecosystem properties and functions, altering the interactions and trophic behavior of native environments, nutrient cycling, and energy balance in the system (Higgins and Richardson, 1998; Chen et al., 2008). An additional negative impact is the high temperatures that occur during fire events, which impede the natural regeneration of the Cerrado (D’Antonio and Vitousek, 1992; Ribeiro et al., 1998), change the richness of its natural fauna and flora communities, and change the productivity of these ecosystems (Mack et al., 2000; Hooper et al., 2005). Invasion of alien species is one of the main destabilizing factors in the ecosystems of many Conservation Units (UCs). According to estimates by Ziller (2006), invasions are recurrent in about 100 UCs across 17 states in Brazil, and Pinus spp. top the list. Few studies have suggested ways to manage these alien species, and there are almost no woody cerrado species cultivated for the purpose of recovering degraded environments (Durigan et al., 2004).

In a pioneering study on the subject, conducted by Zanchetta and Diniz (2006) at the Itirapina Ecological Station, the biological invasion and persistence of Pinus spp. was found to be associated with proximity to a seed source as well as to its preference for wetlands, where the authors found 81% more individuals than in dry areas. This result is directly related to the fact that the Experimental Station is contiguous with the Ecological Station, where there is a high density of planted forest containing Pinus spp. Despite knowledge of the factors that favor occupation by these invasive species in the Itirapina phytophysiognomies, little is known about the history of this contamination. The same authors (as well as the scientific community that studies the area) urge further research to better understand, manage and conserve open physiognomies. The Conservation Unit Management Plan prioritizes studies on the subject, aiming to produce knowledge that can inform appropriate management practices to be adopted by the Unit’s managers. The objective is to minimize the problem of invasive species and ensure the protection of biodiversity in the open Cerrado physiognomies of this important fragment.

Therefore, in this work we seek to analyze the history of invasion by Pinus spp. and the possible causes of its implantation process over time at the Itirapina Ecological Station, using orbital images of the Landsat 5 satellite for the years 1985–2011, a period of continuous activity of the Thematic Mapper (TM) sensor.

Material and methods

Study Area

The Itirapina Ecological Station is located in the interior of São Paulo State, between the municipalities of Itirapina and Brotas, and covers an area of 2,300 hectares (ha). Like the Experimental Station, the Ecological Station is under administration of the "Instituto Florestal" (Figure 1). It is characterized by open grassland physiognomies, with a prevalence of grasses, some shrubs, and an absence of woody cover except on the small fragments of "cerradão" (Zanchetta et al., 2006)
According to the management plan (Zanchetta et al., 2006), "campo úmido" physiognomy covers 675 ha of the Itirapina Ecological Station (Figure 2). Some factors beyond those under investigation may have a direct influence on the collection of orbital data at a temporal level. Therefore, following noise elimination criteria—absence of management in the sample area, nonoccurrence of fire (1985 and 2011), and proximity between areas—we selected 514 ha, representing 76% of the total area of "campo úmido" occurrence in this Conservation Unit.

**Invaded area description**

To characterize the vegetation and thus identify the patches of *Pinus* spp., we orthorectified and atmospherically corrected an image for October 2, 2016, using the "Operational Land Imager" sensor (OLI), path 220/row 75, with 30-meter spatial resolution. The images used in this paper were acquired from United States Geological Survey (USGS; http://earthexplorer.usgs.gov).

Based on the assumption that the reflectance of the target in bands 4 (red, 0.76 to 0.90 µm) and 5 (near infrared, 1.50 to 1.75 µm) is a positive function of its phytomass vigor (Du Plessis, 1999; Galvão et al., 2000; Peñuelas et al., 2001; Dong, 2003; Wessels et al., 2006; Garroute et al., 2016), these bands were used to calculate the Normalized Difference Vegetation Index (NDVI).

