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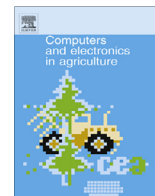
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## Application note

## Vuln-Indices: Software to assess vulnerability to climate change

R. Lardy<sup>1</sup>, G. Bellocchi\*, R. Martin

Grassland Ecosystem Research Unit, French National Institute for Agricultural Research (INRA), 5 chemin de, 6 Beaulieu, 63039 Clermont-Ferrand, France

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## ABSTRACT

Vuln-Indices Java-based software was developed on concepts of vulnerability to climate change of agro-ecological systems. It implements the calculation of vulnerability indices on series of state variables for assessments at both site and region levels. The tool is useful because synthetic indices help capturing complex processes and prove effective to identify the factors responsible for vulnerability and their relative importance. It is suggested that the tool may be plausible for use with stakeholders to disseminate information of climate change impacts.

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## 1. Introduction

Vulnerability is the degree to which a human or environmental system is likely to experience harm before being damaged (Turner II et al., 2003). Understanding what potentially unprecedented ecological and climatic changes might do to human well-being and the integrity and functioning of agro-ecosystems is perceived as a central issue in a range of regional and national concerns (Ericksen, 2008). In climate change impact studies, in particular, vulnerability indices are calculated from state variables characterising the system under study and linked to a threshold or a baseline (Lardy et al., 2014). These indices can be generated from simulations under current and altered climate scenarios and used to provide a description of the system performance under climate-change induced hazards or locate vulnerable systems and regions. A line of evolution of vulnerability studies is to enlarge the scale of study (Frazier, 2012), as the complexity in modelling shifts towards applications at progressively larger scales (e.g. Ewert et al., 2011). Maps of vulnerability indices are thus often represented to move from site-based to regional analyses (Metzger and Schröter, 2006; Metzger et al., 2006; Nelson et al., 2010).

To the best of our knowledge, freely available software solutions are not available to compute vulnerability indices in custom developed applications. This paper documents a novel software tool (Vuln-Indices) based on vulnerability concepts from the Intergovernmental Panel on Climate Change (IPCC, 2001) and

revised by Füssel and Klein (2006). In Section 2, details are provided about the metrics implemented in Vuln-Indices. Examples are considered in Section 3 to illustrate the effectiveness of the indices. Conclusions are drawn in Section 4, where the issue of vulnerability assessment is discussed in the context of current research.

## 2. Vulnerability indices and software support

Lardy et al. (2014) reviewed the indices used in vulnerability studies and proposed their utilization in climate change impact assessments (Table 1).

Vuln-Indices Java-based software allows computing vulnerability indices of Table 1 (with an option to extend them) from series of state variables (e.g. time series of simulated annual yields). The tool is meant to perform vulnerability assessment on agro-ecological systems, such as crop and grass-based production systems. Input data contain yearly series of impact variables characterising the system (primary production, harvested yield, etc.), generally obtained via model-based simulations under alternative climate forcing conditions. The main Graphical User Interface (GUI) is based on SWING (<http://docs.oracle.com/javase/7/docs/technotes/guides/swing>) and JFreeChart libraries (<http://www.jfree.org/jfreechart/>) using platform-independent Java language to allow users to load and visualize the input data, as well as display and export outputs in the form of summary tables, histograms and radar scores (Fig. 1). The data formats of input (I) and output (O) files supported are CSV and NetCDF, with export capabilities in Excel and PDF formats.

Comma Separated Values (CSV) is a simple, widely supported (by almost all spreadsheet software and database management

\* Corresponding author. Tel.: +33 4 73624866; fax: +33 4 73624457.

E-mail addresses: [romain.lardy@toulouse.inra.fr](mailto:romain.lardy@toulouse.inra.fr) (R. Lardy), [gianni.bellocchi@clermont.inra.fr](mailto:gianni.bellocchi@clermont.inra.fr) (G. Bellocchi), [raphael.martin@clermont.inra.fr](mailto:raphael.martin@clermont.inra.fr) (R. Martin).

<sup>1</sup> Current address: UMR 5505 IRIT, CNRS, University of Toulouse, 31062 Toulouse, France and UMR 1248 AGIR, INRA-INPT, 31326 Castanet-Tolosan, France.

