"Monitoring the encroachment of Northern Argentinean grasslands by invasive species using NDVI"

Thesis

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Abstract

Grasslands are among the largest biomes on Earth and constitute the main source of feed for wildlife and domestic animals. In turn, animal husbandry in those ecosystems constitutes a major source of income for millions in many regions of the world.

The role of grasslands as suppliers of ecosystem services, i.e. conservation of biodiversity, carbon dioxide sequestration, soil nutrient and water cycling, etc., as well as their susceptibility to different processes leading to land degradation (such as bush encroachment, soil erosion, loss of nutrients, fragmentation) and the effects of climate change, are being intensively studied.

In Argentina, the livestock sector contributes to approximately 37% of national agricultural gross domestic product; most of the livestock keeping systems are based on natural and semi-natural grasslands. In the province of Corrientes, where this study was conducted, raising cattle is the most important agricultural activity and occupies approximately 50% of total provincial land.

Typically, natural grasslands in the region of study are composed of highly digestible C4 grasses as dominating species accompanied by shrubs, forbs and poor quality grasses. Nevertheless, changes in community structure have been observed and often attributed to variations in grassland management practices.

The goals of this study were to evaluate the Normalized Difference Vegetation Index (NDVI) as a tool for the assessment of encroachment in grasslands and to compare the density of *Vernonia chamaedrys* Less. within and among paddocks under different grazing intensities and fire regimes. NDVI values were obtained using a hand-held spectrometer calibrated to measure reflected radiation at wavelength intervals corresponding to bands 3 and 4 of Landsat satellites (0.63-0.69 and 0.76-0.90 µm respectively). A two stage sampling design was established in two paddocks of the research station of the National Institute for Agricultural Technology (INTA) located 20 km south of Corrientes city, and in one paddock of a nearby farm.

Enclosures had the same soil and grassland types, and no herbicides or fertilizers were applied. In both paddocks at the INTA research station, fire was applied once every three years through 2005, and prohibited thereafter. They differed only in grazing intensity,

being it kept at approximately 0,75 Livestock Units per hectare (LU/ha) in one paddock and approximately 1 LU/ha in the other. In the third enclosure recommended fires have always been applied once every two years and the stocking density has been kept at about 1 LU/ha.

A total of 28 five square meter sampling circles per paddock were randomly allocated. In each circle total number of *V. chamaedrys* plants was registered, water infiltration was measured and two soil samples (0 to 15 cm and 15 to 30 cm depth) were taken to analyze five properties (bulk density, organic matter, available phosphorus, pH and electrical conductivity). Additionally, for each circle ground cover (bare soil and standing dry material plus litter) was estimated visually.

Comparison of means by a t-Test showed that both density of *V. chamaedrys* and NDVI were significantly different among paddocks ($p<0.0001$; $\alpha = 0.05$). However variation in NDVI could not be attributed to variation in plant density, as indicated by the low determination coefficient obtained: $r^2= 0.11$.

In addition, no clear relationship was found, between plant density and soil properties. With a multiple regression analysis, the highest determination coefficient obtained was $R^2=0.60$ ($p<0.0001$; $\alpha = 0.05$) for water infiltration and pH from the top layer, in just one paddock.

Differences in soil cover and standing dry material plus litter among paddocks were also observed.

Results suggest that, for the conditions of this study even though NDVI was able to reflect changes, it was not a highly sensitive tool to identify the encroachment with *V. chamaedrys*. It is considered necessary to conduct more studies during the year to be able to detect higher contrasts in total green biomass due to weeds and grasses. Results would improve if other weed species would be taken into account and the combination of NDVI with appropriate vegetation indices would increase accuracy in those paddocks presenting high percentage of bare soil and dry biomass.

Different densities of *V. chamaedrys* may indicate that its establishment is linked to grassland management practices which would justify controlled experiments.

Development and adaptation of new technologies allowing accurate and regular monitor of changes in grasslands at farm scale would permit farmers to make proper management decisions on time and prevent further encroachment and land degradation.

Abreviations

AVHRR	Advanced Very High Resolution Radiometer
GPS	Global Positioning System
IBONE	Instituto de Botánica del Nordeste (Institute of Botanic of the Northeast)
INDEC	Instituto Nacional de Estadísticas y Censos (National Institute of Statistics and Census)
INTA	Instituto Nacional de Tecnología Agropecuaria (National Institute of Agricultural Technology)
LU/ha	Livestock Units per ha
NOAA	National Oceanic and Atmospheric Administration
USDA	United States Department of Agriculture

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1. Introduction

1.1 Background

1.1.1 Livestock keeping in the Corrientes Province

Most livestock production systems in Argentina are based on the use of natural and semi-natural grasslands which cover a significant share of the national territory. In the northeast region of the country, cattle raising is one of the most important production activities, particularly in the Province of Corrientes, where up to 50% of the total land is set aside for this purpose (Navarro Rau, 2011, pers. com.), mainly through the use of the natural grasslands that cover its territory (Fig. 1.1).

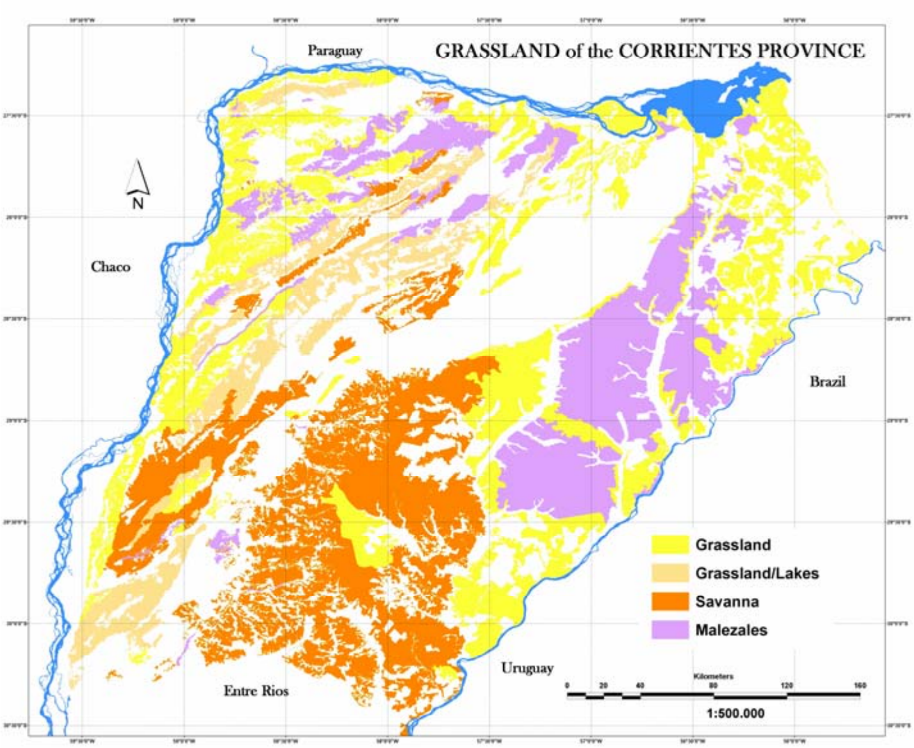

Fig. 1.1 Distribution of different grassland types within the Province of Corrientes (Navarro Rau, 2011. In press)

Due to the vast areas of natural grasslands and relative lower fertility levels of its soils (as compared to other regions of the country) that limited the development of agriculture, in the province of Corrientes livestock keeping has traditionally been the most prominent productive activity.