The NDVI is a mathematical relationship between the near infrared (NIR) and red bands and can be described by following equation (Rouse et al., 1973):

$$NDVI = \frac{\lambda_{NIR} - \lambda_{Red}}{\lambda_{NIR} + \lambda_{Red}}$$

The vegetation indexes minimize the angulations and atmospheric effects of imaging satellites in relationship with the sun, as well as the distorting effects of a heliosynchronous orbit, which is very common in temporal analysis. One of the key features of the NDVI is its low sensitivity to leaf area index (LAI) values between 2 and 3 (Prince, 1992). However, this index is adequate for Cerrado, where the average LAI is approximately 1 (Miura et al., 2003)
The NDVI output is a numerical matrix where each value corresponds to 900 m², a regular area of 30 m x 30 m (i.e. pixel). The values range from -1.0 (exposed soil, total absence of vegetation) to +1.0 (dense vegetation, with large canopy and high phytomass vigor).

We classified and compared these data to aerial images for the same date, with 20-cm spatial resolution. The NDVI classification noises were adjusted to respond to pre-identified patches of pines in the aerial images that were used to validate this classification.

To reconstruct the historical variation of the vegetation (1985–2011), we used images from Thematic Mapper sensor (TM), from Landsat 5, path 220/row 75, with 30-m spatial resolution, acquired from United States Geological Survey (USGS). We used one image per year, standardized for the month of April to minimize radiometric variations due to different climatic conditions throughout the year. We also considered the fact that April represents the start of dry season, during which cloud density is lowest and atmospheric visibility is high in the study region, increasing the possibility of a consistent time series of images.

To determine the soil occupation by invasive vegetation (Pinus spp.), we used the NIR band. In this wavelength (0.76–0.90 µm), dense vegetation presents the highest reflectance values. Sensitive to canopy roughness, the NIR band is widely used to map areas occupied by Pinus spp. and Eucalyptus spp., because they present a differentiated spectral signature in relation the native vegetation (Hunt and Rock, 1989).

To determine whether the radiometric response of the NIR band is a good indicator of soil occupation by Pinus spp., we sampled random polygons inside the "campo úmido" area and extracted the following information: i) total area of polygon, ii) relative area occupied by Pinus spp., and iii) average NIR (Figure 3). Each polygon contained different extents and proportions of invaded area. We used a polynomial model to explain the relationship between the relative area occupied by Pinus spp. (%) and the NIR reflectance, considering each polygon.

\[ \bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \]

Figure 3. Sample design. Was determined the total area of each polygon. The proportion of invaded area (%) was calculated considering the total area occupied by pine trees in each polygon, divided by total area of the polygon, and multiplied by 100. The average NIR is the sum of all pixels’ NIR reflectance, divided by total number of pixels.
The "campo úmido" vegetation is defined by grasses and a few shrubs. We assume that, relative to the wet grassland matrix (Clevers, 1989), a wider than normal variation indicates an increase in area occupied by high phytomass vegetation, specifically through invasion of Pinus spp. We used the average NIR reflectance as an indicator of the area occupied by invasive vegetation per year, and a polynomial model to explain the behavior of invasive Pinus spp. in "campo úmido" over time. We calculated the NDVI to quantify the increase in biomass and vegetation density, and we used linear models to explain the biomass accumulation in the system over time.

The elevation model was reconstructed with an SRTM product (Shuttle Radar Topographic Mission), at 30-m spatial resolution, obtained from USGS. We used the Universal Transverse Mercator (UTM) projection, zone 23S and Datum WGS84. Images were processed in ArcGis® v. 10.4.1 (ESRI, 2011). The statistical analyses were performed in open-source R® code (R Core Team, 2015) and plotted using ggplot2 package.

**Results and discussion**

**Area invaded by Pinus spp.**

The areas invaded by Pinus spp. were defined through supervised classification of NDVI and validated with aerial images at 20-cm resolution. NDVI values between 0.25 and 0.36 corresponded with the invaded areas, which covered a total of 305 ha, representing 59% of the natural "campo úmido" area analyzed in this paper (Figure 4).

