BIOLOGICAL CONSERVATION 127 (2006) 62–71

available at www.sciencedirect.com

SCIENCE @ DIRECT®

journal homepage: www.elsevier.com/locate/biocon

Buffelgrass (*Pennisetum ciliare*) land conversion and productivity in the plains of Sonora, Mexico

Kim A. Franklin[a], *Kelly Lyons*[b], *Pamela L. Nagler*[c], *Derrick Lampkin*[d], *Edward P. Glenn*[c,*], *Francisco Molina-Freaner*[b], *Therese Markow*[a], *Alfredo R. Huete*[d]

[a]*Center for Insect Science, University of Arizona, Tucson, AZ 85726, USA*
[b]*Universidad Nacional Autonoma de Mexico, Hermosillo, Mexico*
[c]*Environmental Research Laboratory, ERLAB, University of Arizona, 2601 East Airport Drive, Tucson, AZ 857065, USA*
[d]*Department of Soil, Water and Environmental Science, Shantz Bldg. 38, Rm. 429, University of Arizona, Tucson, AZ 85726, USA*

ARTICLE INFO

Article history:
Received 29 July 2004
Received in revised form 3 July 2005
Accepted 21 July 2005
Available online 19 September 2005

Keywords:
Invasive plants
Rangeland productivity
Land conversion
Remote sensing
Desertification

ABSTRACT

Bufflelgrass (*Pennisetum ciliare* syn. *Cenchrus ciliaris*) is an African grass that has been widely introduced in subtropical arid regions of the world to improve rangelands for cattle production. However, it can have a negative effect on the diversity of native plant communities. Buffelgrass was introduced to Sonora, Mexico in the 1970s as a means to bolster the cattle industry. “Desmonte,” the process by which native desert vegetation is removed in preparation for buffelgrass seeding, alters the land surface such that buffelgrass plots are easily detectable from aerial and Landsat satellite images. We estimated the extent of conversion to buffelgrass in a 1,850,000 ha area centered on Hermosillo, from MSS and TM images from 1973, 1983, 1990 and 2000. We then compared the relative above-ground productivity of buffelgrass to native vegetation using Normalized Difference Vegetation Index values (NDVI) from Landsat and Moderate Resolution Imaging Spectrometer (MODIS) satellite sensor systems. Buffelgrass pastures have increased from just 7700 ha in 1973 to over 140,000 ha in 2000. Buffelgrass pastures now cover 8% of the land surface in the study area. Buffelgrass pastures have lower net primary productivity, estimated by MODIS NDVI values, than unconverted desert land. The desmonte process removes trees and shrubs, while the buffelgrass plantings are often sparse, leading to an apparent net loss in net primary production from land conversion. We recommend that the desmonte process be discontinued until its efficacy and safety for native ecosystems can be established, and that a comprehensive plan for preserving biodiversity while accomodating economic development be established for this region of the Sonoran Desert in Mexico.

1. Introduction

Human alteration of the Earth’s land surface is occurring at increasing rates in tropical and subtropical regions (Lambin et al., 2003). Current rates of land conversion to agriculture and pastures have been recognized as major threats to biological diversity (Sala et al., 2000) and major disrupters of ecosystem functions (Vitousek et al., 1997). Extensive tracts of desert scrub, thorn scrub and tropical deciduous forest in Mexico have been converted to exotic grassland to facilitate higher cattle stocking rates (Masera et al., 1997; Burquez-Montijo et al., 2002). Buffelgrass (*Pennisetum ciliare*, syn. *Cenchrus ciliaris*),

* *Corresponding author*: Tel.: +1 520 626 2664.
E-mail address: eglenn@ag.arizona.edu (E.P. Glenn).
0006-3207/$ - see front matter
doi:10.1016/j.biocon.2005.07.018

a perennial cespitose, C-4 grass native to Africa, was first introduced to Mexico in the early 1950s but large-scale planting began in the 1970s with subsidies from the State of Sonora (Cox et al., 1988b; Ibarra-Flores et al., 1995, 1999; Vazquez-Leon and Liverman, 2004). Buffelgrass grows and persists well in desert habitats due to the species' ability to respond with vigorous growth to erratic rainfall events and its tolerance of drought and grazing. It is considered a high-value forage plant (Ramirez, 1999; Ramirez et al., 2001; Sanderson et al., 1999).

Unfortunately, buffelgrass is known to reduce native plant diversity and interfere with natural ecosystem functions in other parts of the world (Fairfax and Fensham, 2000; Franks, 2002; McIvor, 2003). In northern Mexico, its use has resulted in direct and indirect negative impacts on biotic communities (Burquez-Montijo et al., 2002; Johnson and Navarro, 1992), the sustainability of buffelgrass lands is in question (Castellanos et al., 2002). The introduction of buffelgrass into Sonora, Mexico involved major modifications of natural vegetation (Yetman and Burquez, 1998). Generally, clearing of existing vegetation by chain or bulldozer, a process called "desmonte", precedes seeding of buffelgrass and results in habitat homogenization (Johnson and Navarro, 1992). In the Sonoran Desert buffelgrass readily spreads into adjacent habitats (Cox et al., 1988b; Burguess et al., 1991; Burquez-Montijo et al., 2002) and appears to be facilitated by disturbance (K. Lyons, pers. Obs.). As a consequence of its spread into adjacent areas, buffelgrass is now a dominant or subdominant species of roadside shoulders and city lots (Burquez-Montijo et al., 2002). It has also spread into unconverted desert land, riparian corridors and hillsides, but the extent of infestation in these habitats and effects on ecosystem functioning have not been well documented.

African grasses are known to modify fire regimes in colonized areas (Freifelder et al., 1998; Rossiter et al., 2003). Buffelgrass has made a major impact through alteration of fire regimes in the Sonoran desert (Cox et al., 1988a; Martin et al., 1999). Fire has in the past been a highly localized phenomenon on the desert floor, limited by a lack of fuel between tree–shrub complexes and cacti. Buffelgrass closes these gaps causing continuous, long-lived fires that threaten native woody species that are not adapted to fire disturbance (McLaughlin and Bowers, 1982; Burquez-Montijo et al., 2002). Both active and indirect alteration of the Plains of Sonora to a buffelgrass dominated system has and is likely to continue to have substantial impacts on native species persistence.

Several estimates suggest that very large tracts of desert scrub and thorn scrub have been converted from native range to buffelgrass pastures in Sonora, through bulldozing and seeding (Burquez-Montijo et al., 2002; Johnson and Navarro, 1992; Castellanos et al., 2002; Vazquez-Leon and Liverman, 2004). However, government statistics on buffelgrass conversion are considered inaccurate, as many cleared areas are larger than officially granted, and many are converted illegally, especially in the newly privatized ejido lands (Yetman and Burquez, 1998; Burquez-Montijo et al., 2002). Masera et al. (1997) concluded that reliable data on the extent of conversion of desert scrub to pasture land in Mexico were lacking.

