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Agroecosystem stability: environmental indexes for sustainable land-use planning in Azul, Argentina

Estabilidad de los agroecosistemas: índices ambientales para la planificacion sostenible del uso de la tierra en Azul, Argentina

Estabilidade dos agroecossistemas: índices ambientais para o planeamento sustentável do uso da terra em Azul, Argentina

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Abstract

Lack of land use planning has led to large-scale land degradation processes. Understanding and assessing their environmental impacts and costs becomes essential for sustainable development. Fragility is the maximum risk to land degradation. It is an inherited characteristic and can be fully expressed by land use. Agroecosystems are complex and their stability is an emerging property which indicates the resilience of agroecosystems in relation to land use intensity. The main objective of this work was to characterise land fragility in the Azul district, Buenos Aires province, Argentina, and to evaluate its stability. Physical, chemical, and biological degradation fragility indicators were applied and mapped. Based on these indicators, the fragility to degradation index (IFDE) was developed, applied, and mapped. The instability index (II) was developed and applied based on soil mesofauna to determine stability. The vulnerability index (IV) was developed and applied to determine current degradation. Physical fragility to degradation was the most important and significantly different between the north and the south of the Azul district. Similar results were observed for the IFDE between north and south. For the land use scenarios proposed, high intensity expressed 83% of the IV, whereas low intensity expressed 8% of the IV. Index IV allows a current analysis of the expression of degradation due to land use by the combination of IFDE and II. The environmental indicators and indices used in this work made it possible to identify the areas to which land use planning actions and policies should be directed.

Key words: complex systems; land fragility; fragility to degradation; land use.

Resumen

La falta de planificación del uso de la tierra provocó grandes procesos de degradación. Comprender y evaluar sus impactos es esencial para el desarrollo sostenible. La fragilidad es el máximo riesgo de degradación de la tierra. Es una característica heredada y puede expresarse mediante el uso. Los agroecosistemas son sistemas complejos y su estabilidad es una propiedad emergente. Esta indica lo resilientes que son en relación con su uso. El objetivo fue caracterizar la fragilidad de las tierras en el partido de Azul, provincia de Buenos Aires, Argentina y evaluar su estabilidad. Se aplicaron indicadores de fragilidad a la degradación física, química y biológica. En base a estos se desarrolló y aplicó el índice de fragilidad a la degradación (IFDE). Se desarrolló y aplicó el índice de inestabilidad (II) basado en la mesofauna edáfica para determinar la estabilidad. Se desarrolló el índice de vulnerabilidad (IV) y aplicó para determinar la degradación actual. La fragilidad a la degradación física fue la más importante y diferente entre el norte y el sur. Se observaron mismos resultados entre el norte y el sur para el IFDE. Para los escenarios de uso de la tierra propuestos: una alta intensidad, expresó el 83% del IV. Por el contrario: una baja intensidad, expresó el 8% del IV. El IV permite un análisis actual de la expresión de la degradación debida al uso de la tierra. Los indicadores e índices medioambientales utilizados en este trabajo permitieron identificar las áreas a las que deben dirigirse las acciones y políticas de planificación del uso del territorio.

Palabras clave: sistemas complejos; fragilidad de las tierras; fragilidad a la degradación; uso de las tierras.

Resumo
A falta de planejamento do uso da terra levou a amplos processos de degradação. Compreender e avaliar seus impactos é essencial para o desenvolvimento sustentável. A fragilidade é o risco final da degradação da terra. É uma característica herdada e pode ser expressa por meio do uso. Os agroecossistemas são sistemas complexos e sua estabilidade é uma propriedade emergente. Ela indica o quanto eles são resilientes em relação ao seu uso. O objetivo foi caracterizar a fragilidade da terra em Azul, província de Buenos Aires, Argentina, e avaliar sua estabilidade. Indicadores de fragilidade foram aplicados à degradação física, química e biológica. Com base neles, foi desenvolvido e aplicado o índice de fragilidade à degradação (IFDE). O índice de instabilidade (II), baseado na mesofauna edáfica, foi desenvolvido e aplicado para determinar a estabilidade. O índice de vulnerabilidade (IV) foi desenvolvido e aplicado para determinar a degradação atual. A fragilidade à degradação física foi a mais importante e diferente entre o norte e o sul. Os mesmos resultados foram observados entre o norte e o sul para o IFDE. Para os cenários de uso do solo propostos: uma intensidade alta expressou 83% do IV. Por outro lado, uma intensidade baixa expressou 8% do IV. O IV permite uma análise atual da expressão da degradação devida ao uso da terra. Os indicadores e índices ambientais usados neste trabalho permitiram identificar as áreas para as quais as ações e políticas de planejamento do uso da terra devem ser direcionadas.

Palavras-chave: sistemas complexos; fragilidade da terra; fragilidade à degradação; uso da terra.