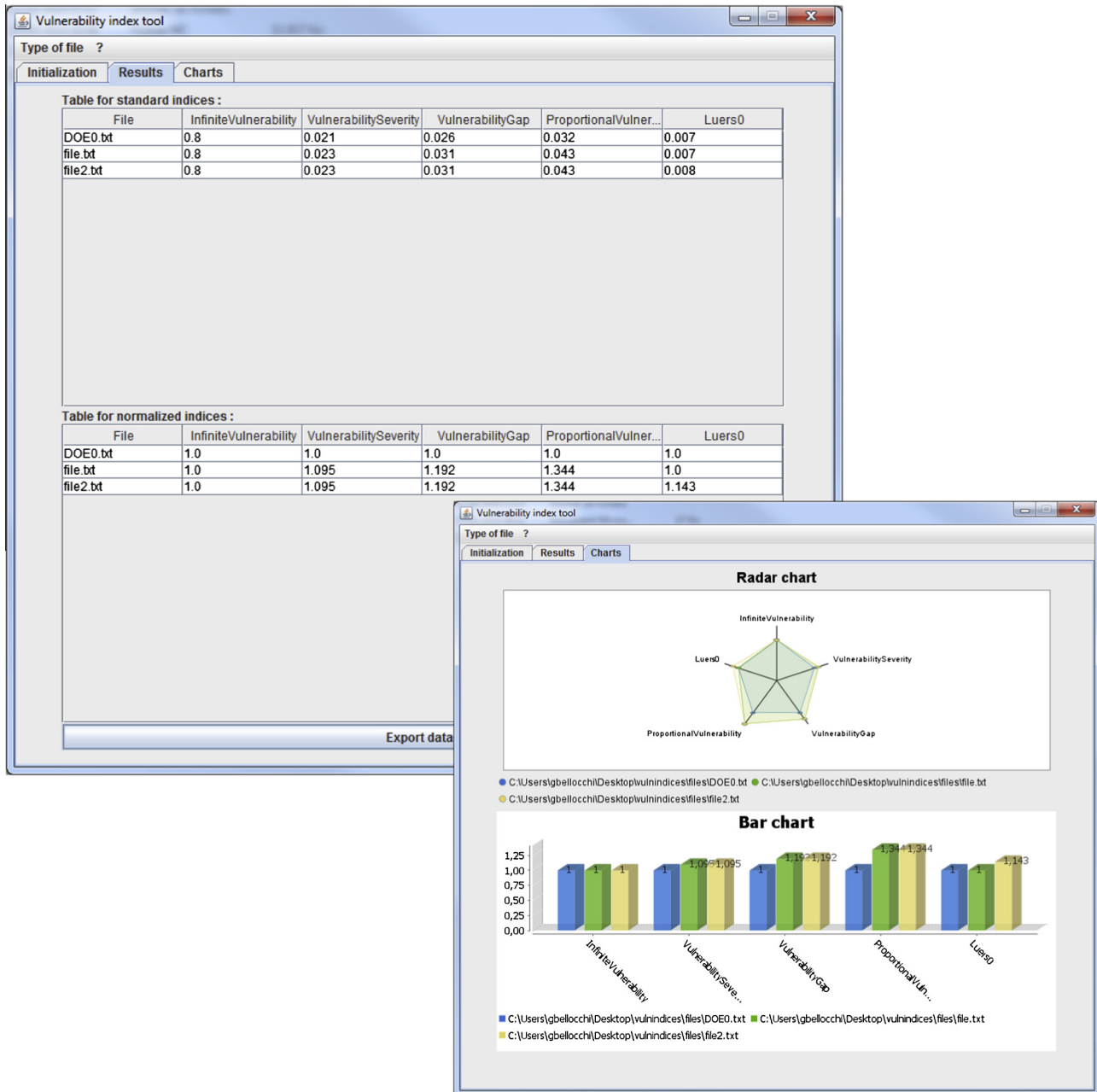


Fig. 1. Screenshot of the Vuln-Indices user interface.

systems) file format. CSV files are meant for site-specific vulnerability assessment. In this case, different sets of projection data can be used to take into account different uncertainty sources (e.g. alternative climate models or downscaling methods), the user being enabled to set weighting factors for expressing the relative probability of each feature at each location.

To facilitate moving from site-based to regional analyses, we use NetCDF file for pixel-based assessments covering large regional areas. The NetCDF (Network Common Data Form, <http://www.unidata.ucar.edu/software/netcdf>) binary format is a self-describing, compact binary format, used to store and distribute large volumes of data in machine-independent way. The NetCDF files also include embedded information on the spatial grid, making explicit the time dimension (other than latitude and longitude) as well as the units of the gridded variables. A large set of software tools and languages (e.g. R, Matlab, Java, C++) have libraries or packages to treat this

format, which is used for global and regional simulations provided for the Fifth Assessment Report (AR5) of the IPCC (Williams et al., 2009). NetCDF is already widely used in the community of spatial modelling because it is suitable to handle with pixel-wise data acquired over a defined geographical area. The result of the pixel-based rendering can be displayed in maps of vulnerability indices, as generated by using applications which plot geo-gridded arrays.