The rationale for planting buffelgrass is that it increases the carrying capacity of the range for cattle (Martin-R et al., 1995). However, there has been limited research on the productivity of buffelgrass used as forage in the Sonoran Desert. Values for annual forage yields reported from around the globe vary widely, from less than 1000 (Rao et al., 1996) to values near 9000 $kg\,ha^{-1}\,yr^{-1}$ for pastures under intense management (Gonzalez and Dodd, 1979). The variability in these figures reflects that productivity and therefore success as a forage grass is highly dependent on meteorological, edaphic and ecological factors. In our study area, Martin-R et al. (1995) reported productivity rates of 7000 $kg\,ha^{-1}\,yr^{-1}$ for dense stands of buffelgrass excluded from grazing in an experimental farm north of Hermosillo. They extrapolated from this data to conclude that buffelgrass pastures in Sonora were 2–3 times more productive than native range grasses.

These and similar estimates made under experimental range conditions (e.g., CIPES, 1989), are the basis on which large-scale buffelgrass planting has been recommended to ranchers by the State of Sonora (Johnson and Navarro, 1992). On the other hand, productivity under ideal conditions does not necessarily reflect what happens under the heavy grazing pressure typical of Sonora (Lopez, 1992). Castellanos et al. (2002) and Yetman and Burquez (1998) reported that many buffelgrass plantings fail in Sonora.

Our first objective was to increase the accuracy of the estimate of the extent of buffelgrass land conversion in the Plains of Sonora using ground, aerial, and satellite methods. Due to concomitant bulldozing and fencing that accompanies buffelgrass planting, desert shrubland that has been converted to grassland is relatively easily identified through aerial photography and satellite imagery. Our second objective was to compare relative primary productivity of buffelgrass pastures with native rangeland and other vegetation associations using satellite imagery. We used the Normalized Difference Vegetation Index (NDVI) from the Enhanced Thematic Mapper (ETM+) and the Moderate Resolution Imaging Spectrometer (MODIS) satellite sensors on the Terra satellite to compare relative values of foliage density of different plant associations.

2. Materials and methods

2.1. Study area

The study area is in the center of the Plains of Sonora subdivision of the Sonoran Desert (center coordinates: Lat: 29°02′46″N; Long: 110°51′28″W) (Fig. 1). We selected an 1,850,000 ha study area centered around the city of Hermosillo for analysis. This region of the Sonoran Desert has been subjected to the most extensive conversion of native desert-scrub vegetation to buffelgrass grasslands. Native vegetation includes a variety of legume trees, most abundantly *Olneya tesota*, *Cercidium microphyllum* and *Prosopis glandulosa* whereas *Encelia farinosa* is the dominant shrub (Shreve, 1964). This area has been extensively grazed, both before and after the introduction of buffelgrass (Lopez, 1992). Hills and low mountain ranges (to 1000 m) generally running in a north-south direction break up the broad valley floor (ca. 200–500 m elevation). Hillsides and desert floor plant communities, compared in this study, are similar in vegetation composition (Turner and

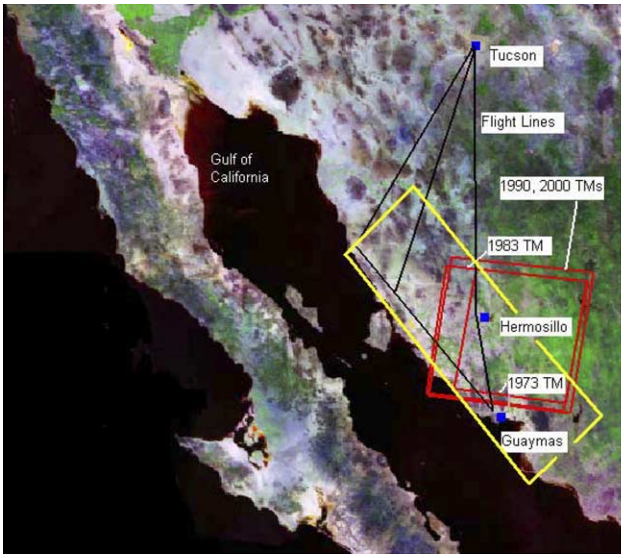


Fig. 1 – Location of Thematic Mapper images and flight lines for survey of buffelgrass in Sonora, Mexico. The yellow rectangle encloses the area identified by Burquez-Montijo et al. (2002) as having the highest density of buffelgrass plantings on the Plains of Sonora.

Brown, 1982), but the hillsides are more heavily vegetated as they are more lightly grazed. Buffelgrass has spread extensively into both unconverted desert and hillside plant communities (Burquez-Montijo et al., 2002).

2.2. *Aerial and ground surveys*

Aerial surveys of central Sonora were conducted in May through July 2003, in a light aircraft flown at altitudes varying from 300 to 3000 m above ground level (AGL). The flight lines are illustrated in Fig. 1. Buffelgrass pastures were clearly visible on the ground at these altitudes. They take the form of irregular polygons bounded by fences or perimeter roads, with altered land cover inside compared to unaltered desert range. Trees are usually absent, or nearly so. These broad-scale aerial surveys were not quantitative, but allowed us to develop a qualitative picture of the general extent of buffelgrass land conversion and of the different types of buffelgrass pastures that have been developed.

In July 2003 we took aerial photographs at 16 point locations at 300 m AGL that were selected from a ground survey the day before as representing typical grazed desert and converted buffelgrass sites in the study area. These were along Highway 15 from Hermosillo to Benjamin Hill, and included nine areas of unconverted desert and seven areas of grazed buffelgrass pastures on working ranches. During the ground survey we also observed the desmonte process by which buffelgrass pastures are created. To obtain aerial photographs (ca. 70 m × 100 m field of view, 0.5 m resolution), the aircraft was banked so that each site was photographed, as much as possible, from a vertical angle. The aerial photographs were georeferenced to ground survey locations by using hand-held GPS units on the ground and in the airplane, and by reference to land features such as roads and field boundaries. They were also georeferenced to the Year 2000 ETM+ image. Each photograph was quantified with respect to percent cover of soil, grass, shrubs, and trees. To accomplish this, photographs were imported into Adobe Photoshop software, and a 100 point grid was placed over the photograph, then the landcover class at each intersection was scored (Nagler et al., 2005). Trees and shrubs had distinct green canopies, whereas grass cover was either green or brown (dormant), but could be distinguished from bare soil, which was generally light colored. Canopies >2.5 m in diameter were scored as trees, whereas smaller canopies were scored as shrubs.

2.3. *Satellite imagery and analysis*

We obtained Landsat scenes (Path 35 Row 40) for this region of the Sonoran Desert from the following time periods: April 1973; April 1983, August 1990, and September 2000. The 1973 and 1983 images were from the Landsat 3 satellite and utilized the MSS sensor system, with original resolution of 90 m, resampled to 60 m. The 1990 (Landsat 5) and 2000 (Enhanced Thematic Mapper, ETM+) images utilized the Thematic Mapper sensor system and had 30 m resolution. The 1973–1990 images were obtained from an archived source (ARIA, Department of Arid Land Studies, University of Arizona, Tucson, AZ), whereas the 2000 image was purchased from EarthSat, Inc. It was chosen from a series of dates from 2000 to 2002 to represent the maximum "greening" period following summer rains. For this image, pixel values were converted from digital numbers to exoatmospheric reflectance values by EarthSat, Inc., based on sensor gain values and sun angle at the time of acquisition. Our study area covered 1,840,000 ha roughly centered on the city of Hermosillo; we quantified the extent of conversion of desert rangeland to buffelgrass pastures within this area. This same approximate coverage was available on the 1990 and 1983 images but the 1973 image was missing a portion of the full scene, reducing the study area by 25% in this year.