Introduction

Natural resources are finite in time and space. Recognising and assessing the environmental impacts and costs of human activities in an agroecosystem plays a key role in achieving sustainable development (Massobrio, 2004). Lack of land-use planning has led to extensive degradation processes (Halbac-Cotoara-Zamfir et al., 2020). Throughout history, the fall of many civilizations has been associated with collapses in food production caused by land degradation (Cendrero et al., 2006; Vico Martín, 2018). The evidence is that tillage systems do not usually correspond to a transgenerational criterion of land use (Lal, 2015). In developing countries, soil degradation is even worse than in developed countries, because of insufficient economic funding for public institutions, universities, and farmers, as well as increasing population growth rates (De Paz et al., 2006).
Since the 1990s, a major conceptual and methodological transformation related to the study of so-called non-linear phenomena (which, in contrast to a linear system, cannot be explained by a mathematical relationship of proportionality, i.e. a linear relationship between two variables) has taken place in almost all fields of science (Munné, 1995; Mandelbrot, 1983; Miramontes, 1999). Therefore, the term "complex systems" is widely used and encompasses a research approach to problems in many disciplines. They are systems constituted by many components which may interact with each other (i.e. an agroecosystem) (Martínez Mekler, 2000; Bar-Yam, 2002; García, 2008). So-called emergent properties are the spatio-temporal properties of complex systems that spontaneously arise from the interaction among their components (Morowitz, 2004; Massobrio, 2003; Quiroz Guerrero et al., 2021). As an interdisciplinary domain, complex systems draw contributions from many different fields (Bar-Yam, 2002). ‘Complex systems’ is therefore used as a wide term that encompasses a research approach to problems in many disciplines.

According to FAO (1980), land degradation is an anthropogenic process which reduces the current and potential capacity to produce goods and services, both qualitatively and quantitatively. There is, additionally, an increase in the energy necessary for production. Land degradation generates environmental and economic liabilities (Tsoraeva et al., 2020). Lack of planning, inherited fragility and the intensity of land use explain land degradation. (Massobrio and Gutiérrez, 1998; Massobrio, 2004; Cendrero et al., 2006; Duque Escobar, 2007). Fragility is the maximum risk to land degradation (Druille et al., 2013; Gabella and Campo, 2016). For its evaluation, all non-permanent and unstable factors (i.e. vegetation, current land use) must be removed. Fragility only has a time-independent validity when it is based on relatively stable or permanent factors (i.e. soil, climate) (Santanatoglia et al., 1992). It is an inherited characteristic and can be fully expressed by land use intensities. This process generates environmental sustainability costs. Furthermore, fragility allows prediction of the expected degradation over time with different land uses scenarios (Cendrero et al., 1992; Cendrero, 1997).

Innovative research has been aimed at studying agroecosystem functioning as complex systems (Sugihara, 2012; Ruggerio and Massobrio, 2020; Turner, 2021). According to Cassani et al. (2020; 2021) agroecosystem stability is considered an emerging property. This indicates how stable agroecosystems are in relation to the external anthropogenic energy they receive (i.e. land use intensity) and their capacity to metabolise it. Different authors (Socarrás and Rodriguez, 2005; Socarrás, 2013; Socarrás and Izquierdo Brito, 2014; Cassani et al., 2020) used biological indices of soil mesofauna to characterise agroecosystem stability at different land-use intensities. Balpande et al. (1996), Stolbovoi et al. (1999), Soriano et al. (2000) and De Paz et al. (2006) used the methodology proposed by FAO (1980) to develop soil physical, chemical, and biological degradation maps. However, it is still necessary to advance in the development and optimisation of environmental indicators and indices for fragility to degradation and agroecosystem stability. To achieve a trans-generational criterion of land use, environmental indicators and indices can be applied to identify uses which do not compromise their ecosystemic receptivity (Massobrio, 2004) and stability level (Cassani et al., 2020; 2021). Human activities should be regulated in these areas, whereas regulations for more resilient lands could be less restrictive (De Paz et al., 2006). In the last decades, there has been an agricultural intensification and expansion at the expense of livestock farming in the Azul district. These agro-productive changes were reflected in the loss of environmental regulation and ecosystem services (Vázquez and Zulaica, 2013; Lara et al., 2023). Likewise, Vázquez et al. (2016) analysed changes in land use caused by the process of agriculturalization in the period between 1995 and 2011. According to these authors, the agricultural advance took place from peripheral hills to hills and depressed plains environments. Hills agroecosystems were the most affected (Rocha, 2018; Gandini et al., 2019). The main objective of this research was to characterise the fragility of land in Azul and assess its stability. The specific objectives were to: (a) calculate the physical, chemical, and biological fragility of land degradation; (b) develop an agroecosystem fragility to degradation index (IFDE); and (c) evaluate the stability of agroecosystems with different land use intensities in the peripheral hilly sub-environment of Azul.

Materials and methods

Location and characterisation of the study area

Azul district is located in the centre of Buenos Aires province, Argentina (36°14`S – 37°27`S and 59°8`W – 60°10`W), in the Pampa region (Matteucci, 2012). It has a total area of 6,551 km² (Figure 1) and is divided into two large areas: 'Pampa Serrana' in the south, and 'Pampa Deprimida' in the north (Matteucci, 2012). According to Piscitelli and Sfeir (2004), Azul is divided into five physical-geographical environments: (a) hilly environment, (b) undulating foothill environment, (c) gently undulating plain environment, (d) spill plains, and (e) alluvial plains. The former two belong to the 'Pampa Serrana' area, the latter three to the 'Pampa Deprimida' area (*Matteucci, 2012*). Within the hilly environment, two sub-environments can be recognised: hills and peripheral hills.