Introduced by Spaniards in the 16th century, it is assumed that cattle played an important role in shaping current characteristics of grasslands of the province (Carnevalli, 1994). In the beginning cattle grazed freely in open lands, and there was no strict control on reproduction. As a result, increase on total herd size was rather slow. It only reached one million heads in the mid-19th century. However, with the adoption of fencing systems (mainly the use of barbed wire) and subsequent division of paddocks plus the exploitation of natural forests, cattle population increased steadily and reached approximately 3.44 million heads by the year 1873 (Carnevalli, 1994). During the last century herd size continued growing to stabilize around 3.8 million heads by the year 1988, according to a nation-wide agricultural census conducted that year (INDEC, 1990).

However, the expansion of agriculture into the Argentinean "Pampas" and "Chaco" regions that took place in the last decade, led to a shift in traditional livestock movements among regions, and Corrientes' ranchers started to fatten the calves they produce within the province's boundaries (instead of sending them to the "Pampas", as they had done before). This resulted in 30% increase in total cattle population in Corrientes during the period 2003-2007, although currently the herd size is gradually returning to traditional levels (Calvi, 2010, Fig. 1.2).

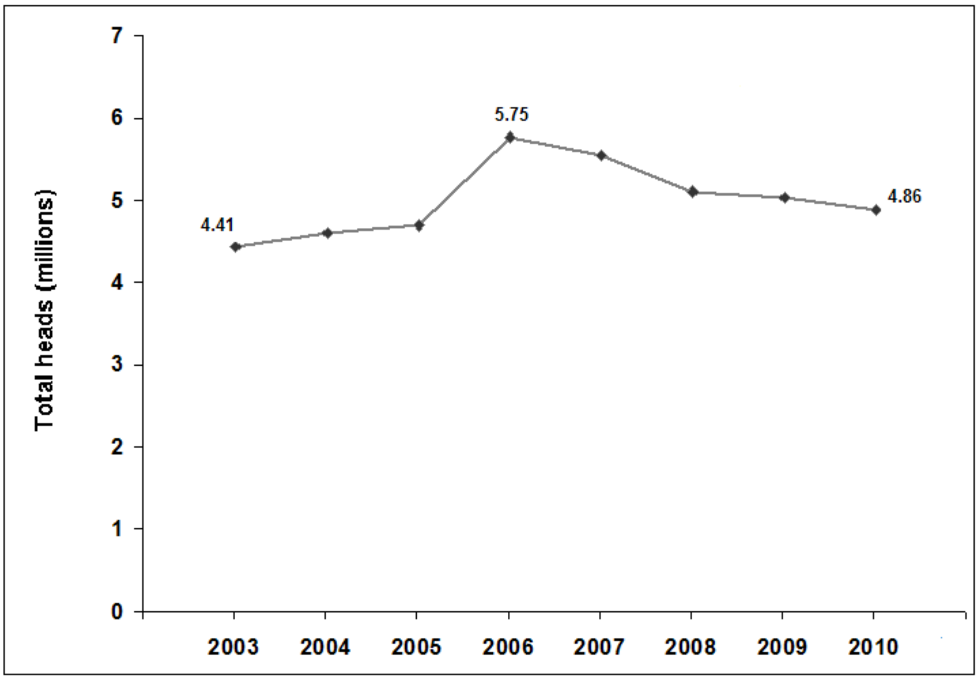

Fig. 1.2 Changes in provincial cattle herd size through the period 2003-2010 (Calvi, 2010)

Considering that Corrientes has a total area of 8.968.700 has and that grasslands occupy 50% of total land, a stock of 5.5 million heads means an averaged stocking rate of 1.22 LU/ha, which is higher than the carrying capacity calculated by Deregibus (1988) for most productive grasslands of the province (1.1 LU/ha).

1.1.2 Grassland management practices. An overview

To make the most out of their feeding resources farmers can use a variety of management techniques. These include: adoption of more intense grazing schemes (i.e. changing continuous, by rotational grazing systems); division of large paddocks into smaller plots; use of fertilizers and various weed control methods; regulation of the stocking rate (i.e. number of animal individuals per unit of land area) and the use of prescribed fires.

Regulation of stocking rate aims to fit the optimum animal density to forage availability on grasslands (White, 1987), which in turn is strongly influenced by climatic conditions, soil fertility, grasses response to grazing and ability to compete with other plant species, and management practices.

In subtropical humid and sub-humid grasslands, above ground biomass production is often limited by low winter temperatures, since grasses are susceptible to frosts. In systems based exclusively on grazing – i.e. no external forage inputs – significant decrease in steers growth rates or even weight loss during the cold season can occur (Pizzio *et al.*, 2000). Failing to adjust stocking rates could also lead to sub-optimal or over-use of forage resources i.e. overgrazing. This could result in reduced production efficiency or more severe consequences that could threaten the systems productivity in the long run such as, unfavorable changes in species composition, decrease in plant cover and increase of bare soil and susceptibility to soil erosion, reduced soil carbon and nutrients content, etc. (Kurtz and Ligier, 2008; Tessema *et al.*, 2011; Van Auken, 2000; Aguiar and Sala, 1998).

One option to anticipate and increase forage availability when conditions for higher plant growth rates are restored – i.e. late winter or beginning of spring - is the use of fire (Sacido *et al.*, 2004; Laterra *et al.*, 1998). Prescribed burning is widely used and accepted as a managing tool, since it’s inexpensive, is always available, and when used under proper conditions usually yields the expected results with no (or minimum) harmful effects in grasses. Such changes in above ground biomass availability of grasses is the result of replacing the poor quality dead plant material, which is burned, by highly digestible green shoots, as a consequence of accelerated tillering rates (Laterra *et al.*, 2003); but could also result from an opening in tall grasses canopy and litter removal, leading to changes on soil temperatures or light interception by other forage species that would promote their growth (Laterra, 1997). However, it's also been registered that prescribed burnings could eventually lead to unfavorable changes in species diversity threatening the sustainability of grasslands, even where fires are regularly applied to control bushes and suppress tree recruitment (Masocha *et al.*, 2011;Fidelis *et al.*, 2008).

These kinds of shifts often result from the introduction of species able to quickly colonize the open spaces left by action of fires, or by other species featuring fire resistant traits like the presence of underground reservoir organs and ability to re-sprout from them (Fidelis *et al.* 2008), or short life cycles and high seed production (Grime, 1977), among other possible mechanisms.

1.2 *Vernonia chamaedrys* Less., a native bush spreading throughout highlands of Northeastern Argentina.

V. chamaedrys is a perennial evergreen bush belonging to the Asteraceae family, native to provinces of the Northeastern region of Argentina and neighboring regions of bordering countries (Burkart, 1969). It is possible to find it in undisturbed as well as in regularly burned grasslands. Cattle do not feed on it. This species bears a xylopodium, which is an organ resultant of the thickening of the main root for water (Font Quer, 2001) and carbohydrates (Apezzato-Da-Glória and Cury, 2010) storage, from where rhizomes and stems grow. It flowers in summertime and produces plenty of small fruits easily spread by wind. Due to its competitive capacity, in paddocks where *V. chamaedrys* establishes, farmers usually resort to mechanical weed control methods with only short-term success, since xylopodia guarantee the regeneration of stems (the author). An overview of grasslands invaded with this species is shown in plate 1.1. Plate 1.2 shows a specimen from the herbarium of the IBONE.