![Figure 4. Classification of areas invaded by Pinus spp. in "campo úmido" at the Itirapina Ecological Station. Red color indicates invaded areas; white color shows the non-invaded areas.](image-url)

According to Zanchetta and Diniz (2006), *Pinus elliottii* is the predominant alien species at the Itirapina Ecological Station and is concentrated in "campo úmido" areas. The propagule sources include the pine reforestation that borders the Ecological and Experimental Stations, as well as three Pinus plots, two of which were removed in the 2000s (Zanchetta; Pinheiro, 2007). The authors note that the *Pinus* invasion of this open physiognomy has been successful in areas with a water surplus, due not only to the proximity of these areas to the *Pinus* plantation, but also to the high availability of water and light. Water availability at the beginning of germination and high luminosity are cited in the literature as key factors in the growth of *Pinus*, facilitating its invasive behavior and enabling its successful establishment in humid areas and open physiognomies (Durigan, 2007; Ziller, 2000; Jankoviski, 1996; Richardson; Bond, 1991).
According to Jankovski (1996), in the first year of *Pinus elliottii* growth, moisture is the limiting factor, but in subsequent years, luminosity is more important than moisture and determines the growth rate.

These physiognomies suffer the impact of anthropic activities, a scenario that is complicated by the removal of native species and an improper use of fire (Hanna et al., 1995), which enable the germination of *Pinus* seeds soon after invasion.

Percentage of area occupied by *Pinus* spp.

We found a logarithmic relationship between the percentage of area occupied by *Pinus* spp. inside "campo úmido" polygons and the NIR reflectance (Figure 5), observing a positive and direct relationship between those factors ($R^2 = 0.99$, $p \leq 0.01$). The polygons with low proportions of their area under invasion by *Pinus* spp. showed comparatively lower NIR reflectance values than the polygons with more extensive invasion. This result shows that an increase in area invaded by *Pinus* spp. also increases the surface interaction between vegetation and electromagnetic radiation, thus increasing the reflected energy. The logarithmic behavior of the NIR reflectance curve indicates possible reflectance saturation from the target; however, the good fit of the log model suggests predictability.

In a study of open physiognomies of the Lagoa do Peixe National Park, analyzing a similar time interval (1986–2011), the authors observed a sharp increment in invaded area, from 61 to 252 hectares—i.e., the area occupied by *Pinus* spp. increased by more than 153% (Portz et al., 2011).

![Figure 5. Relation between the NIR reflectance and percentage of area occupied by *Pinus* spp.](image)

Temporal density analysis of invasion by *Pinus* spp.

We validated the possibility of using NIR reflectance as an indirect measurement of area occupied by *Pinus* in an open physiognomy matrix. We applied the annual mean NIR reflectance in a polynomial model, for the period 1985–2011, to reconstruct the species’ historical occupation in "campo úmido", where the first reports of *Pinus* invasion originated.

The results presented in Figure 6 show the fit of the model for determining the NIR reflectance behavior over time ($R^2 = 0.61$, $p \leq 0.01$). From this result, we can infer that invasion occurred over a period of two decades. The colonization rate shows stagnation in the first ten years (1985–1995) and then exponential growth in the next decade (1995–2005). After 2005, the colonization rate of the invasive vegetation shows a stabilization trend, possibly limited by space depletion and intra-specific competition. The results indicate that *Pinus* spp. have a high capacity to expand their populations in humid areas over short time periods.

526
A period of decades may follow the introduction of *Pinus* spp. into a given area before a mass invasion occurs and leads to effective losses in native ecosystems (De Abreu; Durigan, 2011). Some authors have observed a period of immobility among *Pinus* spp., related to their reproductive age, which precedes their invasion and subsequent predominance. For *Pinus elliottii*, for example, this period can be 7 to 14 years (Zanchetta; Pinheiro, 2007). Regarding a decline of invasion, the most plausible hypotheses are related to a lack of space and to the limited capacity of *Pinus* species seeds and seedlings to germinate and develop in a forest containing adult individuals of the same genus. Ledgard et al. (2008) and Pena et al. (2008), reporting on early development of *Pinus* spp. in optimal matrix conditions, verified high rates of growth during the first years of invasion. After 5 years, however, the invasive population stagnated due to the production of non-viable seeds and to the low growth potential of seedlings in shaded areas. After about 7 years, the adult vegetation continued to accumulate biomass, and new viable individuals were added to the community, which returned to the initial rate of invasion. Concurrent with such intervals, some stochastic factors and particular climatic conditions have the potential to cause natural disturbances that contribute to the invasion. Among the most cited events are intense frosts and fires, the latter being more restricted to the native vegetation near the source areas of *Pinus* spp. (Brando and Durigan, 2004; Abreu and Durigan, 2011). The period corresponding to an exponential rate of invasion by *Pinus* spp. in the Itirapina Ecological Station was marked by winters with severe frosts, especially in the year 2000.