According to the Köppen classification (Kottek et al., 2006), Azul has a humid temperate climate (Cfb) with year-round rainfall and warm summer. It has an annual average of 921 mm (1931-2017 series) and 14.2 °C (1997-2018 series) of precipitation and temperature, respectively. January is the hottest month with an average temperature of 21.8 °C and August is the coldest with an average of 7 °C. Precipitation events are evenly distributed throughout the year (SMN, 2018; NOAA, 2019; Cassani et al., 2021).

Soils are Argiudolls, Hapludolls, Natraquolls and Natraqualfs. (Piscitelli and Sfeir, 2004; INTA 2005; Piscitelli et al., 2010).

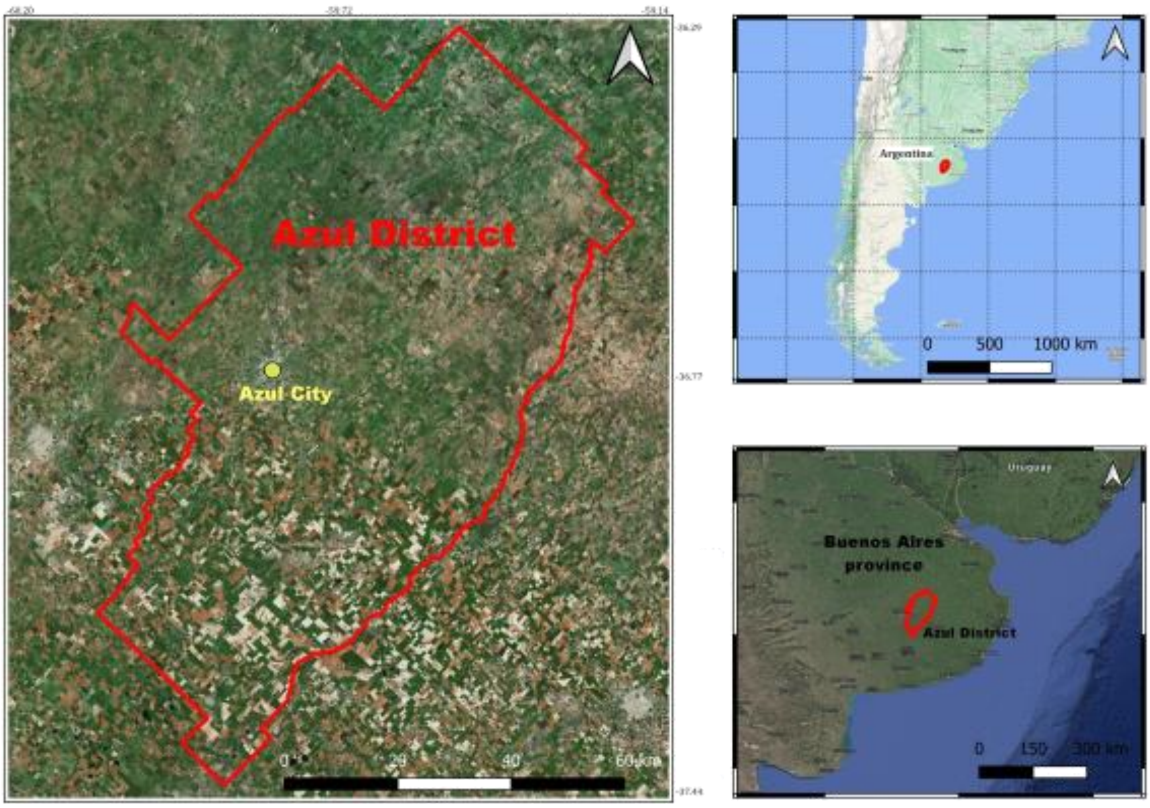

Figure 1: location of Azul in the Argentine Republic. (Landsat/Copernicus image. ©Google, 2020).

Fragility to physical, chemical, and biological degradation

Fragility to physical and chemical degradation calculations were applied according to methodology by FAO (1980) and Cendrero (1997), with modifications. Fragility to biological degradation was calculated using the methodology by De Paz et al. (2006). These methodologies were standardised and, as a result, physical, chemical, and biological fragility are dimensionless units. Fragility to land degradation indicates the maximum value of degradation reached by a given land. Calculation is based on the permanent factors of the inherited geosphere, using climate as an aggression parameter and the soil system as a resistance parameter:

Fragility to degradation= C x S x T

Where:

C = Climatic factor.

S = Soil factor.

T = Topography factor.

Fragility to physical degradation

It was calculated following formula.

Climatic factor (C):

According to FAO (1980) and Massobrio et al. (1993) methodology, the climate factor (C) value is obtained from the rainfall erosivity factor (R), as shown in Table 1. For the working scale (1:50000) the rainfall erosivity factor R (Wischmeier and Smith, 1978) was used to characterise the climatic factor. It was 406 ($MJ . mm . ha^{-1} \cdot hr^{-1} \cdot yr^{-1}$) for Azul district (Gaitán et al., 2017). We performed an interpolation using table 1, resulting in a C value of 6.78.