We used the 16 sample sites surveyed on the ground and photographed from the air as training sites for interpreting satellite images. Using visual interpretation, we were able to distinguish three basic land classes with respect to buffelgrass. The first type was unconverted desert land. These areas were generally unfenced and had dense vegetation in the arroyos (channels carved by water during monsoons), visible as false-color red (near infrared reflectance) on Landsat images. By contrast, areas converted to buffelgrass by bulldozing were visible on satellite images as irregularly shaped polygons of a lighter shade than the surrounding area. The polygons were defined by fencelines or perimeter roads, and the lighter soil color was due to the fact that the soil was disked or bulldozed prior to planting buffelgrass seed, to remove native vegetation and create a seedbed. Bulldozing homogenized the soil and disrupted the normal darker-colored soil crust present in the native desert. Natural land features such as arroyos were reduced in prominence, as bulldozing was generally conducted over the entire fenced area. Two types of buffelgrass pastures were noted; those with or without the stripping pattern, produced by windrows of dense brush.

Our accuracy in interpreting the 2000 ETM+ image was assessed by comparing the locations of known buffelgrass pastures or unconverted desert land to our scoring of those sites based on examination of the satellite image. We tested our ability to distinguish between non-buffelgrass desert range and buffelgrass pasture at 36 test sites that had been surveyed on the ground by one of us (K. Lyons). The 21 sites that had been converted to buffelgrass by bulldozing were all identified correctly on the satellite image. We also correctly scored the 15 unconverted desert sites. However, six of the unconverted desert sites actually contained dense stands of buffelgrass that had either established as volunteers or were seeded into the desert sites without bulldozing. Hence, our estimates capture areas that had been fenced and bulldozed to plant buffelgrass, but they do not provide an estimate of the actual extent of buffelgrass cover over the landscape. As noted by others, buffelgrass has spread widely into adjacent ecosystems (Burquez-Montijo et al., 2002).

We used the normalized difference vegetation index (NDVI) to compare relative values of buffelgrass range versus native range and other land cover classes, where

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red}). \quad (1)$$

NIR is the near infrared band (ca. 800 nm) while Red is the visible red band (ca. 600 nm) of the TM and MODIS satelliteborne sensors. NDVI values range from −1 to +1 and can be used to distinguish between water, bare soil, and vegetation. Water reflects Red but strongly absorbs NIR, hence NDVI values for water are negative (Jensen, 2000). Soils generally reflect NIR slightly more than Red, hence NDVI values are around 0.2. Chlorophyll in green vegetation strongly absorbs Red but the leaves reflect NIR, hence NDVI values are up to 0.8, depending on chlorophyll content of the leaves and the leaf area index of the plant.

NDVI values were calculated for each buffelgrass pasture ($n = 74$) on the 2000 scene. Adjacent to each buffelgrass pasture we selected an area (500 ha) of similar topography but not exhibiting signs of buffelgrass conversion and we recorded the NDVI of this adjacent patch of land as well. In addition, we compared the NDVIs of bare soil, hillside vegetation, riparian vegetation and roadside buffelgrass pastures on areas selected on the ETM+ image ($n = 10$–20 per land cover class).

We documented the temporal response of buffelgrass and other land cover types to rainfall using the Moderate Resolution Imaging Spectrometer (MODIS) sensor system (resolution = 250 m for the Red and NIR bands) on the Terra satellite (Huete et al., 2002). We obtained these processed, 16-day composite NDVI images from the EROS Data Center (Sioux Falls, South Dakota). We selected seven buffelgrass pastures and four areas of adjacent desert for comparison (three of the desert areas were between selected buffelgrass pastures and served as controls for both). The buffelgrass pastures were selected from among the polygons mapped on the ETM+ image as typical in terms of appearance and NDVI (close to the mean value for all buffelgrass pastures). We selected flat sites that were homogeneous over at least 1 km^2 area, to ensure that the MODIS pixel did not sample mixed scenes. We also included hillside vegetation for comparison. We compared 16-day, composite NDVI values from MODIS to rainfall data from Hermosillo over four growing seasons, 2000–2003.

2.4. *Productivity estimates*

We were not able to conduct ground experiment to directly calibrate our NDVI measurements to pasture productivity. However, Hill et al. (1998, 2004) correlated pasture growth rate (PGR) measured on the gorund with 14-day, time-series NDVI images collected by the Advanced Very High Resolution Radiometer (AVHRR) satellite sensor system over southwestern Australia, and we applied their model to our study site. The pastures in Hill et al. (2004) are grazed, mixed shrub and grass land with approximately 500 cm of annual rainfall, of which 73% falls in winter. The pasture grows in a distinct, 5–7 month seasonal pattern over late summer, fall and winter, similar to buffelgrass in Sonora (see Fig. 4).

Their NDVI values ranged from approximately 0.2 at the start of the growing season to 0.7 at the peak, and their mean PGR values averaged approximately 6900 kg ha^{-1} yr^{-1} (range = 4209–7700 kg ha^{-1} yr^{-1}) over their study. Their range of NDVI values was similar to those in our study (see Section 3) and their maximum PGR was similar to the value obtained by Martin-R et al. (1995) for buffelgrass over three years (1985–1987) at an experimental (ungrazed) plot within our study area, 82 km north of Hermosillo. Hence, potential productivity values and seasonal growth patterns of the two pasture types are similar. Furthermore, MODIS and AVHRR NDVI values have been intercalibrated, so they can be compared among studies (Gallo et al., 2004). Therefore, we applied the relationship between NDVI and PGR in their study to our results. We regressed their measured values of mean annual PGR against their measured values of NDVI for each year and location ($n = 11$) and obtained the following equation:

$$\mathrm{PGR} = 20,290(\mathrm{NDVI} - 0.2), \quad (2)$$

where PGR is in kg ha^{-1} yr^{-1} of dry matter and NDVI is the mean value over the growing season and 0.2 is dormant-season NDVI, which was the same in both Australian and Sonoran pastures. The coefficient of determination for the equation was 0.87 ($P < 0.001$) when the equation was constrained to pass through the origin (PGR = 0 when NDVI = 0.2).

2.5. *Statistical methods*

NDVI values of different land cover classes were compared by one-way Analysis of Variance and correlation coefficients between rainfall and MODIS values were calculated by the least squares method (Snedecor and Cochran, 1989).