Since NIR reflectance is limited by the percentage of alien vegetation on the soil surface (Figure 5), it is a good indirect indicator of the area occupied by *Pinus* spp. in an open physiognomy matrix. However, NIR reflectance does not provide information regarding the density and total biomass of this system. For that, we used a linear model to explain the NDVI behavior over time, presented in Figure 7. This model presented a good fit ($R^2 = 0.85$, $p < 0.01$). It shows an absence of biomass accumulation during the period 1985–1995; i.e., the time interval before the explosion of the *Pinus* spp. population is characterized only by deviations from the mean, probably due to dynamics of the native vegetation and to establishment of the founders. Since 1995, there has been a significant and constant increase of biomass in this area.
Vegetation density (NDVI) by occupied area (NIR)

An important factor to consider is that, although the NIR demonstrates that the peak expansion of area occupied by *Pinus* spp. occurred over a 10-year period and tended toward stabilization, the densification of alien vegetation, as well as of the biomass stock represented by the NDVI, did not appear to be sensitive to spatial limitation and continued to increase incrementally (Figure 8). This increase is possibly a consequence of the growth and biomass accumulation of individuals already established in the area ($R^2 = 0.62, p < 0.01$). Thus, we verified that biomass accumulation through the invasion of *Pinus* spp. was not sensitive to spatial limitation, but rather maintained a constant growth (Figure 8).

Similar to the results presented in this paper, the results of Alvares et al. (2013) show a linear increase in NDVI values as a measure of biomass over time in sites of *Pinus* spp. production, as well as a high growth rate during the early development stages of *Pinus* spp., with vegetation index values varying from 0.4 to 0.6. Despite the limitations of estimating biomass using NDVI, other studies have used the technique to efficiently estimate above-ground biomass in similar contexts (Gunawardena et al., 2006; Portz et al., 2011), and it is widely recommended for monitoring the growth of species of the genus *Pinus* (Schimleck and Evans, 2004; Vicente-Serrano et al., 2011;
Portard et al., 2011). Denardi et al. (2015) suggested using EVI (Enhanced Vegetation Index) to complement NDVI analysis, because EVI optimizes the vegetation signal in high biomass conditions, whereas NDVI tends to show saturation and reduce noise generated by analyses that consider only this index.

**Conclusion**

Although not a vegetation index, near infrared reflectance (NIR 1.50–1.75 µm) was a good indicator of Pinus invasion in the open Cerrado physiognomy "campo úmido", its estimation of the percentage of occupied area serving to complement the Normalized Difference Vegetation Index (NDVI) analysis. This evaluation procedure showed that the Pinus spp. invasion in the Itirapina Ecological Station has stabilized and is not occupying new areas, though the remaining individuals continue to develop and accumulate biomass over time.

However, to understand why the invasion stabilized, the natural vegetation matrix of "campos úmido" in Itirapina Ecological Station should be maintained. Further research should be prioritized in this area and ought to include a quantification of soil chemical conditions; analyses of groundwater level dynamics, local climatic factors, and the dispersion and germination behavior of Pinus spp.; and the identification and monitoring of Pinus spp. in the vicinity.

We recommend continuous monitoring of the invasion process and the implementation of a natural heritage management program aimed at the eradication of alien woody species, which, in the case of Itirapina Ecological Station, are represented mainly by Pinus spp.

**Acknowledgments**

Thanks to the United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) for supplying the multi-spectral images used in this work; to the Secretariat of the Environment and the "Instituto Florestal" of the state of São Paulo, for financial support; and especially to the employees and researchers of the Itirapina Units, for providing access to physical and technological infrastructure.

**Reference**


De Abreu, R. C. R, Durigan, G. 2011. Changes in the plant community of a Brazilian grass land savannah after 22 years of invasion by Pinus

529
elliottii Engelm. Plant Ecology & Diversity 4, 269-278.


Ledgard, N. J., Paul, T. S. H., 2008. Vegetation...
successions over 30 years of high country grassland invasion by Pinus contorta. New Zealand Plant Protection 61, 98-104.