Table 1: conversion to obtain the climate factor (C) from the rainfall erosivity factor (R).

R =	0-50	50-500	500-1000	>1000
C =	0-5	5-7,5	7,5-10	10

Soil factor (S):

For the 1:50000 scale, the K-factor of Wischmeier and Smith (1978) ($tn \cdot ha \cdot yr \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$) was used as a way of characterising the soil factor.

$$K = (2.1\ x\ [(\%silt + very\ fine\ sand).(100 - \%clay)].14\ x\ 10 - 4\ x\ (12 - \%OM) + 3.25\ x\ (B - 2)$$

Where:

Silt: 2 a 50 µm size

Very fine sand: 50 a 100 µm size

Clay: size less than 2 µm

OM: topsoil organic matter in %.

B: soil structure.

1: very good. Very fine granular.
2: good. Fine granular.
3: regular.
4: poor, laminar, or massive.

C: permeability.

1: very fast, more than 12.5 cm . $hour^{-1}$.
2: moderately fast, 6.25 to 12.5 cm . $hour^{-1}$.
3: moderate, 2.0 to 6.25 cm . $hour^{-1}$.
4: moderately slow, 0.5 to 2.0 cm . $hour^{-1}$.
5: slow, 0.125 to 0.500 cm . $hour^{-1}$
6: very slow, less than 0.125 cm . $hour^{-1}$.

Topographic factor (T): dominant decline (Soil Survey Manual, 1993). The value for this factor is 1 (a dimensionless unit).

According to FAO (1980), classes were established for which the intensity of the process is expressed (Table 2). These classes indicate the fragility to physical degradation as a percentage increase in bulk density per year for silty-clay soils (an average bulk density of 1–1.25 g·cm^{-3}, Arshad et al., 1996).

Table 2: classes of fragility to physical degradation classes expressed as a percentage increase in bulk density per year for silty-clay soils (an average bulk density of 1 – 1, 25 g·cm^{-3}).

Classes	Annual change (%)
none to slight	< 2,5
moderate	2,5 – 3,5
moderate-high	3,5 – 5
high	5 – 7,5
very high	>7,5

<u>Fragility to chemical degradation</u>

It was calculated following formula (1).
Climate factor (C) (a dimensionless unit) was calculated using formula (3).
C= (Σ P-PET)/100 for all P-PET>0
Where:
P: rainfall (mm)
PET: potential evapotranspiration (mm)
Soil factor (S) (a dimensionless unit):
Textural class and soil mineralogy were used to characterise the edaphic factor.
S= textural x mineralogy (4)

The textural classes of the World Soil Map (FAO-UNESCO, 1980) were used:
2: Coarse texture (epipedons with a clay content lower than 18% and sand content higher than 65%)
1: Medium texture (less than 35% clay and more than 65% sand, or between 18 to 35% clay and more than 65% sand).
0.5: Fine texture (epipedons with a clay content of more than 35%).
For mineralogy, the dominant clay type was considered:
1: Kaolinite
0.5: Illite
0.25: Montmorillonite
Topographic factor (T):
Same value (T=1) as topographic factor for fragility to physical degradation (a dimensionless unit).

According to FAO (1980), classes were established, for which the intensity of the process is expressed (Table 3). These classes indicate the fragility to chemical degradation as a percentage decrease in base saturation per year. For soils with 50% or higher base saturation.

Table 3: classes of fragility to chemical degradation as a percentage decrease in base saturation per year. For soils with 50% or higher base saturation.

Classes	Decrease in base saturation
None to slight	< 1,5 % annual
Slight	1,5 – 2,5 % annual
Moderate	2,5 – 5 % annual
High	5 – 10 % annual
Very high	> 10 % annual

Fragility to biological degradation

Biological degradation is the decrease of organic matter content in soils. In a wide sense, soil organic matter includes all organisms living in or on the soil, as well as all material originating from them and their transformation, decomposition, and resynthesis products. In a restricted sense, it refers to soil organic matter without considering living organisms and plant roots (Baldock and Nelson, 2000). In this case, soil organic matter may represent 2-10% of the mineral solid fraction.

We applied the biological degradation index (IDB) (5) proposed by De Paz et al. (2006) under the guidelines by FAO (1980) (a dimensionless unit). It considers only the content of organic matter, in a restricted sense, as the main factor of biological degradation.

Calculations were made doing a quotient between 1 and the organic matter percentage values:

$$\mathrm{IDB} = \frac{1}{OM\%}$$

OM%: Organic matter content (%)

Classes were established according to De Paz et al. (2006) (Table 4). These classes indicate the fragility of the land to biological degradation.

Table 4: classes of fragility to biological degradation as a biological degradation index (IDB).

Fragility to biological degradation classes	Biological degradation index (IDB)
Very low	0 – 0,1
Low	0,11 – 0,2
Moderately low	0,21 – 0,3
Moderately high	0,31 – 0,6
High	0,61 – 1
Very high	1,1 – 2,5

Fragility to Degradation Index (IFDE)

We followed Cendrero et al. (2002) methodology to propose a novel fragility to degradation index (IFDE) (dimensionless unit) (7). It combined the fragility to physical, chemical, and biological degradation indicators. Before using the IFDE, each of the fragility values were adjusted according to table 5. Then values were normalised according to formula (6), to obtain values between 0.1 and 1.