3. Results

3.1. *Ground and aerial surveys*

In ground surveys, we observed two types of land preparation for creating buffelgrass pastures, and these could be distinguished from each other on aerial photographs and TM satellite images. In some fields, trees, cacti, and shrubs are first removed by dragging a chain over the land, and raking the debris into windrows at intervals of approximately 100 m. Then a bulldozer with a ripper bar rips the soil at 1 m intervals to a depth of 1 m, and buffelgrass seed is broadcast from a seed hopper behind the bulldozer. Ripping and seeding is timed to coincide with the onset of summer rains in July. The windrows are visible on aerial and satellite images, and the land between windrows appears to be largely denuded of vegetation. In some fields, the chaining step is omitted, and only bulldozing and seeding is conducted (D. Yetman, University of Arizona, personal communication). The bulldozer goes around many of the trees rather than removing them. These fields tend to retain more native vegetation than those that receive the full desmonte process. In other fields, the windrowed brush from the original desmonte event was burned to make charcoal, which was removed, and the fields have been bulldozed and replanted several times since the original clearance; these also lack windrows.

Over a hundred buffelgrass pastures were observed in the aerial surveys over Sonora. In general, the low mountain and hill terrain that divides up the valleys has not been converted to buffelgrass. Although buffelgrass pastures extend to the coast, where they tend to be placed in riparian corridors, they are most numerous in the central valley extending from Ciudad Obregon to Hermosillo then north to Magdelena, where rainfall is higher than on the coast. As shown in Fig. 2, many of the pasture borders overlap, showing that the same piece of land has been subjected to the desmonte process several times. Along Highway 15, where we quantified the land cover

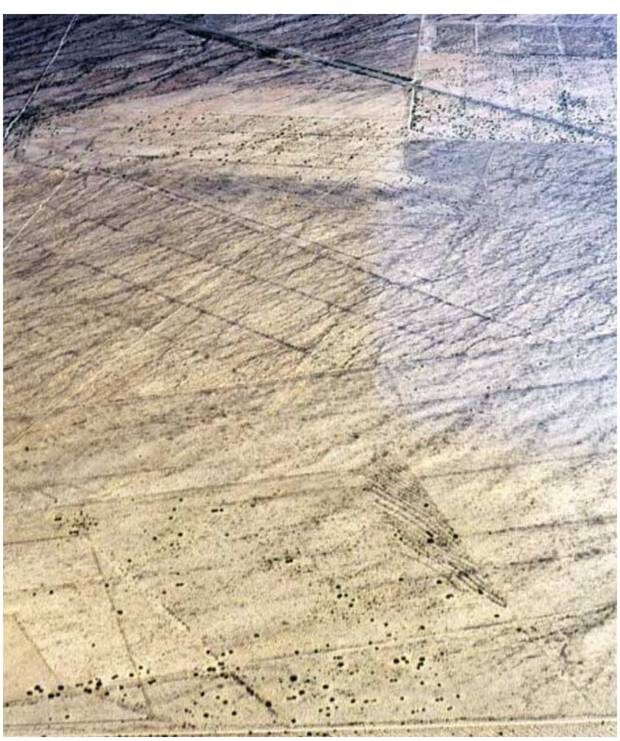


Fig. 2 – A series of overlapping buffelgrass pastures in the central valley of Sonora north of Hermosillo. Note the windrows of dead brush in some of the pasture areas.

Table 1 – Percent cover of bare soil, grass, shrubs, and trees on unconverted desert and buffelgrass pastures along Highway 51 from Hermosillo to Benjamin Hill, Sonora, Mexico

Cover class	Desert	Buffelgrass pastures
Soil (%)	50.8 (3.4)	58.8 (4.8)
Grass (%)	26.0 (1.3)	30.3 (4.1)
Shrub (%)	6.6 (0.9)	9.9 (3.3)
Tree (%)	16.8 (4.0)	1.4 (0.6)

Data were interpreted from aerial photographs taken July 22, 2003. Nine desert plots and seven buffelgrass plots were surveyed. Means and standard errors of means are given. Desert and Buffelgrass plots differed significantly ($P < 0.001$) in percent cover of trees but differences between soil, grass, and shrub cover was not significant ($P > 0.05$).

on low-altitude photographs, buffelgrass pastures had significantly ($P < 0.001$) fewer trees than unconverted desert land, as expected (Table 1). Buffelgrass pastures tended to have more bare soil, grass, and shrub cover than desert land, but differences between buffelgrass pastures and unconverted desert were not significant for these individual cover classes ($P > 0.05$).

3.2. *Extent of conversion to buffelgrass*

The total amount of land converted to buffelgrass pastures increased from 7700 ha in 1973 to over 140,000 ha in 2000 (Table 2). Buffelgrass pastures ranged in size from 70 ha to over 10,000 ha, with mean values of approximately 1,300 ha to 1,900 ha over the years. We estimated an 82% increase in buffelgrass coverage between 1990 and 2000 alone, giving an annual land conversion rate of 0.33% yr^{-1} for that time interval. Based on the 2000 scene we estimated that 8% of this subdivision of the Sonoran Desert has been converted to buffelgrass pastures. Areas that had been converted to buffelgrass pasture on the 1990 image were still visible as buffelgrass pastures on the 2000 image. However, when the shape files for 1990 buffelgrass pastures were overlain on the 2000 shapefiles, nearly all of the pastures had different perimeter boundary lines in 2000 compared to 1990. This shows that the existing pastures were reworked between 1990 and 2000, as evident in Fig. 2.

3.3. *NDVI values*

We converted pixels on the September 2000 ETM+ image to NDVI values to estimate foliage density of the different land cover classes (Fig. 3). The mean bare soil value was 0.18. Values for buffelgrass pastures or desert range were low (0.26-0.31) compared to hillsides (0.37), which were partially protected from grazing. Roadside buffelgrass patches also had high NDVI (0.41); not only were these stands protected from grazing, they received rain runoff from the tarmac. In September, 2000, the mean NDVI of buffelgrass pastures exhibiting windrows (0.26) was significantly lower than that of pastures without windrows (0.31)($P < 0.001$). While most buffelgrass pastures had low NDVI, a few had values of 0.4–0.5.

Table 2 – Increase in buffelgrass pastures on the Plains of Sonora, 1973–2000, based on analyses of Landsat images

Year	Coverage area (ha)	Buffelgrass pastures (count)	Buffelgrass pastures (ha)	Buffelgrass pastures (%)
1973	1,348,800	5	7700	0.6
1983	1,701,800	19	37,900	2.2
1990	1,845,800	62	74,800	4.1
2000	1,845,800	74	143,504	7.8

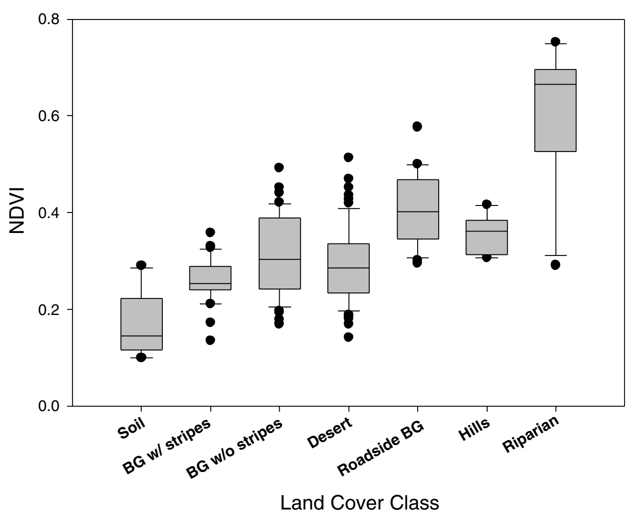


Fig. 3 – NDVI values for different land cover classes in Sonora, Mexico, based on a September, 2000, ETM+ image. Data for buffelgrass pastures (BG) with ($n = 21$) and without ($n = 53$) stripping (windrows of dead brush from land clearing) are for all the polygons located within the study area; desert values ($n = 74$) are for unconverted desert areas outside each polygons. Data for roadside buffelgrass ($n = 20$), hillside vegetation ($n = 20$), and riparian vegetation ($n = 10$) were from randomly selected samples of each land cover type. Box plots show the upper and lower 25% quartiles (shaded boxes), the median (center line), the 95% confidence intervals (error bars), and outliers (individual points).