Plate 1.1 Grassland from Northwest Corrientes bearing a high density of *V. chamaedrys*.

Plate 1.2 Specimen of V. chamaedrys from IBONE herbarium (National Northeast University, Corrientes, Argentina).

Scientific literature about the species is scarce. In a comprehensive literature research performed by the author, botanical descriptions plus information about its distribution, chemical composition of leaves and other aerial parts, and miscellaneous were found. Surprisingly however, despite its wide distribution in Argentina and capacity to compete with grasses, which makes farmers spend resources to control it, no scientific work relating its establishment and grassland management practices was found.

Presence of native or invasive plant species not consumed by domestic animals should be monitored, to detect significant increases in their cover and/or density and minimize negative responses on carrying capacity and economic values of grasslands (Mugasi *et al*, 2000), by making proper management decisions on time.

1.3 Using remote sensing to monitor ecosystems

Remote sensing techniques have numerous applications in different sciences. They have increasingly been used in environmental studies, such as land use/land cover classification, land degradation, estimation of aboveground net primary productivity, among others. Paruelo *et al* (2000), for instance, have found that above ground net primary production of grasslands from the Argentinean ‘Flooding pampas’ can be estimated with acceptable accuracy by means of NDVI derived from both NOAA/AVHRR and Landsat satellites; Hill et al (2004) went beyond and estimated pasture growth rate from NDVI of NOAA/AVHRR satellites and climate data for the southwest region of Australia;

High frequency on data collection, ability to sense a diversity of radiations and good to high detail of graphic display, are characteristics that make remote sensing techniques valuable tools to monitor ecosystems (Lillesand *et al.*, 2007).

1.3.1 Basic principles of remote sensing

Objects on Earth surface interact in different ways with incident radiation. Parts of it may be absorbed or transmitted, and part reflected, which depends on intrinsic characteristics of each material and the region from the electromagnetic spectrum considered. Such interaction has been studied for numerous materials and this allowed to know the reflectance of each material at different wavelengths, (i.e. the spectral signature)

(Rees, 2001). Figure 1.3 shows typical reflectance for four materials on a spectrum range of 0.4 to 2.8 μm.

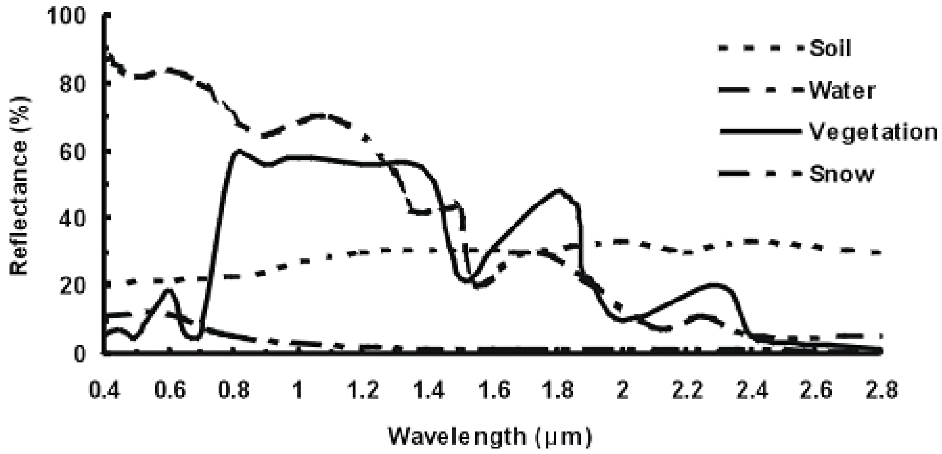

Fig. 1.3 Reflectance of four different materials on Earth surface (Richards and Jia, 1999)

Radiation reflected by objects on Earth surface can be detected by different sensors aboard satellites orbiting the planet (satellite-borne sensors), on airplanes (air-borne sensors) or by fixed sensors located on towers or hand-held devices.

Three main characteristics differentiate satellite-borne sensors: the spectral resolution is the ability of sensors to collect reflected radiation from given intervals of the light spectrum, which is an attribute fixed during the sensor assemblage; temporal resolution refers to the revisiting frequency of a satellite sensor for a specific location.; and spatial resolution, which refers to the pixel size of the image generated by sensor (Short, 2011). Those attributes will determine the possible uses for the images produced.

Data collected by sensors is transmitted to bases on earth, where it is processed to correct influence of atmosphere, georeferenced (i.e. to give the coordinates of location on earth to each pixel forming a satellite image), enhanced, among other procedures, and only then it is ready to be distributed among interested users (Lillesand, 2007).

For remote sensing of vegetation the most used wavelengths range between about 0.4 and 12 μm, which is a small part of the light spectrum (Fig. 1.4).

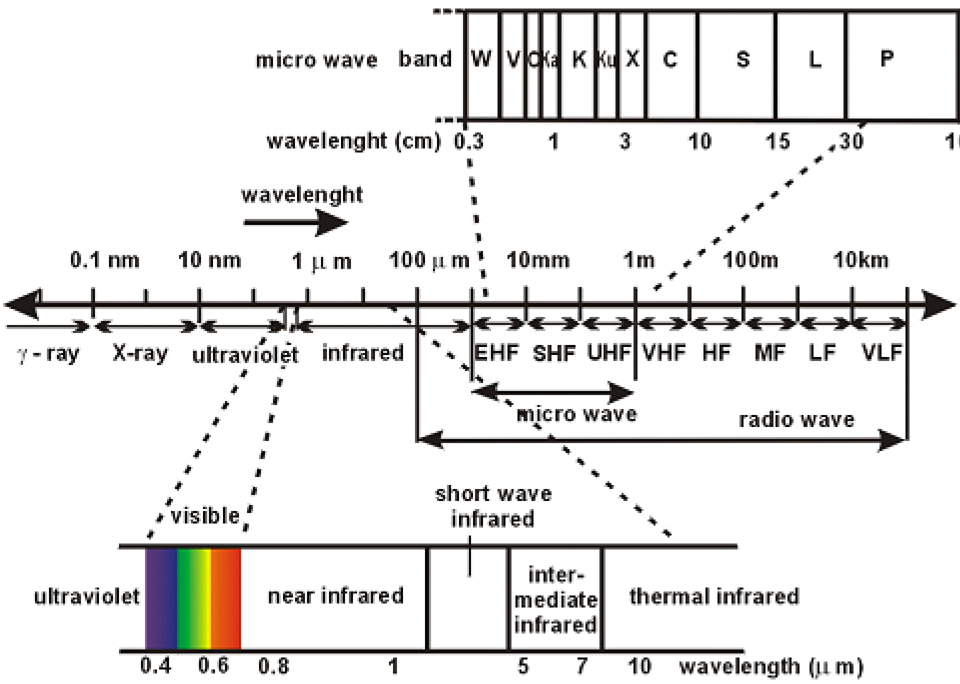

Fig. 1.4 Electromagnetic spectrum between 0.1 nm and 10 km (Rau, 2005)

1.3.2 The Normalized Difference vegetation Index (NDVI)

NDVI is one of several indices obtained by comparing the amounts of radiation of two specific wavelengths reflected by objects on the Earth's surface. It is based in the fact that chlorophylls a and b of green leaves strongly absorb radiation from the red region (with a absorption peak around 690 nm), at the time that cell walls strongly reflect and transmit light from the NIR region (about 850 nm) (Tucker, 1979).