Table 5: transformation of values for fragility to physical, chemical and biological degradation for further use in the fragility to degradation index (IDFE).

Fragility to physical degradation	
Values	They become:
< 2,5 %	2,5
2,5 % to 7,5 %	remain unchanged
> 7,5 %	7,5
Fragility to chemical degradation	
Values	They become:
< 1,5 %	1,5
1,5 % to 10 %	remain unchanged
> 10 %	10
Fragility to biological degradation	
Values	They become:
< 0,3	0,3
0,3 to 1	remain unchanged
> 1	1

$$\text{Value N} = 1 - [\frac{(\text{IM} - \text{I min})}{\text{I max} - \text{I min}}]$$

Where:
Value N = Normalised value
IM= Measuring indicator.
Imax= Maximum indicator value.
Imin= Minimum indicator value.

$$IFDE = \{1 - [(Value\ N\ phy\ x\ (0{,}8)) + (Value\ N\ che\ x\ (0{,}1)) + (Value\ N\ bio\ x\ (0{,}1))]\}.100$$

Where:
IFDE: fragility to degradation index
Value N phy: normalised value of fragility to physical degradation indicator.
Value N che: normalised value of fragility to chemical degradation indicator.
Value N bio: normalised value of fragility to biological degradation indicator.

A higher importance was assigned to physical than to chemical and biological degradation, because higher responses were found for fragility to physical degradation than for the rest in Azul district (results section, Figure 2 A, B and C).

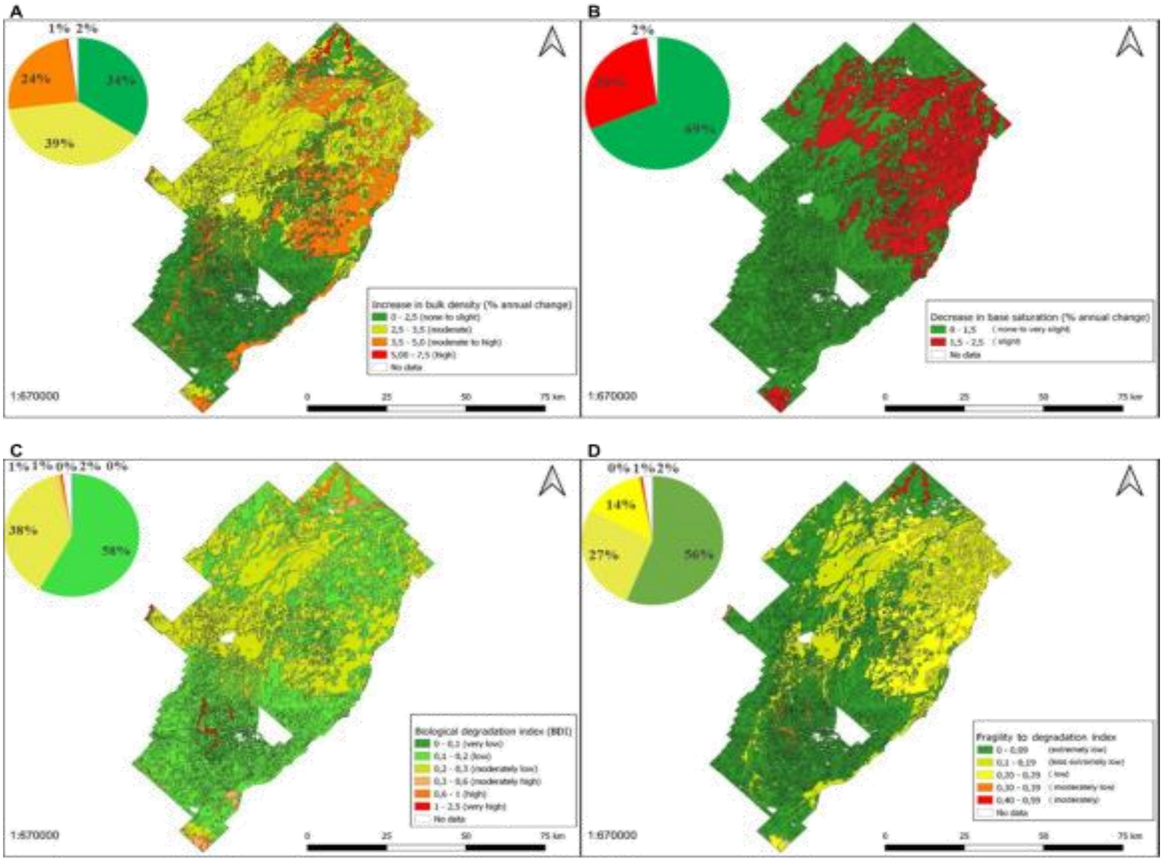

Figure 2: fragility to physical degradation results. Classes as a percentage increase in bulk density per year (% annual change) (A); fragility to chemical degradation results. Classes as a percentage decrease in base saturation per year (% annual change) (B); different biological degradation index results. Classes as a biological degradation index (BDI) (C); fragility to degradation index (IFDE) result and classes (D). All maps shown the percentage of occupied area (%).

Classes were established for the values (Table 6). These indicate the fragility to degradation.