One single JAR file is freely distributed together with a file documenting the indices, software design and use.

### 3. Illustrative cases

The numerical examples provided here refer to simulations of European grasslands using the Pasture Simulation model (PaSim,

**Table 1**  
Vulnerability indices implemented in Vuln-Indices.

| Index                      | Equation  | Description  | Source               |
|----------------------------|---|--|----------------------|
| Proportional vulnerability | $V_0 = \frac{q}{n}$   | It corresponds to the ratio of vulnerable individuals to total individuals in a population (e.g. the proportion of years over a period of time in which agricultural production is below the threshold)  | Foster et al. (1984) |
| Vulnerability gap          | $V_1 = \frac{1}{n} \cdot \sum_{t=1}^q \left( \frac{W_0 - W_t}{W_0} \right)$   | In a population of individuals, it represents the mean proportion of deficit of vulnerable individuals from the value selected as threshold (e.g. the difference from the threshold of below-the-threshold annual production values over a number of years)  | Foster et al. (1984) |
| Vulnerability severity     | $V_2 = \frac{1}{n} \cdot \sum_{t=1}^q \left( \frac{W_0 - W_t}{W_0} \right)^2$ | In a population of individuals, it represents the mean proportional distance of vulnerable individuals from the threshold. The quadratic distance to threshold is used, which gives more weight to the most vulnerable cases, i.e. the greater the vulnerability is skewed towards the most vulnerable case (e.g. the least productive year) the greater is the severity | Foster et al. (1984) |
| Most vulnerable individual | $V_\infty = 1 - \frac{\min(W_t)}{W_0}$  | It is the distance from one of the ratio of the state of the most vulnerable case (e.g. the least productive year) to the threshold.   | Lardy et al. (2012)  |
| Luers-based                | $V_L = \frac{dW/dX}{W/W_0}$   | It accounts for the sensitivity of the system to a stress factor (e.g. changes of agricultural production with aridity conditions), with respect to a given state. The coefficient of variation calculated over a series of states (e.g. a time series of agricultural production values) is adopted here to represent sensitivity (after Lardy et al., 2014)            | Luers et al. (2003)  |

$q$ , number of vulnerable individuals (e.g. number of vulnerable years).

$n$ , population size of individuals (e.g. number of years).

$\bar{W}$ , average state of the system over a time period (e.g. mean agricultural production over a number of years).

$W_t$ , state of the system at time  $t$  (e.g. agricultural production at a given year).

$W_0$ , threshold value of the state of the system (e.g. agricultural production below which the system is considered vulnerable).

$dW$ , variation of the state of the system over a time period (e.g. variability of agricultural production over a number of years).

$dX$ , variation of a climate exposure factor over a time period (e.g. variability of aridity conditions over a number of years).

Ben Touhami et al., 2013; Ma et al., 2015), which is engineered for distributed computing to meet the needs of high-resolution regional simulations (Vital et al., 2013).

### 3.1. Site-specific assessment

Table 2 reports four vulnerability indices calculated upon grassland yields (harvested dry biomass) per year obtained at a low productivity upland permanent pasture in France (Theix; 45°43' North, 03°01' East, 850 m a.s.l.) for three 30-year time horizons (extracted from a simulation from 1970 to 2099), representative of near past (1970–1999), near future (2020–2049) and far future (2070–2099). The hourly weather data used to force the model were from the SRES-A2 storyline, which envisages high emissions of greenhouse gases as a result of continuous population growth and regionally-oriented economic development (IPCC, 2000). To quantify the probability for the grassland system to incur potentially hazardous climate events, precipitation and temperature hazardous events in each year were quantified via an agro-climatic metric of aridity,  $b \geq 0$ , arid conditions being represented by small values of  $b$  (after Diodato and Ceccarelli, 2004). The results show that the overall mean annual yield may increase with climate change. However, a greater chance of exposure to heat and drought stress (shift towards lower  $b$  values) may also lead to higher inter-annual variability (higher standard deviation of yields). The vulnerability indices are presented as both absolute and relative changes with respect to the baseline (time slice 1970–1999). A relative value greater than one is indicative of higher expected vulnerability for adverse climate effects in the future, while a value less than one provides the clue to less vulnerability. Due to the specific construction of the Luers-based index, this normalisation also makes it independent on the threshold setting.