NDVI is calculated as follows:

NDVI = (NIR – VIS)/(NIR+VIS)

Being: NIR, spectral reflectance measurement of the object in Near Infrared region;

VIS, spectral reflectance measurement of the object in Visible (red) region

NDVI can vary between 1 and -1. High positive values correspond to green vegetation, whereas senescent vegetation yields intermediate positive values (Short, 2011). This also permits to differentiate crops or pastures under stress, since the chlorophylls content can be affected (Fig. 1.5)

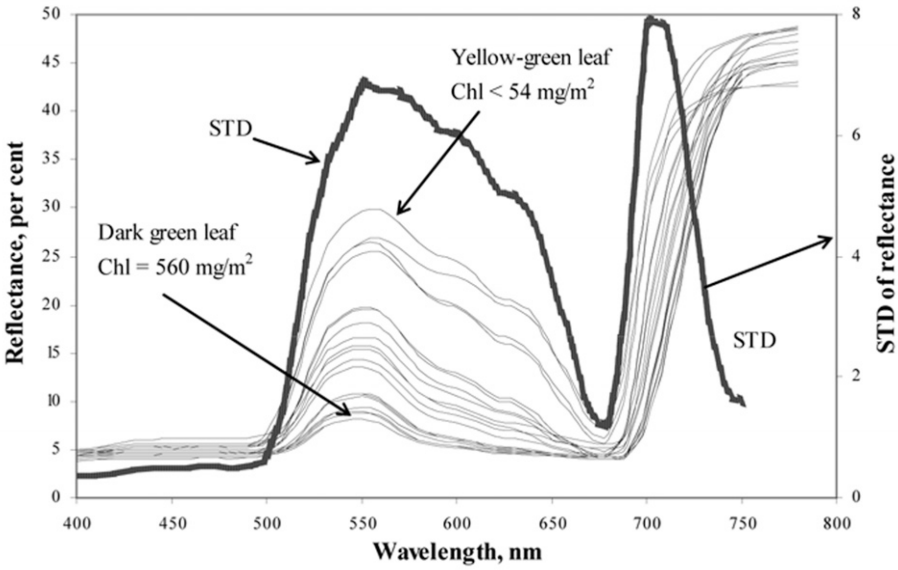

Fig. 1.5 Reflectance spectra of maize leaves and standard deviation of reflectance (Hatfield *et al,* 2010).

Furthermore, very different vegetation structures can also show varying spectrum signatures due to specific leaf anatomy characteristics, canopy structures, etc. This allows for instance to distinguish forests from savannahs, prairies, crops etc (Short, 2011).

2. Hypothesis and Objectives

2.1 Hypothesis

In all ecosystems species occurrence is determined by a balance among their bio-physical requirements, the ability of the habitat to supply such conditions and interactions with other species (Ricklefs and Miller, 2000). When equilibrium is disturbed (like in most of human interventions) depending on the intensity, duration of the disturbances and resilience of the ecosystem, the result can be the transition to a new state (Westoby *et al*., 1989) with changes in structure of the original community.

It can be expected that different grasslands canopies resulting from changes in community structures, will diverge in amounts of specific wavelength radiations reflected. In this regard it is hypothesized that diversity in community structure of grasslands from the northwest region of Corrientes Province (Argentina), product of different densities of *V. chamaedrys*, would yield different NDVI values obtained by means of a hand-held radiometer, according to the encroachment level.

2.2 Objectives

The main objective of this study was to evaluate NDVI as a tool for the study of encroachment of grasslands.

The following questions led this investigation:

1) Can the density increase of *V. chamaedrys* in semi-natural grasslands of the northwest region of Corrientes Province, Argentina, be satisfactorily monitored in situ by measurements of NDVI?
2) Is it possible to find correlations between the density of *V. chamaedrys* and different grassland management practices, i.e. changes of stocking rates or prescribed burns, to justify more intensive investigations?
3) Could the density of *V. chamaedrys* be correlated to changes in soil properties?

3. Materials and Methods

3.1 Location of the study area

Considering the purposes of this work, the study area comprises the northwest region of Corrientes Province, Argentina. However, due to its extension, logistic and lack of basic road infrastructure, the studies were concentrated in two paddocks located in the experimental station Corrientes – INTA and another paddock located in the vicinity. (Fig. 3.1)

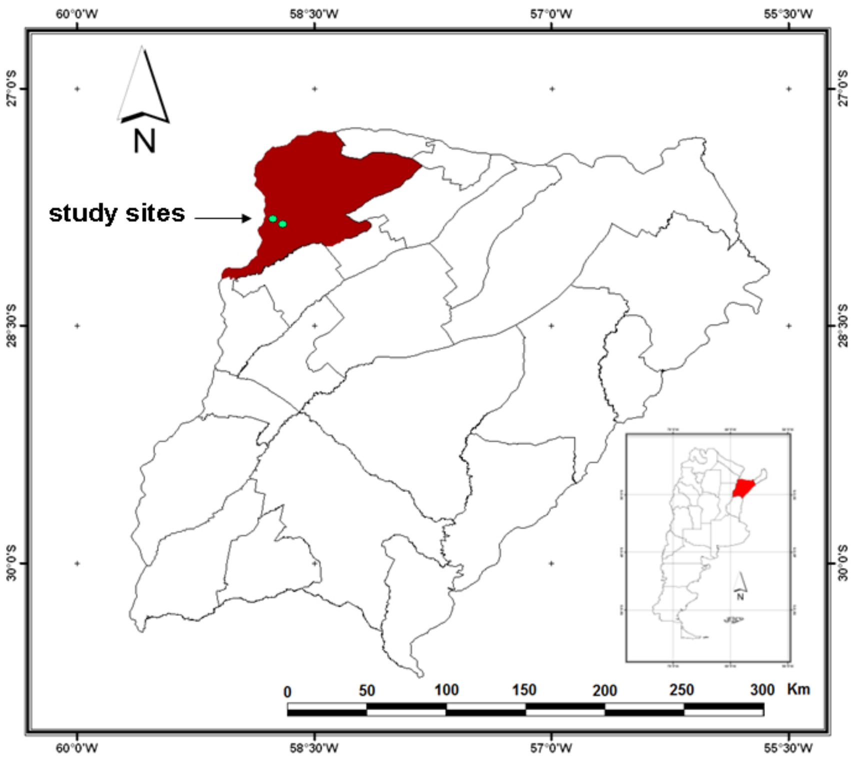

Fig. 3.1 Location of the study sites within the study area in the Province of Corrientes

3.2 Site description

3.2.1 Soils

High soil diversity, even at farm scale, is one of the main characteristics of the Province. Seven of the twelve soil orders described by USDA Soil Taxonomy are present in the province (Escobar *et al.*, 1996). Such multiplicity of soils is a result of the interaction of different parent materials and pedogenic processes that have taken place for millennia leading to the formation of mainly coarse textured acidic soils, with low fertility levels specially due to the scarce content of Phosphorus, Calcium and Magnesium. Slow drainage characterizes extensive areas of the central and northern regions due to a plain relief and gentle slopes. This often contributes to water logging of soils after heavy or repeated rain events (Escobar *et al.*, 1996).