3.4. *Seasonal NDVI values and productivity of buffelgrass pastures*

Seasonal trends in foliage density were followed using 16-day, composite MODIS images over four growing seasons (2000–2003) at point locations in the study area (Fig. 4). The 16-day NDVI values were averaged to produce a time-integrated NDVI value ($n = 89$ dates), covering Julian Days 0-365 of each year. The buffelgrass sites (NDVI = 0.278, S.E. = 0.009) had lower mean NDVI values than desert range sites (NDVI = 0.330, S.E. = 0.011) ($P < 0.001$). The NDVI time series were compared by correlation analysis (Table 3). The greening response of buffelgrass and desert range sites were highly correlated, whereas the hillside vegetation was slightly out of phase with the other sites. For all vegetation types, however, the growing season extended from July (the beginning of the summer monsoons) through December and it was significantly ($P < 0.05$) correlated with rainfall. Hillside vegetation was more highly correlated to rainfall than buffelgrass or desert vegetation. When Equation [2] was applied to the MODIS data, the mean annual PGR value for buffelgrass pastures was 1583 kg ha^{-1} yr^{-1}, compared to 2638 kg ha^{-1} yr^{-1} for unconverted desert and 5783 kg ha^{-1} yr^{-1} for hillside vegetation (Table 4).

4. Discussion

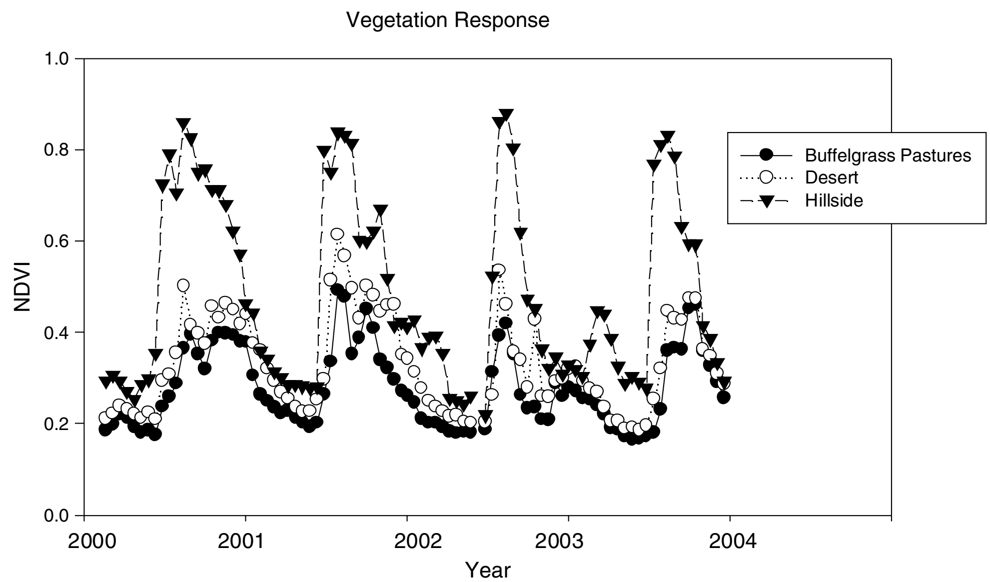
4.1. *Expansion of buffelgrass pastures in Sonora*

In our study area, buffelgrass pastures have doubled in area approximately every 10 years since 1973. The region of peak buffelgrass conversion in Sonora is believed to form a rectangle centered near Hermosillo with a length of 260 km parallel to the coast, and a width of 100 km, an area of approximately 2,600,000 ha (Burquez-Montijo et al., 2002) (see Fig. 1). If 8% has been converted to buffelgrass as in our study area, buffelgrass pastures now cover approximately 208,000 ha in this rectangle. Statewide, from 700,000 ha (Castellanos et al., 2002) to as much as 1.6 million ha (10% of the land area) may have been seeded with buffelgrass (Burquez-Montijo et al., 2002). The conversion process is still active, as buffelgrass pastures in our study area nearly doubled between 1990 and 2000. Not only was new acreage added, but existing pastures were reworked. Inspection of recent ETM+ images (2003) from the Guaymas and Ciudad Obregon areas also show a high density of buffelgrass pastures in valley areas not converted to agriculture (not shown). Hence, central Sonora has undergone land conversion on an eco-region wide scale over the past several decades.

4.2. *Productivity of buffelgrass pastures*

The ETM+ and MODIS analyses show that buffelgrass pastures have equal or lower NDVI values than unconverted desert ground. Unconverted desert and buffelgrass pastures both had >50% bare soil in the analysis of aerial photographs. The only consistently high NDVI values we observed for buffelgrass were along the roadsides where it is protected from grazing and receives supplemental water from runoff from the tarmac. A few high-NDVI buffelgrass pastures were also seen on the 2000 TM image, presumably representing well managed pastures, or pastures with unusually favorable growing conditions.

When we applied data relating NDVI to PGR from southwestern Australia pastures to Sonora, we estimated a mean annual production rate of 1583 kg ha^{-1} yr^{-1} for buffelgrass pastures in our study area. Our productivity estimates are only approximations, because we were not able to correlate NDVI values with concurrent ground measurements of PGR at our study site. When we substituted our NDVI values into algorithms developed for other arid or semi-arid rangelands to estimate PGR from NDVI (Hill, 2004), the estimates ranged