Table 6: classes of fragility to degradation as a fragility of degradation index (IFDE).

Classes	IFDE Index
Extremely low	0 – 0,09
Less extremely low	0,10 – 0,19
Low	0,20 – 0,29
Moderately low	0,30 – 0,39
Moderate	0,40 – 0,59
Moderately high	0,60 – 0,69
High	0,70 – 0,79
Less extremely high	0,80 – 0,89
Extremely high	0,90 – 1

Instability index (II) of agroecosystems

We proposed a novel instability index (II) (dimensionless unit) $_{(10)}$ based on the combination of two biological indicators: Oribatida/Prostigmata (Andres, 1990) and Acari/Colembolla (Mateos, 1992). To calculate II, the values of the biological indicators oribatid/prostigmata and acari/collembola were normalised according to formula $_{(8)}$ and $_{(9)}$ respectively. For the oribatid/prostigmata indicator, a minimum value of 0.1 (as the worst condition) and a maximum value of 1 (as the best condition) were defined. Values > 1 are transformed into 1. These ranges are based on the values observed by Cassani (2020):

For the oribatid/prostigmata indicator:

$$Value\ N\ = (IM - 0.1)/(1 - 0.1)$$

Where:

Value N = Normalised value

IM= Measuring indicator

For the acari/collembola indicator, a minimum value of 1 (as the best condition), and a maximum value of 4 (as the worst condition) were defined. Values > 4 are transformed into 4. These ranges are derived from the values observed by Cassani (2020):

$$Value\ N\ = 1 - [\frac{(IM-1)}{4-1}]$$

Where:

Value N = Normalised value

IM= Measuring indicator

Biological indicators consider the edaphic mesofauna suitable for assessing agroecosystem stability (Socarrás, 2013). The Oribatida/Prostigmata indicator takes values ≥ 1 in stable agroecosystems, and values < 1 in unstable agroecosystems. The Acari/Collembola indicator takes values ≤ 1 in stable agroecosystems, and values > 1 in unstable agroecosystems.

In formula $_{(10)}$, both indicators have the same relevance or importance of 50% (0.5):

$$II = 1 - \left(\left(Value\ N \frac{Oribatid}{Prostigmata} \right) x\ (0.5) \right) + \left(\left(Value\ N \frac{Acari}{Collembola} \right) x\ (0.5) \right)$$

Where:
Value N oribatida/prostigmata: normalised oribatida/prostigmata indicator.
Value N acari/collembola: normalised acari/collembola indicator.
In addition, a classification of the values of the instability indices (II) was carried out.

Land Vulnerability Index (IV)
We proposed the Land Vulnerability Index (IV) as an index that included land use. It was obtained from the IFDE and II indices according to equation (11).

$$IV = (IFDE\ x\ II)$$

Where:
II: instability index
IFDE: fragility to degradation index

Mapping different degradation and application of the developed indices
Physical, chemical, biological fragility, and IFDE were calculated for each soil map unit present in the 1:50000 maps of Azul district (INTA, 2005; Cruzate et al., 2010): in consociations, fragility was calculated from the edaphic information corresponding to the dominant series; and in complexes and associations, values were calculated by pondering the results of each of the series that form the soil map unit. Results were mapped using QGIS v3.10.8-A Coruña (QGIS, 2021) software. Index IV was applied to determine the stability of two different scenarios for the MP16 soil map unit of Azul district based on Cassani et al. (2021) (Supplementary data).
The scenarios with different land use intensity considered were:
-Conventional tillage scenario (high-intensity land use): primary tillage with mouldboard plough, then secondary tillage with disk harrows and tooth harrows for the last 25 years.
-Naturalised grassland (low-intensity land use): Closure for the last 25 years.

Results

Fragility to physical degradation
Most lands in the south of Azul were classified as none to slight classes. In contrast, most of the land in the north of Azul was classified as moderate to moderate-high. There was also one sector with moderate to high fragility in the centre west and another in the north (Figure 2 A).

Fragility to chemical degradation
Most lands in Azul were classified as none to slight category. However, a sector classified as slight was observed to the east (Figure 2 B).

Fragility to biological degradation
Most lands in Azul were classified as very low to moderately low (Figure 2 C).

Fragility to degradation index (IFDE)
More than half of the lands in the Azul district had IFDE values between 0 and 0.09, which correspond to a very low fragility to degradation. These lands are mainly located to the south

of Azul, but also, there is an area to the north and another to the west. In contrast, the lands located to the northeast of the district showed a moderate fragility, with values between 0.1 and 0.29 (Figure 2 D).

Mapping different degradation and application of the developed indices.

For cartographic unit MP16 (supplementary data), the indices II and IV were assessed considering two contrasting land use scenarios: conventional tillage and closure. Data obtained by Cassani et al. (2021) for the biological indicators in the soil map units and the values previously calculated for the IFDE were used.

Thus:

Conventional tillage scenario (high-intensity land use) a):

Oribatid/prostigmata Indicator = 0.25

Acari/collembola Indicator = 3.5

Closure scenario (low-intensity land use) (b):

Oribatid/prostigmata Indicator = 1.25

Acari/collembola Indicator = 1.5

IFDE: 0.01

In high-intensity land use, i.e., conventional tillage, the value of II and IV indices were 0.8333 and 0.0083, respectively (Table 8). While for low-intensity land use, closure, the value of II and IV were lower: 0.08 and 0.0008, respectively (Table 9).