For the purposes of this study, soil sampling and "in situ" measurements were performed exclusively in paddocks located on a representative soil series of the northwest region of the Province, which corresponds to the order Mollisols (Soil Survey Staff, 1999). The selected soil is an 'aquic argiudoll', locally known as "Serie Treviño" and comprises approximately 37500 ha (Escobar *et al.*, 1996). This soil series occupies areas of normal relief, with slopes ranging from 1 to 1,5%. Its drainage is moderate to slow and it is frequently water-logged for short periods. Compared to other soils of the region it is moderately fertile, but problems related to drainage and susceptibility to erosion constrain the diversity of crops suitable to be cultivated on it. Table 3.1 shows detailed data regarding texture and nutrient contents in a typical profile of the series.

Table 3.1 Soil series "Treviño". Typical profile characteristics (modified from Escobar *et al.*, 1996).

Horizon	Depth (cm)	Organic Mater	Clay	Silt	Sand	pH	Ca	Mg	K	Na	Interchangeable Sodium
		(%)					(mEq/100 g)				%
A1	0 - 17	1.72	11.6	21.5	66.9	5.6	3.5	2.9	0.1	0.3	3.8
A2	17 - 30	1.09	13.7	21.4	64.9	5.8	5.7	2.4	0.1	0.4	4.1
Bat	30 - 39	1.16	20	22.3	57.7	6	8.9	2.9	0.1	0.5	3.3
Bt1	39 - 66	0.9	32.6	16.1	51.3	6.3	13.9	3.9	0.2	0.8	3.6
Bt2	66 - 87	0.66	32.9	16.6	50.5	7	14.6	4	0.3	0.7	3.3
Btk	87 +	0.28	30.5	16.6	52.9	7.4	14.2	4.1	0.3	0.7	3.3

3.2.2 Climate

The climate of the study area is subtropical humid, type Cfa according to Köppen (1936) classification. Mean annual temperature is 21,6 ºC. There are only 2 to 3 frosts events per year, which usually occur between late June and late July. Total annual precipitation is 1124 mm, with above average monthly rainfall from late spring to early autumn, and below average during winter time. However, water deficits are frequent during summer time due to high evapotranspiration rates (Escobar *et al.*, 1996). Fig. 3.2 is a diagram summarizing conditions of climate in Corrientes city.

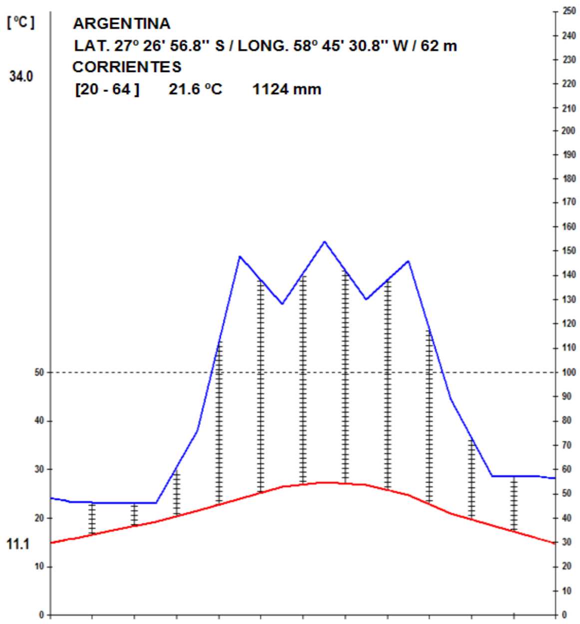

Fig. 3.2 Climate diagram for Corrientes city, Argentina (Castro et al., 1991)

3.2.3 Vegetation

Grasslands of Corrientes Province are part of the "Campos" region of South America **(**Royo Pallarés *et al*, 2005). Different grassland types featuring particular vegetation structures and species composition have developed according to each site's characteristics in terms of soil properties, relief and hydrological regimes. However, due to common climate features, most grasslands are dominated by C4 megathermic Gramienae species (Burkart, 1975) including numerous associated species from diverse families.

Carnevalli (1994) classifies the region of the study area as "Parque Chaqueño-sub distrito Correntino" and describes it as grasslands dominated by *Andropogon lateralis* Nees and *Schizachyrium paniculatum* (Kunt) Herter, including *V. chamaedrys* as the most conspicuous associated species, which is one of the reason why this study focuses on that particular species.

3.3 Sampling design

3.3.1 Site Selection

Several criteria were considered to select the study site. Taking into account the aims of this work, availability of large-scale soil maps and long-time data on grassland management practices were decisive factors for selection of farms. Paddocks that had been under continuous grazing at least over the last 15 years; with an aquic argiudoll soil in at least 50% of the area; and with presence of *V. chamaedrys*, were considered for selection.

Three paddocks satisfied those requirements: two located in INTA’s experimental station and the last one in a nearby farm. In all cases, paddocks were included in a set of enclosures used in rotational grazing systems and were been grazed at the time of survey.

3.3.1.1 Management practices applied in selected paddocks

The following is a brief description of specific management practices used in each paddock.

Paddock #1: Located in the INTA’s experimental station. Prescribed fires had been applied every three years and once a year (low fire regime) through 2005. Thereafter fires were prohibited. Mean annual stocking rate has been kept approximately at 0.75 LU/ha. In 2010 a “knife roller” was used to control weeds but no herbicide has been applied for at least the last 9 years. Total area of the paddock is 15 ha.

Paddock #2: Located in the INTA’s experimental station. Fire regime has been the same as in paddock 1. Mean annual stocking rate has been estimated in 1 LU/ha at the time of this survey. No mechanical or other method for weed control has been recently applied. It occupies an area of 30 ha.

Paddock #3: Located in a farm near to the INTA’s experimental station. Prescribed fires have regularly been applied every two years. Mean annual stocking rate has been kept in approximately 1 LU/ha. No herbicides or mechanical weed control methods have been applied in the recent years. Total area of the paddock is approximately38 ha.

3.3.2 Delimitation of sampling area

Final sampling area for each paddock was delimited with a GPS device. Forest patches, watering holes and temporary waterlogged sites and another areas, which would become detrimental for normal growth of *V. chamaedrys*, were not considered. As a result, sampling areas had irregular shapes and different final size: 7.6 ha in paddock 1, 5.2 ha in paddock 2 and 12.8 ha in paddock 3.

3.3.3 Bush survey design

To estimate the density of *V. chamaedrys* a two-stage sampling design was adopted (Elzinga et al., 1998). First, sampling area in each paddock was divided according to its final size in a particular number of macro plots of approximately 2500 m^2. Then, four macro plots were randomly selected on each paddock. After a pilot sampling, performed in 1 m^2 circles, seven 5 m^2 sampling circles within each macro plot were randomly obtained, totaling 28 sampling circles per paddock. This work was carried out using the software ESRI ArcView version 3.2. Coordinates of each sampling circle were loaded to a GPS device to locate them on the field.

3.4 Variables studied

Plate 3.1 Counting plants in one sampling circle.