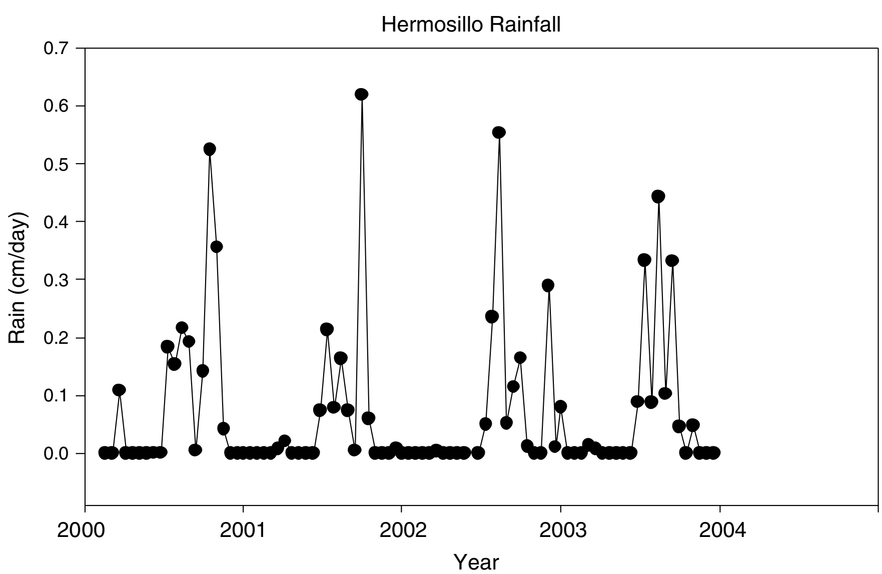


Fig. 4 – Phenology of buffelgrass greening, as determined from 16-day, composite NDVI values from the MODIS satellite sensor system, 2000–2003. Shown are mean 39 values for 7 buffelgrass sites and 4 adjacent desert sites and a hillside site for comparison; rainfall for Hermosillo, Sonora is also shown.

Table 3 – Correlation matrix between NDVI values for buffelgrass pastures, desert control sites and hillsides and for rainfall in the Sonoran Plain around Hermosillo, Mexico

	Buffelgrass	Desert	Hills	Rainfall
Buffelgrass	1.00	0.93	0.73	0.46
Desert		1.00	0.76	0.45
Hillside			1.00	0.57
Rain				1.00

The NDVI values are a time series of 16-day composites from 2000 to 2003 ($n = 89$), from MODIS imagery. Rainfall values are the corresponding 16-day values for Hermosillo, Mexico. All correlation coefficients are significant at $P < 0.001$.

from 370 kg ha^{-1} yr^{-1} (Aase et al., 1987, in a mixed prairie grassland in North Dakota) to as high as 2893 kg ha^{-1} yr^{-1} (Wylie et al., 1991, for annual grasses in Niger), with other values intermediate (e.g., 750 kg ha^{-1} yr^{-1} (Tucker et al., 1983, 1985) for mixed grasses in the Sahel; and 1492 kg ha^{-1} (Todd et al., 1998) mixed grasslands in Colorado). The mean value for all estimates was 1418 kg ha^{-1} yr^{-1} and the standard error of the mean was 433 kg ha^{-1} yr^{-1}. These estimates are much

Table 4 – Mean annual NDVI values and calculated pasture growth rate (PGR) of different land cover classes in Sonora, Mexico

Year	Buffelgrass pastures	Unconverted desert	Hillside vegetation	Rainfall (mm)
2000				
NDVI	0.286 (0.020)	0.332 (0.023)	0.554 (0.054)	307
PGR	1745	2678	7183	
2001				
NDVI	0.309 (0.019)	0.386 (0.024)	0.501 (0.022)	211
PGR	2212	3773	6107	
2002				
NDVI	0.246 (0.015)	0.294 (0.019)	0.433 (0.042)	237
PGR	933	1907	4728	
2003				
NDVI	0.271 (0.019)	0.206 (0.020)	0.458 (0.039)	252
PGR	1441	2151	5235	
Means				
NDVI	0.278 (0.009)	0.330 (0.011)	0.485 (0.022)	252 (51)
PGR	1583 (268)	2638 (414)	5783 (538)	

PGR values (kg ha^{-1} yr^{-1}) were calculated from results obtained for southwestern Australia pastures by Hill et al. (2004). Values are means and standard errors for each year and over years.

lower than the value of 7000 kg ha^{-1} yr^{-1} measured by Martin-R et al. (1995) on ungrazed test plots in the study area.

The most likely cause of low productivity of buffelgrass pastures is overstocking of the range with cattle, which causes a decline in net productivity, and the preferential removal of the most palatable vegetation (Wilson and Macleod, 1991). Sonora has a long history of heavy cattle grazing (Lopez, 1992; Sheridan, 2001). Balling et al. (1998) showed that northwest Sonora rangelands in general have higher albedo and higher land surface temperatures than control points on the US side of the border, due to removal of vegetation by overgrazing in Mexico. A comprehensive survey of 37 ranching units in Sonora showed that the range was overstocked by 177% in 1981 (maximum sustainable carrying capacity was estimated at 1 animal unit per 22 ha but the actual stocking rate was 1 animal per 8 ha)(Lopez, 1992). Heavy grazing is known to reduce the productivity of buffelgrass pastures by preventing the formation of deep roots that can effectively harvest the annual rainfall (Chaieb et al., 1996). Similar to our results, a ground survey of 167 sites over the entire State of Sonora estimated that 18.1% of buffelgrass pastures were in good condition, while the rest were in poor to fair condition (Castellanos et al., 2002).

Socioeconomic studies have concluded that buffelgrass conversion provides little benefit to the ejidatarios (small-scale ranchers on communal land), who make up 70% of the ranchers in Sonora (Yetman and Burquez, 1998; Vasquez-Leon et al., 2003; Vasquez-Leon and Liverman, 2004). The productivity of converted land declines rapidly, and ejidatorios often lack the funds to repeat the desmonte process. Commercial ranchers receive subsidies from the State of Sonora to plant buffelgrass, and they repeat the process every five or six years; they generally perceive that the desmonte process improves their rangelands (Vasquez-Leon et al., 2003). However, a drought in 1994–1995 showed that dependence on buffelgrass made rangelands more, rather than less, vulnerable to climate variability (Vasquez-Leon et al., 2003). Ranchers who left part part of their land in native vegetation suffered less loss of cattle, because native grasses and shrubs produced at least some foliage during the drought, whereas buffelgrass became dormant (Chavez, 1999). Range scientists, who in the 1970s advised ranchers to put as much land as possible into buffelgrass, now recommend that no more than 15% of the range should be converted, due to its vulnerability to drought and its negative effect on soil properties (Ibarra-Flores et al., 1999).

4.3. *Conservation implications and recommendations*

The desmonte process negatively affects the natural desert ecosystem in several ways. First, the land is often denuded of native trees, cacti, and shrubs, reducing habitat and feed sources for insects, reptiles, mammals, birds and other wildlife that evolved to depend on these plants (Burquez-Montijo et al., 2002). Second, conversion of natural vegetation to pastures is usually associated with major changes in soil erosion (Maass et al., 1988), nutrient dynamics (Maass, 1995; Ellingson et al., 2000) and primary productivity (Maass, 1995; Kauffman et al., 2003). These changes make it more difficult for native vegetation to reestablish even if the desmonte process is discontinued. In Queensland, Australia, native plant species richness was up to 295% higher in native pastures than in pastures that had been cleared and replanted with buffelgrass, and differences persisted for as long as 41 years after clearing (Fairfax and Fensham, 2000; Franks, 2002). Thus, conversion of desert to buffelgrass pastures results in reduced biodiversity, lower standing stocks of biomass, and, as this study showed, apparent reduced primary productivity compared to unconverted desert.