Table 7: Calculation for the instability index (II) and vulnerability index (IV) in high intensity scenario (Conventional tillage) a):

a) Conventional tillage scenario (high intensity):

Standardisation of biological indicators:

oribatid/prostigmata = 0,25

$$\text{N Value} = (\text{IM} - 0{,}1)/(1 - 0{,}1)$$

Therefore:

$$\text{N Value} = \frac{(0{,}25 - 0{,}1)}{1 - 0{,}1} = 0{,}1667$$

acari/collembola = 3,5

$$\text{N Value} = 1 - [\frac{(\text{IM} - 1)}{4 - 1}]$$

Therefore:

N Value $= 1 - [\frac{(3{,}5 - 1)}{4 - 1}]$ **= 0,1667**

$$\text{II} = 1 - [\left(\left(\text{N Value}\,\frac{\text{Oribatid}}{\text{Prostigmata}}\right) \cdot (0{,}5)\right) + \left(\left(\text{N Value}\,\frac{\text{Acari}}{\text{Collembola}}\right) \cdot (0{,}5)\right)]$$

Therefore:

$$\text{II} = 1 - [\left((0{,}1667) \cdot (0{,}5)\right) + \left((0{,}1667) \cdot (0{,}5)\right)]$$

$$\text{II} = 1 - (0{,}08335 + 0{,}08335) = 0{,}8333$$

$$\text{IV} = (\text{IFDE} \cdot \text{II})$$

Then:

$$\text{IV} = (0{,}01 \cdot 0{,}8333)$$

$$\text{IV} = 0.008333$$

Table 8: Calculation for the instability index (II) and vulnerability index (IV) in low intensity scenario (closure) b):

b) Closure scenario (low intensity) (b):

Standardisation of biological indicators:

Oribatid/Prostigmata = 1,25

$$\text{N Value} = (\text{IM} - 0{,}1)/(1 - 0{,}1)$$

Therefore

$$\text{N Value} = \frac{(1 - 0{,}1)}{1 - 0{,}1} = 1$$

Acari/Collembola = 1,5

$$\text{N Value} = 1 - [\frac{(\text{IM} - 1)}{4 - 1}]$$

Therefore:

N Value= $1 - [\frac{(1{,}5-1)}{4-1}]$ **= 0,8334**

$$\text{II} = 1 - [\left(\left(\text{N Value}\frac{\text{Oribatid}}{\text{Prostigmata}}\right) \cdot \left(\frac{0{,}5}{2}\right)\right) + \left(\left(\text{N Value}\frac{\text{Acari}}{\text{Collembolo}}\right) \cdot \left(\frac{0{,}5}{2}\right)\right)]$$

Therefore:

$$\text{II} = 1 - [\left((1) \cdot (0{,}5)\right) + \left((0{,}8334) \cdot (0{,}5)\right)]$$

$$\text{II} = 1 - (0{,}5 + 0{,}4167) = 0{,}08$$

$$\text{IV} = \text{IFDE} \cdot \text{II}$$

Then:

$$\text{IV} = (0{,}01 \cdot 0{,}08)$$

$$\text{IV} = 0.0008$$

Table 9: instability index values and the given instability classes of the agroecosystem.

II Values	Instability classes
0,01 – 0,1	Maximum stability
0,11 – 0,2	Moderately high stability
0,21 – 0,40	Moderate stability
0,41 – 0,60	Moderately low stability
0,61 – 0,80	Low stability
0,81 – 0,90	Very low stability
0,91 – 1	Non to slight stability

In a) high-intensity land use scenario, the II value was 0.83, with a very low stability (Table 8). In high-intensity land use, vulnerability expresses 83% of the inherited fragility.

For b) low land use intensity, II value of 0.08 was obtained, with a maximum stability (Table 9). In a low-intensity land use, vulnerability expresses 8% of the inherited fragility.

Discussion

Fragility to physical degradation was the most important and showed the greatest variation for the lands in the Azul district, with a marked difference between the southern and northern lands. This coincides with the division of environments in the Azul district (geomorphology): 'Pampa Deprimida' to the north and 'Pampa Serrana' to the south. In the northern sector, fragility to physical degradation was moderate to moderate-high, while in the south it was null to slight . Soils with a high percentage of exchangeable sodium (%PSI) predominate in the northern area. Sodium acts as a dispersing agent for colloids, so that they are deflocculated (Imbellone et al., 2010). This results in weak structures and low permeability, giving a high Wischmeier K value (Wischmeier and Smith, 1978) (Supplementary data). In the southern part, on the other hand, the large amount of organic matter and loamy textures give the soils stronger structures (Agostini et al., 2018), allowing adequate permeability, with low Wischmeier's K values (Wischmeier and Smith, 1978) (Supplemental data). Results showed the important impact they may have for the Azul district. According to Vázquez et al. (2016), the expansion of agriculture shifted from peripheral hills to hilly and plain environments, that is, from areas with lower fragility to physical degradation to lands with higher fragility.