3.4.1 Bush density

Total number of plants occurring in each circle was later divided by the area, to obtain the final number of plants m^{-2} (i.e. bush density) (Plate 3.1).

3.4.2 NDVI

Plate 3.2 In situ determination of NDVI

To obtain NDVI data a field radiometer, model "Skye four channel sensor SKR 1850/SS2 1106 31731" was used. The sensor was calibrated according to bands 1 to 4 of Landsat TM (0.45 to 0.90 μm) to measure reflected radiation. Due to the narrow angle of the acceptance of the reflected light sensor (25º), it was held at 2.54 m (Plate 3.2) from the ground to attain a 1 m^2 measurement area, pointing to the center of the sampling circle.

Readings were performed under clear sky

conditions, in a time frame between 10:00 a.m. and 2 p.m., once per sampling circle.

3.4.3 Soil cover

Bare soil and senesced grasses plus litter covering the ground on each 1 m^2 central circle were visually estimated and expressed as percentage of ground cover (Plate 3.3).

Plate 3.3. Soil cover at two different sites. Low aboveground biomass and bare soil (a). High aboveground biomass (b). Note the presence of individuals of *V. chamaedrys.*

3.4.4 Soil properties

The following soil attributes were studied to find out if dissimilar grassland management practices applied resulted in variations of different soil properties among paddocks and if such changes could be related to variations on the density of the studied bush.

3.4.4.1 Water infiltration

To quantify water infiltration, the single ring method was used (Bouwer, 1986). A 14 cm diameter, steel cylinder was put 10 cm vertically into the ground and a volume of 360 cm^3 of water was added. Accumulated water infiltration in one hour was determined once per sampling circle.

Plate 3.4 Measuring water infiltration.

(Plate 3.4) Measurements in all paddocks were done when soil moisture was approximately at field capacity (at least 48 hours after a rain event).

3.4.4.2 Soil properties analyzed in laboratory

Physical Properties

Bulk density: To determine this property in each central circle two undisturbed core samples were taken at two soil depths: 0 to 15 cm and 15 to 30 cm, using a steel cylinder of a known volume. Later, soil core samples were weighted, dried at air temperature during one week and weighted again. Bulk density was calculated by dividing the mass of dry soil by the volume of the cylinder.

Chemical Properties

In each sampling circle two 1 kg simple soil samples – one for 0 to 15 cm depth and other for 15 to 30 cm depth - were taken and sent to laboratory to analyze the following properties: i) Organic matter by the Walkley-Black method (Walkley,1932); ii) Plant available Phosphorus, by Bray-Kurtz method (Bray, 1945); iii) pH, measured by a Hanna HI 8424 pHmeter and iv) Electrical Conductivity, measured with a Altronix CT2 conductimeter. Last two properties were determined using a soil/distilled water ratio of 1:2,5.

3.5. Data analysis

For all variables studied, mean, standard deviation and 95% confidence intervals were calculated.

Variability of NDVI, density of *V. chamaedrys* and soil properties among paddocks, were compared using the t-Test for comparisons of means and a significance level of 0.05 (α=0.05). Assumptions for normal distribution were first checked. Only the variable "density of *V. chamaedrys*" was transformed into "square root" to fit a normal distribution before running the t-Test.

Dependence of NDVI on density of *V. chamaedrys* was tested by means of a general linear regression model for each paddock's dataset as well as for the complete dataset.

One multiple regression analysis for each paddock's dataset was performed considering soil properties studied as predictor variables and density of *V. chamaedrys* as response variable, following a “stepwise selection” procedure and using a significance level of 0.05 to add and retain predictor variables.

Statistical analyses were performed using the Infostat v. 2011e software (Di Rienzo *et al*., 2011).

4 Results

4.1 NDVI and density of *V. chamaedrys*

The analysis of both NDVI and density of *V. chamaedrys* showed significant differences among paddocks. The highest NDVI corresponded to paddock 3, which had the highest density. How ever, the lowest NDVI was obtained in paddock 1, which showed an intermediate level of encroachment. In contrast to the high variability observed on density, NDVI showed very low coefficients of variation (Table 4.1).

Table 4.1 NDVI (from central 1 m^2 circle, N= 28) and density of *V. chamaedrys*, (from 5 m^2 circles N=28) within surveyed paddocks ('a'=Mean ± 95% confidence interval; 'b'=coefficient of variation; different letters in columns indicate means are significantly different according to t-tests with *P*<0.05)

Paddock	NDVI		density (pl m^{-2})	
	a	b	a	b
1	0.60490 ± 0.00327 c	0.01394	2.94 ± 0.48 b	0.41
2	0.61280 ± 0.00329 b	0.01383	1.48 ± 0.39 c	0.66
3	0.62122 ± 0.00155 a	0.00642	4.90 ± 0.86 a	0.47

However no clear relationship was found between both variables, since the highest coefficient of determination obtained was R^2=0.11, when considering dataset of all paddocks together (Table 4.2).

Table 4.2 Parameters of simple linear regressions of NDVI on density of *V. chamaedrys* for the surveyed paddocks: adjusted coefficient of determination (R^2), intercept (a), slope (b) and standard error of estimates (s).

Paddock	Model parameters				
	R^2	a	s	b	s
1	0.1082	0.59829	0.00402	0.00225	0.00126
2	0.0694	0.60947	0.00286	0.00225	0.00162
3	0.0037	0.62174	0.00182	-0.00011	0.00034
all paddocks	0.1172	0.60807	0.00180	0.00158	0.00048

Fig. 4.1 is a scatter plot representing the complete dataset of both variables for all paddocks. It shows that in paddock 3 the variability of NDVI was more restricted than in

paddocks 1 and 2, as shown in Table 4.1 by the coefficients of variation, and that values were in a higher level in that particular paddock. It is also possible to see that for the first and second enclosures density of *V. chamaedrys* was found to be restricted to a range between 0 and approximately 6 pl m^{-2}, whereas in the last enclosure it was more widely spread (up to 10 pl m^{-2}).

Despite the low coefficient of determination obtained in the regression analysis, it can be seen that as density increased, NDVI increased as well (i.e. a positive slope of the regression line).

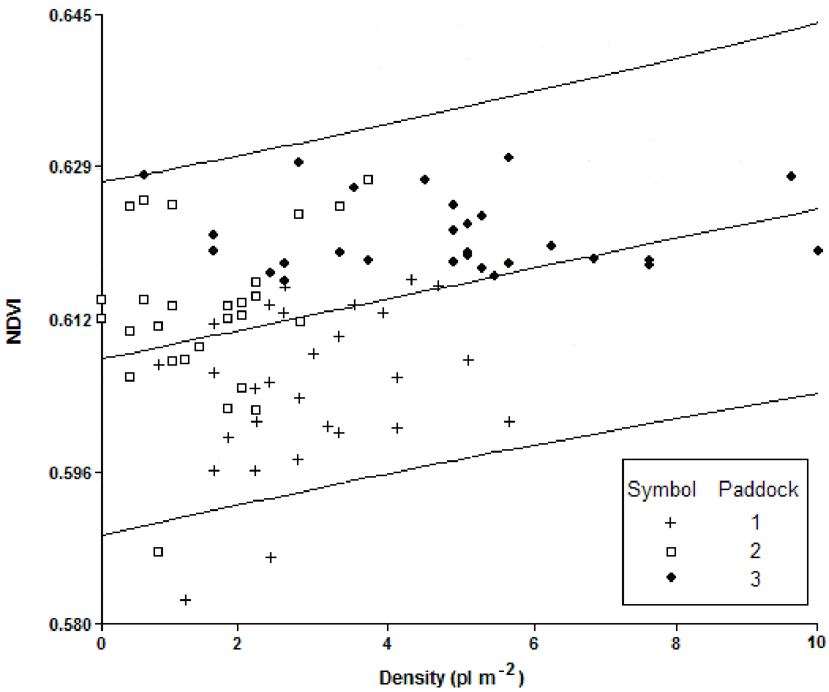

Fig. 4.1 Linear regression of NDVI on density of V. chamaedrys (central line) and 95 % confidence interval limits (upper and lower lines).