Although this study focused on the deliberate conversion of desert land to buffelgrass pastures, ecological damage is not confined to the pastures. Buffelgrass is considered to be highly invasive (Arriaga et al., 2004), and it now occupies numerous niches outside the pasturelands in Sonora (Bestelmeyer and

Schooley, 1999; Burquez-Montijo et al., 2002), and has spread into Arizona in the United States (Burguess et al., 1991). Its niches include unconverted hillside and desert habitats, roadsides, and city lots. Buffelgrass displaces native species and spreads fire in these habitats (Freifelder et al., 1998), to the detriment of humans as well as native species (Burquez-Montijo et al., 2002). Buffelgrass fires along highways impede traffic and cause accidents due to smoke. Repeated cycles of fire severely reduce populations of trees and columnar cacti upon which many bird and insect species depend. Unfortunately, the remote sensing techniques we employed did not allow us to quantify the spread of buffelgrass outside the pastures.

The main conclusion of the present study is that the environmental degradation caused by buffelgrass conversion appears not to be balanced by increased productivity on the rangelands of Sonora. We recommend that range studies be undertaken under realistic field conditions to assess the actual value that is derived from converting desert range to buffelgrass. Ecological studies should be undertaken to determine the primary and secondary effects of buffelgrass conversion on adjacent ecosystems. The practice of desmonte should be discontinued in Sonora until it is demonstrated that it actually improves the range and that negative effects on adjacent ecosystems can be controlled.

Large-scale exclusion areas (parks) are also needed, where planting of exotic vegetation and grazing of cattle is prohibited. These exclusion areas should include desert thorn scrub, hillsides, and riparian habitats. They must be large enough to be protected from the perpetual seed rain of buffelgrass from adjacent pastures and roadsides (Tix, 2000). These exclusion areas should then be actively managed to encourage the reestablishment of native shrubs, trees, cacti, and other vegetation, and their associated fauna. Tix (2000) reviewed the conditions needed to restore buffelgrass-invaded rangelands. First, buffelgrass density on the site must be reduced through physical or chemical means to the point that it cannot spread fire. Second, native shrubs and trees should be planted on the site. Once established, these can control buffelgrass levels by competitive exclusion, as buffelgrass is intolerant of shade. Ultimately, buffelgrass control should be part of a comprehensive plan to promote sustainable ranching and agricultural practices, maintain biodiversity, and accommodate the rapid economic and social changes that are occurring on both sides of the US–Mexico border in the Sonoran Desert, as recommended by organizations such as the International Sonoran Desert Alliance (Laird and Anderson, 1996).

REFERENCES

Aase, J.K., Frank, A.B., Lorenz, R.J., 1987. Radiometric reflectance measurements of Northern Great Plains rangeland and crested wheatgrass pastures. Journal of Range Management 4, 299–302.

Arriaga, L., Castellanos, A., Moreno, E., Alarcon, J., 2004. Potential ecological distribution of alien invasive species and risk assessment: a case study of buffel grass in arid regions of Mexico. Conservation Biology 18, 1504–1514.

Balling, R., Klopatek, J., Hildebrandt, M., Moritz, C., Watts, C., 1998. Impacts of land degradation on historical temperature records from the Sonoran Desert. Climatic Change 40, 669–681.

Bestelmeyer, B., Schooley, R., 1999. The ants of the southern Sonoran desert: community structure and the role of trees. Biodiversity and Conservation 8, 643–657.

Burguess, T.L., Bowers, J., Turner, R., 1991. Exotic plants at the Desert Laboratory, Tucson, Arizona. Madroño 38, 96–114.

Burquez-Montijo, A., Miller, M., Martinez-Yrizar, A., 2002. Mexican grasslands, thornshrub, and the transformation of the Sonoran Desert by invasive exotic buffelgrass (*Pennisetum ciliare*). In: Tellman, B. (Ed.), Invasive Exotic Species in the Sonoran Region. University of Arizona Press, Tucson, pp. 126–146.

Castellanos, A., Yanes, F., Valdez-Zamudio, D., 2002. Drought-tolerant exotic buffelgrass and desertification. In: Tellman, B. (Ed.), Weed Across Borders: Proceedings of a North American Conference. Arizona-Sonora Desert Museum, Tucson.

Chaieb, M., Henchi, B., Boukhriss, M., 1996. Impact of clipping on root systems of 3 grass species in Tunisia. Journal of Range Management 49, 336–339.

Chavez, O., 1999. The 1994–1995 drought: what did we learn from it? The Mexican perspective. Natural Resources Journal 39, 35–60.

CIPES, 1989. 20 anos de investigacion pecuaria en el CIPES. Centro de Investigaciones Pecuarias del Estado de Sonora, Hermosillo.

Cox, J., Ibarra, F., Martin, M., 1988. Fire effects on grasses in semiarid deserts. In: Effects of fire management of SW natural resources. USDA foreset Service, Rocky Mountain Forest and Range Experiment Station, Tech. Rep. RM-191, Fort Collins, Colorado.

Cox, J., Martin, M., Ibarra, F., Fourie, J., Rethman, N., Wilcox, D., 1988b. The influence of climate and soils on the distribution of four African grasses. Journal of Range Management 41, 127–139.

Ellingson, L.J., Kauffman, J., Cummings, D., Sanford Jr., R., Jaramillo, V., 2000. Soil N dynamics associated with deforestation, biomass burning and pasture conversion in a Mexican tropical dry forest. Forest Ecology and Management 137, 41–51.

Fairfax, R., Fensham, R., 2000. The effect of exotic pasture development on floristic diversity in central Queensland, Australia. Biological Conservation 94, 11–21.

Franks, A., 2002. The ecological consequences of buffel grass *Cenchrus ciliaris* establishment within remnant vegetation of Queensland. Pacific Conservation Biology 8, 99–107.

Freifelder, R., Vitousek, P., D'Antonio, C., 1998. Microclimate change and effect on fire following forest-grass conversion in seasonally dry tropical woodland. Biotropica 30, 286–297.

Gallo, K., Li, L., Reed, B., Dwyer, J., Eidenshink, J., 2004. Comparison of MODIS and AVHRR 16-day normalized difference vegetation index. Geophysical Research Letters 31, Art. No. L07502.

Gonzalez, C., Dodd, J., 1979. Production response of native and introduced grasses to mechanical brush manipulation, seeding and fertilization. Journal of Range Management 32, 305–309.

Hill, M., 2004. Grazing agriculture: managed pasture, grassland, and rangeland, third ed.. In: Ustin, S. (Ed.), Remote Sensing for Natural Resource Management and Environmental Monitoring, Manual of Remote Sensing, vol. 4 John Wiley & Sons, Hoboken, NJ, pp. 449–529.

Hill, M., Donald, G., Hyder, M., Smith, R., 2004. Estimation of pasture growth rate in the south west of Western Australian from AVHRR NDVI and climate data. Remote Sensing of Environment 93, 528–545.