Regarding fragility to chemical degradation, low differences were observed across lands. Most of them have no to very slight fragility. This is because the predominant type of clay in the Pampean region is illite, a type of clay with a high specific surface area (80 - 100 m^2. g^{-1}) and 2:1 type with high nutrients adsorption (Vázquez et al., 2006; Imbellone et al., 2010). However, chemical fertility in the Pampa region is currently at medium to low levels (Álvarez et al., 2012). It is probable that, due to the very low annual rates of change, it has taken many years to reach the current values of chemical fertility. Similar results were observed for the fragility to biological degradation, which might be explained by the fact that soils in Azul are very well provided with organic matter content, the main factor for calculating this type of fragility (Agostini et al., 2018). Therefore, no major differences in fragility to biological degradation were observed between the lands in the Azul district.

The IFDE allowed a systemic vision for the study of fragility processes to land degradation and the information generated is sustainable in human time, highlighting the permanent limitations of the system. The development of this fragility index allowed the integration of the three calculated land degradation indices (fragility to physical, chemical, and biological degradation) and, depending on which study area is concerned, the importance or weighting of each of them in the calculation could be modified. Bishnoi et al. (2021) and Syed et al. (2022) found physical, chemical, and biological parameters of great relevance for the development of new indices of land degradation. IFDE showed the maximum possible level of deterioration due to the interaction of inherited system characteristics that facilitate, or not, the processes of resource degradation (Cendrero, 1997; Massobrio, 2003; Massobrio, 2004). In addition, according to Casas (2017), Agostini et al. (2018) and Wilson et al. (2020), one of the most significant land degradation processes, due to its effect on agricultural land productivity in Argentina, is physical degradation. Given these considerations, in the development of the IFDE for Azul, it was appropriate to set fragility to physical degradation with a high value of preponderance.

Considering that agroecosystems are complex systems (García, 2008), an analysis of edaphic fauna provided information on agroecosystem responses to human disturbance (Barrios, 2007; Socarrás and Izquierdo, 2014; George et al., 2017; Rocha, 2018). The use of the different mesofauna groups to create the Instability index (II) allowed assessing the stability of the agroecosystem (Cassani et al., 2020).

For an analysis of vulnerability, i.e., an analysis of the disturbances caused by different human activities, the Vulnerability Index (IV) was developed. This used information generated by Cassani (2020) for two contrasting scenarios (Tables 7 and 8). This showed how the different expressions of vulnerability (IV) vary when the index of fragility to degradation (IFDE) is adjusted by the instability index (II). In these results it was observed that the cartographic unit MP16, despite having very low IFDE (0,01), after 25 years of continuous agriculture (high-intensity land use), can express high values of vulnerability. The IV indicates how much of the IFDE is currently being expressed by the different land use intensity. Similar results were obtained by Rocha (2018), who conducted an ecological analysis of a microbasin in Azul using biotic indicators, and observed that they were sensitive to different intensities of land use, being good indicators of agroecosystem instability.

According to Barrios (2007) and Saljnikov et al., (2022), who advocate the search for new methodologies to monitor land use and land degradation, the analysis methodology proposed was useful for the generation of information meeting the objectives of this work. This helps to predict the agroecosystem's response to new or current uses, as a tool for land-use planning. This is in line with George et al., (2017) who propose research lines in monitoring for different land uses using soil fauna. In addition, this new way of studying fragilities allows the introduction of new land degradation control practices, the results of which can be monitored through the effects on mesofauna metrics that show improved levels of stability (Rocha, 2018). Thus, the aim is seeking to identify the best land use and management options that harmonise agricultural production with the rest of the components and factors of an agroecosystem (Barrios, 2007).

Conclusions

There is a strong difference between lands in the north vs. south of Azul regarding fragility to physical degradation. In the case of fragility to chemical and biological degradation, this difference was not observed.
Research on the fragility to physical, chemical, and biological degradation of land allowed the development of a new synthetic fragility index: fragility to degradation. The IFDE integrates three indicators (fragility to physical, chemical, and biological degradation), and allows modifying the importance of each of them in its calculation. In the Azul district, fragility to physical degradation was the most important. The IFDE provides a systemic view of the processes of fragility to land degradation. The information generated is durable in human time, highlighting the permanent limitations of the system (inherited geosphere).
The instability index (II) indicates the sensitivity of the agroecosystem to disturbances caused by different land use intensities.
The vulnerability index (IV) allows an analysis of the expression of degradation due to land use. It revealed the current disturbances caused by different levels of land use intensity, expressing different levels of vulnerability. This novel index (IV) combines static factors, soil and climate, with a non-static factor, mesofauna, that represent current land use.
The fragility to degradation maps obtained allowed identifying areas where preventive and protective actions and policies should be directed.

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Declaración de autoría (CRedit)

MTC. Análisis formal, Conceptualización, Curaduría de datos, Escritura - revisión y edición, Investigación, Metodología, Redacción - borrador original, Software, Validación, Visualización.
MLS. Conceptualización, Escritura - revisión y edición, Metodología.
SPP. Adquisición de fondos, Escritura - revisión y edición, Metodología.
MJM. Adquisición de fondos, Conceptualización, Escritura - revisión, Supervisión.

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