4.2 Soil cover

Bare soil (BS) as well as standing dead material plus litter (SDML) also varied among paddocks. As depicted in figure 4.2, percentage of BS was quite similar in paddocks 2 and 3, ranging from 0 to about 30% and means of about 8%, whereas in paddock 1 estimated BS reached not more than 15%, with a mean of 1% (Fig. 4.2).

Estimations of SDML in paddock 1 were the highest among enclosures, with a mean of 48% of the soil covered by senesced grasses plus litter, but reaching 90% in some sampling circles. Such high values of SDML for this paddock were mainly a consequence of the remaining litter from the mechanical weed control measure performed several months before this survey took place. In the remaining enclosures SDML was much lower, ranging from 0 to 35% and 9 to 57% (paddocks 2 and 3, respectively).

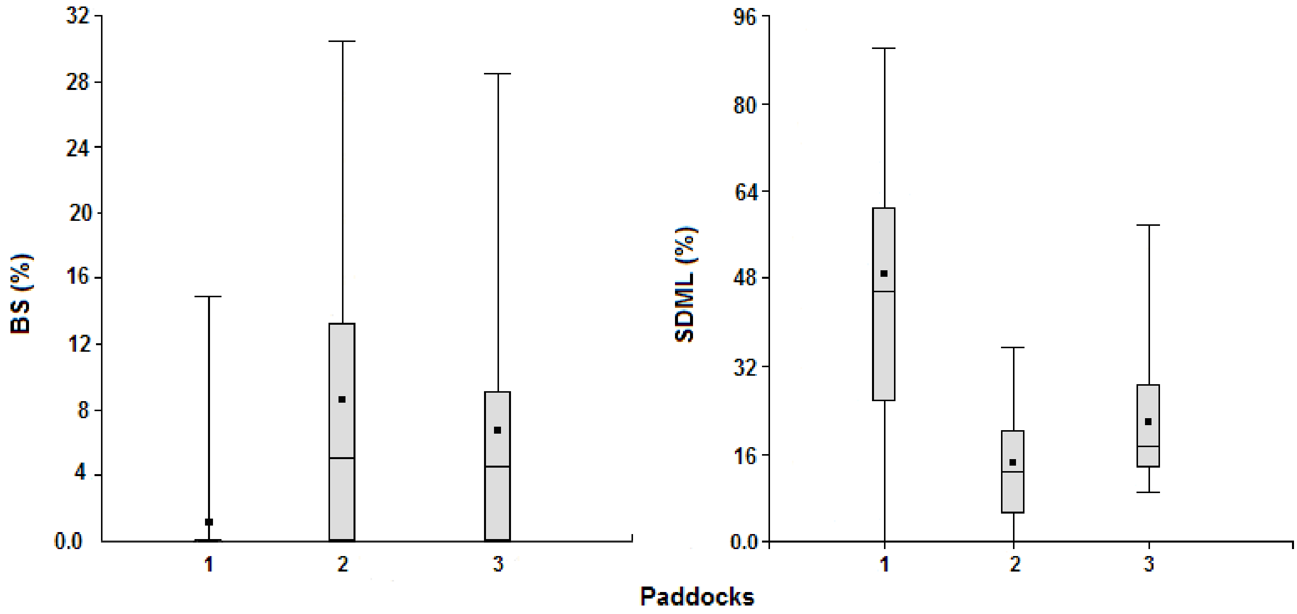

Fig. 4.2 Bare soil (BS) and Standing dead material plus litter (SDML) expressed as percentage of soil cover estimated from 1 m^2 circles (N=28) in the surveyed paddocks.

4.3 Soil properties

Most of the analyzed soil properties were significantly different among the three paddocks. As shown in Table 4.3, water infiltration was the variable that presented the highest variability within enclosures. Paddock 1 presented the highest organic matter content, pH and electrical conductivity in the top layer; bulk density and available phosphorus had the highest values in paddock 3.

In the layer from 15 to 30 cm depth the highest values for organic matter, available phosphorus and pH were found in paddock 1; bulk density in paddock 3, and electrical conductivity in paddock 2 (although difference with paddock 1 was not significant).

Table 4.3 Soil variables within paddocks ('a'=Mean ± 95 % confidence interval CI; 'b'=coefficient of variation) in 5 m^2 circles (N= 28). Different letters in rows indicate significant differences between means determined by t-tests (*P*<0.05).

	Paddocks					
	1		2		3	
Variable	a	b	a	b	a	b
Water Infiltration (mm h^{-1})	0.212 ± 0.063 a	0.77	0.091 ± 0.038 cb	1.08	0.102 ± 0.032 bc	0.82
0-15 cm depth						
Bulk density (g cm^{-3})	1.572 ± 0.017 b	0.03	1.526 ± 0.018 c	0.03	1.610 ± 0.014 a	0.02
Organic Matter (%)	2.374 ± 0.161 a	0.18	1.689 ± 0.148 c	0.23	1.840 ± 0.090 b	0.13
Available Phosphorus (ppm)	3.943 ± 0.796 cb	0.52	3.983 ± 0.660 bc	0.43	5.080 ± 0.513 a	0.26
pH	5.741 ± 0.048 a	0.02	5.439 ± 0.089 c	0.04	5.569 ± 0.035 b	0.02
Electrical Conductivity (dS m^{-1})	0.027 ± 0.005 a	0.46	0.018 ± 0.003 b	0.43	0.011 ± 0.001 c	0.32
15-30 cm depth						
Bulk density (g cm^{-3})	1.607 ± 0.021 b	0.03	1.582 ± 0.021 c	0.03	1.657 ± 0.011 a	0.02
Organic Matter (%)	1.808 ± 0.149 a	0.21	1.168 ± 0.229 cb	0.51	1.331 ± 0.058 bc	0.11
Available Phosphorus (ppm)	3.248 ± 0.905 a	0.72	2.927 ± 0.607 a	0.53	2.976 ± 0.508 a	0.44
pH	5.770 ± 0.064 a	0.03	5.607 ± 0.084 cb	0.04	5.648 ± 0.054 bc	0.02
Electrical Conductivity (dS m^{-1})	0.013 ± 0.002 ba	0.36	0.015 ± 0.003 ab	0.60	0.009 ± 0.001 c	0.19

For each paddock a multiple linear regression analysis of density of *V. chamaedrys* L. as function of the studied soil properties was performed, using the procedure for selection of variables described in materials and methods. Only one variable was retained for paddock 1, yielding a trivial coefficient of determination (R^2). For paddock 2, two variables were retained, presenting a higher but not strong R^2. No variable was retained for paddock 3 (Table 4.4).