Hill, M., Donald, G., Smith, R., 1998. NDVI-based phenological indices; predictive potential for grazing systems, In:

Proceedings of the 9th Australasian Remote Sensing and Photogrammetry Conference, UNSW, Sydney, July, 1998, CDROM.
Huete, A., Didan, K., Miura, T., Rodreguez, E., Gao, X., Ferreira, L., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83, 195–213.
Ibarra-Flores, F., Cox, J., Martin, M., Crow, T., Call, C., 1995. Predicting buffelgrass survival across a geographical and environmental gradient. Journal of Range Management 48, 53–59.
Ibarra-Flores, F., Cox, J., Martin-Rivera, M., Crowl, T., Norton, B., Banner, R., Miller, R., 1999. Soil physicochemical changes following buffelgrass establishment in Mexico. Arid Soil Research and Rehabilitation 13, 39–52.
Jensen, J., 2000. Remote Sensing of the Environment; An Earth Resource Perspective. Prentice Hall Publishing Co., Upper Saddle River, NJ.
Johnson, D., Navarro, A., 1992. Zacate buffel y biodiversidad en el Desierto Sonorense. In: Moreno, J. (Ed.), Ecologia, recursos naturals y medio ambiente en Sonora. El Colegio De Sonora, Hermosillo, Mexico, pp. 117–122.
Kauffman, J.B., Steele, M., Cummings, D., Jaramillo, V., 2003. Biomass dynamics associated with deforestation, fire and conversion to cattle pasture in a Mexican tropical dry forest. Forest Ecology and Management 176, 1–12.
Laird, W., Anderson, J., 1996. Building the International Sonoran Desert Alliance. Arid Lands Newsletter 39, on line journal, no page numbers. Available from: <http://ag.arizona.edu/OALS/ALN/ALNHome.html>, last updated 2 March 2005.
Lambin, E., Geist, H., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Annual Review of Environmental Resoures 28, 205–241.
Lopez, E., 1992. La ganaderia bovina sonorense: cambios productivos y deterioro del medio ambiente. In: Moreno, J. (Ed.), Ecologia, recursos naturals y medio ambiente en Sonora. El Colegio De Sonora, Hermosillo, Mexico, pp. 197–215.
Maass, J., 1995. Conversion of tropical dry forest to pasture and agriculture. In: Bullock, S.H., Mooney, H.A., Medina, E. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, Cambridge, pp. 399–422.
Maass, J.M., Jordan, C., Sarukhan, J., 1988. Soil erosion and nutrient losses in seasonal tropical agroecosystems under various management techniques. Journal of Applied Ecology 25, 595–607.
Martin, M., Cox, J., Ibarra, F., Alston, D., Banner, R., Malecheck, J., 1999. Spittlebug and buffelgrass responses to summer fires in Mexico. Journal of Range Management 52, 621–625.
Martin-R, M., Cox, J., Ibarra-F, F., 1995. Climatic effects on buffelgrass productivity in the Sonoran Desert. Journal of Range Management 48, 60–63.
Masera, O., Ordonez, M., Dirzo, R., 1997. Carbon emissions from Mexican forests: current situation and long-term scenarios. Climatic Change 35, 265–295.
McIvor, J., 2003. Competition affects survival and growth of buffelgrass seedlings – Is buffelgrass a colonizer or an invader? Tropical Grasslands 37, 176–178.
McLaughlin, S., Bowers, J., 1982. Effects of wildfire on a Sonoran Desert plant community. Ecology 63, 246–248.
Nagler, P., Glenn, E., Schiff-Hursh, K., Curtis, C., Huete, A., 2005. Vegetation mapping for change detection on an arid zone river. Environmental Monitoring and Assessment, (in press).
Ramirez, R., 1999. Feed resources and feeding techniques of small ruminants under extensive management conditions. Small Ruminant Research 34, 215–230.
Ramirez, R., Foroughbackhch, R., Haud, L., Alba-Avila, J., Garcia-Castillo, C., Espinosa-Vasquez, E., 2001. Seasonal dynamics of dry matter, crude protein and cell wall digestion in total plant, leaves and stems of common buffelgrass (*Cenchrus ciliaris*). Journal of Applied Animal Research 19, 209–218.
Rao, A., Singh, K., Wight, J., 1996. Productivity of *Cenchrus ciliaris* in relation to rainfall and fertilization. Journal of Range Management 49, 143–146.
Rossiter, N., Setterfield, S., Douglas, M., Hutley, L., 2003. Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. Diversity and Distributions 9, 169–176.
Sala, O., Chapin, F., Armesto, J., Berlow, E., Bloomfield, J., 2000. Biodiversity: global biodiversity scenarios for the year 2100. Science 287, 1770–1774.
Sanderson, M., Voight, P., Jones, R., 1999. Yield and quality of warm-season grasses in central Texas. Journal of Range Management 52, 45–150.
Sheridan, T., 2001. Cows, condos, and the contested commons: the political ecology of ranching on the Arizona-Sonora borderlands. Human Organization 60, 141–152.
Shreve, F., 1964. Vegetation of the Sonoran Desert. In: Shreve, F., Wiggins, I. (Eds.), Vegetation and Flora of the Sonoran Desert. Stanford University Press.
Snedecor, G., Cochran, W., 1989. Statistical Methods. Iowa State Press, Ames, Iowa.
Tix, D., 2000. *Cenchrus ciliaris* invasion and control in southwestern US grasslands and shrublands. Restoration and Reclamation Review 6, on line journal, no page numbers. Available from: <http://hort.agri.umn.edu/h5015/rrr.htm>.
Todd, S., Hoffer, R., Milchunas, D., 1998. Biomass estimation on grazed and ungrazed rangelands using spectral indices. International Journal of Remote Sensing 19, 427–438.
Tucker, C., Vanpraet, C., Boerwinkel, E., Gaston, A., 1983. Satellite remote-sensing of total dry-matter production in the Senegalese Sahel. Remote Sensing of Environment 13, 461–474.
Tucker, C., Vanpraet, C., Sharman, M., Vanittersum, G., 1985. Satellite remote-sensing of total herbaceous biomass production in the Senegalese Sahel – 1980–1984. Remote Sensing of Environment 1, 233–249.
Turner, R., Brown, D., 1982. Sonoran desertscrub. Desert Plants 4, 121–181.
Vazquez-Leon, M., Liverman, D., 2004. The political ecology of land-use change: affluent ranchers and destitute farmers in the Mexican Municipio of Alamos. Human Organization 63, 21–33.
Vasquez-Leon, M., West, C., Finan, T., 2003. A comparative assessment of climate vulnerability: agriculture and ranching on both sides of the US–Mexico border. Global Environmental Change 13, 159–173.
Vitousek, P., Mooney, H., Lubchenco, J., Melillo, J., 1997. Human domination of earth's ecosystems. Science 277, 494–499.
Wilson, A., Macleod, N., 1991. Overgrazing – Present or absent? Journal of Range Management 44, 475–482.
Wylie, B., Harrington, J., Prince, S., Denda, I., 1991. Satellite and groundbased pasture production assessment in Niger: 1986–1988. International Journal of Remote Sensing 12, 1281–1300.
Yetman, D., Burquez, A., 1998. Twenty-seven: a case study in Ejido privatization in Mexico. Journal of Anthropological Research 54, 73–95.