Different vulnerability indices offer complementary insights into the system yet with contrasting views of vulnerability. According to both proportional vulnerability and vulnerability gap (relative values lower than one), the probability for the grassland yields to go down below the threshold value is lower in the future because the distance to the threshold is higher in the past. Vulnerability severity reflects a more complex pattern (relative

value lower than one in the near future, higher than one in the far future) depending on the distribution of all of the distances to the threshold. However, in the metrics used by these indices, there is no analytical expression of the sensitivity of the state variable to a change in the climatic hazard. When the sensitivity factor is taken into account (as reflected in the inter-annual variability of climate conditions), as in the Luers-based index, conditions of higher vulnerability are disclosed (relative values higher than one) due to the expectation of more severe aridity conditions in the future.

### 3.2. Regional assessment

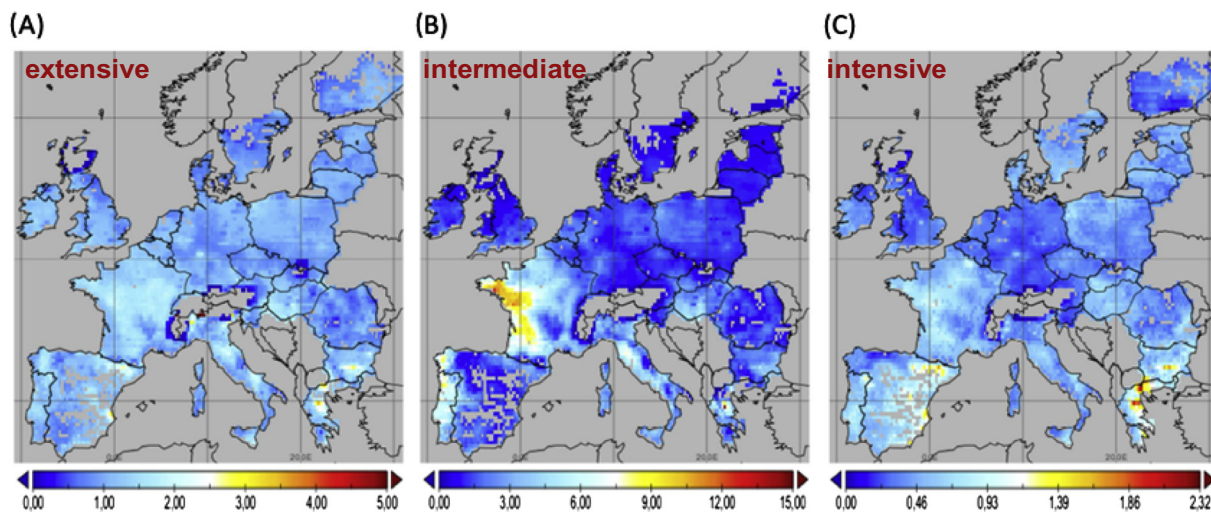
The example sketched in Fig. 2 shows the spatial pattern of Luers-based vulnerability index, as obtained by using freeware Panoply Data Viewer (DataONE, 2014). The index was calculated for 2070–2099 on the harvested dry biomass estimated for three intensification scenarios in Europe according to SRES-A1B storyline, in which current trends in emissions continue leading to a doubling in CO<sub>2</sub> levels by the end of the 21st century (IPCC, 2000). The simulations (based on a protocol established in the frame of EU-FP7 GHG-Europe, <http://www.ghg-europe.eu>) were run on 170 × 278 grid points at 0.25 × 0.25° resolution, spanning from 29.125 to 71.375 latitude North and from 23.875 longitude West to 45.375 longitude East. In some pixels, the index was not calculated (e.g. in some Spanish regions) as the simulated biomass was not sufficient to initiate a harvest. The maps also show the importance of management to influence the vulnerability of grasslands to climate change.

Overall, the IPCC SRES A1B climate change projections to the end of the 21st century are shown to reduce the vulnerability of intensively managed European grasslands (Fig. 2C). The results obtained suggest instead that an increased vulnerability is on average expected with intermediate level of management (Fig. 2B). It is also interesting to see the pattern of regional variations. For instance, climate change is likely driving grassland systems with intermediate management into more vulnerable conditions in a noticeable portion of western France.