Table 4.4 Results of multiple linear regressions of density of *V. chamaedrys* and soil properties ('y'=density of *V. chamaedrys*; **'a'=pH from 0 to 15 cm depth; 'b'=pH from 15 to 30 cm depth; 'c'=water infiltration) for the surveyed paddocks.**

Paddock	Retained variables	Model	Adjusted R^2
1	pH 15-30 cm	y = 20.52 - 3.05 a	0.13
2	pH 0-15 cm + water infiltration	y = -15.31 + 3.04 b + 2.93 c	0.60
3	no variable was retained	-	-

5. Discussion

5.1 NDVI and grasslands encroachment

Results presented in the chapter 5 (tables 2 and 5) show that in situ measurements of NDVI significant differences among paddocks, in agreement with differences in the observed encroachment levels. In a study conducted in the same region during winter time, Kurtz *et al*. (2010) found that grasslands bearing high densities of weeds yielded higher NDVI values (derived from images of Landsat 7 ETM+) than those where weeds were hardly found. Although in this study NDVI was calculated by means of a portable instrument, same results were achieved in two of the three possible comparisons (when comparing paddock 3 to paddocks 1 and 2). However, the relationship between both variables, NDVI and density of *V. chamaedrys* proved to be feeble, since at most 11.7% of variability on NDVI, considering the complete dataset, could be explained by variability of the bush density (Table 6). Such results deserve a deeper analysis which is the aim of chapter.

Even though the paddocks were located on the same grassland type, at the scale of the NDVI measurement (i.e. 1 m^2) high variability on soil cover within and among paddocks was observed (figures 4 and 5). Huete and Jackson (1987) found that senesced grass as well as weathered litter can alter the reflectance of the rangeland canopy. Additionally, Huete and Tucker (1991) pointed out that “the soil background both contributes a reflected signal apart from the vegetation and interacts with the overlying vegetation through multiple scatterings of radiant energy”, hence affecting the ratio of near infrared and visible radiations detected by sensors.

Furthermore, besides bearing the highest bush density paddock 3 presented the highest soil moisture levels at the time of measurement of NDVI (although, not significantly different from other paddocks, according to t-tests and $p<0.05$ - data not shown-), since a rainy period of more than two weeks hindered continuity of measurements. Several authors are still arguing about the importance of moisture in NDVI (Huete, **1988;** Nicholson et al., 1994; Wang et al., 2003).

In addition, as stated by Pearson and Ison (1987), low stocking rates allow a greater diet selection by animals. As a result, homogeneous grazing pressure over grasses hardly occurs. Thus, possible variations in above ground green biomass among measuring sites may have also affected NDVI.

Then, considering that in most natural and semi-natural grasslands it is habitual to find a high diversity of species as well as variability in soil cover, it seems logic to think that early detection of a significant increase in density of a native non-edible species exclusively by means of NDVI data derived from satellite images of moderate spatial resolution (20 to 30 m) would be rather difficult, at least during the growing season. However, in subtropical grasslands having 'ever-green' weeds it might be worthless testing whether NDVI yields similar values before and after frosts, since grasses would result affected by low temperatures but weeds would remain green and thus likely to be detected with NDVI. In this regard, in a study conducted during winter time in similar grasslands of the same region Kurtz *et al.* (2006) found that *V. chamaedrys* reached up to 50.7% of the total aerial biomass, whereas the main grass species summed only 28,7%.

A similar approach followed Wagenseil and Samimi (2007) to detect areas of shrub encroachment in Namibian savannahs by means of monthly variations of NDVI (derived from Landsat 7 ETM images), produced by differences in the length of the growing season of grasses and woody species. In the same way, Clinton *et al.* (2010), demonstrated that abundance of an invasive grass species in rangelands of semiarid western United States can be monitored taking into account the interaction between time series of NDVI (from the MODIS sensor) and precipitation data.

In the same way NDVI could be tested as a tool to monitor encroachment after any event that affects grasses but not weeds (fires, for instance, in the case of fire-resistant weeds).

In addition, several other vegetation indices have been proposed and some of them have successfully been used in combination with, or instead of NDVI. For instance, Liu *et al.* (2004) used the Soil-Adjusted Vegetation Index (SAVI), proposed by Huete (1988) to accurately distinguish different levels of grassland degradation in north west China by means of in situ reflectance measurements of grasslands (by means of a portable spectrometer) and NDVI and SAVI values derived from Landsat imagery. In the same way, Chen *et al.* (2011) found that the Atmospherically Resistant Vegetation Index (ARVI) proposed by Kaufman and Tanre, (1992) and the Simple Ratio Index (SRI, ratio between red and infrared reflected spectra) were the best of four algorithms they used from imagery obtained with HJ-A Chinese satellite, to map the distribution of an invasive shrub corresponding to the Asteraceae botanical family, in central Province of Guizhou (China).

Currently the development of new algorithms and the increasing availability of hyperspectral and high spatial resolution sensors are conducting to considerable improvements in studies of land degradation and biodiversity (Oldeland *et al*, 2010; Ahmed *et al*, 2011; Carter et al, 2005; Andrew and Ustin, 2008). Nevertheless, "old technology" of medium spectral and spatial resolution sensors and their products (vegetation indices) have the potential to be further developed.

In this regard, to achieve better results, future studies should consider several measurements during the year and a period of several years, to avoid possible climate variations. This work has been carried out under the effects of "El niño", with conditions that favored continuous growth of the annual grasses.

The use of a combination of vegetation indices, and precise methods of measurement of above ground biomass and soil cover, instead of visual estimations would also improve results.

5.2 Soil properties, grassland management practices and density of *V. chamaedrys*

Results of analysis of the soil properties studied will be briefly discussed, since no strong assumptions could be done due to the observational character of this study.

Despite the fact that most soil properties studied differed significantly among paddocks, no strong relationship was found among them and density of *V. chamaedrys.*

Regarding grasslands management practices, it was observed that in paddock 3, density of *V. chamaedrys* was higher than in the other paddocks. This would indicate that regular application of fires is favoring the establishment of the species. However to confirm this results exhaustive controlled experiments are required.

Regarding stocking rate, differences on density of *V. chamaedrys* was also observed. Due to different stocking rates applied in the province, it is also considered worth to test how much this management tool affects the establishment of the species.

6. Conclusions

In this study it was possible to distinguish different levels of grassland encroachment by means of NDVI derived from vegetation's reflected spectra measured on the field with a hand-held spectrometer. Nevertheless, variations on NDVI could not be attributed exclusively to changes in density of V. chamaedrys. Variability of green biomass among sampling sites, associated to presence of bare soil and senesced grass and litter, is believed to have affected NDVI as well.

Soil properties varied significantly among paddocks. However such variability was not correlated to density of *V. chamaedrys*. Different grasslands management practices allocated to paddocks might then be related to establishment of the species, which is considered worth to be investigated by means of controlled experiments, due to the species high potential to spread and compete with grasses.

More research to adapt this technology to high variability of soil cover, i.e. use of appropriate combination of vegetation indices, is needed to permit full exploitation of remote sensing advantages. This would permit to monitor grasslands regularly and with acceptable accuracy and prevent further degradation of grasslands at farm and regional scales.

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