**Table 2**  
Grassland yields estimated over three time horizons: climate exposure (mean aridity conditions), mean and standard deviation, and vulnerability indices (threshold yield set equal to 5 t DM ha<sup>-1</sup>).

| Period    | Mean yield<br>t DM ha <sup>-1</sup> | Standard deviation | Mean aridity index ( <i>b</i> ) <sup>*</sup> | Vulnerability indices      |          |                   |          |                        |          |             |          |
|-----------|-------------------------------------|--------------------|--|----------------------------|----------|-------------------|----------|------------------------|----------|-------------|----------|
|           |                                     |                    |  | Proportional vulnerability |          | Vulnerability gap |          | Vulnerability severity |          | Luers-based |          |
|           |                                     |                    |  | Absolute                   | Relative | Absolute          | Relative | Absolute               | Relative | Absolute    | Relative |
| 1970–1999 | 4.25                                | 0.57               | 29.10  | 0.866                      | –        | 0.157             | –        | 0.034                  | –        | 0.158       | –        |
| 2020–2049 | 4.62                                | 0.75               | 27.50  | 0.733                      | 0.846    | 0.101             | 0.643    | 0.024                  | 0.686    | 0.176       | 1.114    |
| 2070–2099 | 4.45                                | 0.81               | 16.50  | 0.733                      | 0.846    | 0.130             | 0.828    | 0.036                  | 1.052    | 0.205       | 1.297    |

<sup>\*</sup>  $b = \frac{1}{2} \cdot \left( \frac{P_Y}{T_Y+10} + \frac{p_a}{T_a+10} \right)$  (De-Martonne, 1942):  $P_Y$ : yearly precipitation total (mm),  $Y_Y$ : mean annual temperature (°C),  $p_a$ : precipitation total of the driest month (mm),  $T_a$ : mean temperature of the driest month (°C).



**Fig. 2.** Luers-based vulnerability index for harvested dry biomass in far future (2070–2099) for: (A) extensive management, (B) intermediate management and (C) intensive management. Index values were normalised over the reference period (1980–2009). Each pixel value is a three-pixel depth average, i.e. the average across 25 pixels, weighted as follows: 0.5 the pixel of interest, 0.3 the eight nearest ones, 0.2 the other 16 pixels (details provided by Lardy (2013), p. 154).

#### 4. Conclusions

We propose a software tool to support quantitative (index-based) assessments of vulnerability to climate change (even if the tool is generic enough to be used for other assessments of vulnerability on virtually any kind of systems). Providing usable values of synthetic indices, the approach allows performing model-based inference of agro-ecological systems vulnerability to a variety of climate forcing scenarios, and can be complementary to probability risk analyses (van Oijen et al., 2013, 2014). The approach proposed seeks to combine an index-based scheme with computer-based simulation modelling, both being part of a deliberative process in climate change studies (e.g. Rivington et al., 2007; Bellocchi et al., 2015). In fact, the latter is a useful means of providing new information to stakeholders (land managers and decision makers) about vulnerability to climate change and generating dialogue around its interpretation. With synthetic indices there is the trade-off between the level of detail provided by climate and impact models under sets of conditions and timeliness for decision-making. Integrating the presentation of spatially refined gridded maps with sensitivity to climate, they may support the communication flow of the vulnerabilities and the co-construction of knowledge among scientists and stakeholders (Rivington et al., 2013).

The results presented here are illustrative and, as such are not meant as conclusive findings on the vulnerability of European grasslands. These results, not accounting for the many sources of uncertainties associated with grassland management, emission

scenarios, climate and impact modelling, are exemplary of the type of achievement that can be attained in vulnerability analysis based on the use of synthetic indices on both site-specific and regional perspectives. Further developments on model-based vulnerability analyses are certainly needed. The investigation should be extended to the recent scenarios used by the 5th IPCC Assessment Report (IPCC, 2013), while covering the pattern of services (not only marketable yield) provided by agro-ecological systems (thus identifying the vulnerabilities to each service). This kind of action is ongoing, in interaction with stakeholders, under the guidance and conditions laid down by the EU-FP7 project AnimalChange (Bellocchi et al., 2013), and other initiatives aiming at assembling Vuln-Indices and other tools for vulnerability assessment, and automate their linking to high-performance computing tools (Bellocchi et al., 2014).

#### Software availability

Name of Software: Vuln-Indices  
Developer: Raphaël Martin  
Contact Address: INRA, UR0874 Grassland Ecosystem Research, 63039 Clermont-Ferrand, France  
Tel.: +33 4 73624872  
E-mail: raphael.martin@clermont.inra.fr  
Availability: On request to the authors  
Cost: free for no-profit use  
Program language: Java



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