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Numerical methods for project vulnerability analyses with guidelines for use

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AnimalChange

SEVENTH FRAMEWORK PROGRAMME

THEME 2: FOOD, AGRICULTURE AND FISHERIES, AND
BIOTECHNOLOGIES



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DELIVERABLE 15.3

Deliverable title: Numerical methods for project vulnerability analyses with guidelines for use

Abstract: The goal of task 15.3 of AnimalChange project is to provide an array of tools to assess vulnerability to climate change of livestock production systems.

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1. Introduction

The climate is composed of both the mean climate signal (e.g. average annual temperature cycle) and its temporal variability, which also includes the occurrence and magnitude of extreme events. Climate change results in both changes in the mean climate signal (e.g. average annual temperature) and its temporal variability (including the occurrence and magnitude of extreme events). In a climate change context vulnerability is therefore defined as “*the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability is a function of the **sensitivity** of a system to changes in climate (the degree to which a system will respond to a given change in climate, including beneficial and harmful effects), **adaptive capacity** (the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate), and the degree of **exposure** of the system to climatic hazards*” (IPCC, 2001). Probabilistic measures and a set of indices of vulnerability, accounting for sensitivity, exposure and adaptive capacity are proposed. The procedures for vulnerability assessment described in this report reflect the methodology outlined by Lardy *et al.* (2011, 2012), and integrates principles from the probabilistic assessment of vulnerability as elaborated by van Oijen *et al.* (2013) in the framework of EU-FP7 CARBO-Extreme project (<http://www.carbo-extreme.eu>). In task 5.2 (Vulnerability analysis of changes in production), the vulnerability to climate change of pastures, arable feed crops and animal production will be assessed for Europe and study regions in Africa and South-America. System models from WP3 and WP4 are meant to be up-scaled to the scale of the project regions in WP5 using datasets and scenarios from WP2 for climate, soil, land-use, crop and pasture management, animal production and manure management. Projections in WP5 will be consistent with baseline and CO₂ stabilization scenarios produced for IPCC AR5.

The goal of task 15.3 of AnimalChange project is to provide an array of quantitative tools to assess vulnerability to climate change of grassland-livestock production systems for application in the project, mainly in task 5.2. This deliverable follows D5.2 (Report on methodology of vulnerability analysis; date of delivery: M18), in which much of the issues about vulnerability analysis were anticipated. They are recapped in this deliverable, whereby the operational aspects of vulnerability assessment are addressed with more detail, including the illustration of a dedicated software tool for the computation of indicators of vulnerability.

The baseline is given by assessments without taking adaptation/mitigation measures (potential impact assessment). However, since vulnerability of an ecosystem to climate change is less when farmers or society are able to adapt to changes, it is also important to assess and compare the vulnerability taking into account adaptive capacity (residual impact assessment). Adaptation/mitigation strategies may aim at decreasing ecosystem sensitivity, changing the threshold of damage, or reducing exposure. For instance, reduction of sensitivity and exposure to drought may be obtained by shifting management practices such as using drip irrigation and taking measures to increase soil water retention. Shifting to more drought resistant crops or dig groundwater wells are also potential measures in the long-term. In the frame of AnimalChange, WP8 provides process-based estimates of mitigation and adaptation options, as related to tasks 8.2 (Integrating mitigation and adaptation options in intensive ruminant production systems by process based modelling) and 8.3 (Integrating mitigation and adaptation options in extensive pasture based production systems by process based modelling). In these tasks, process-based models are used to evaluate the effect of adaptation/mitigation measures under various conditions, which can be dealt with according to the vulnerability assessment concept.

2. Conceptual framework for vulnerability assessment

Below is a list of concepts commonly used and providing a framework for vulnerability assessments. It follows the diagram of Fig. 1, which represents the essential components of vulnerability to climate changes.

1. **HAZARD.** A **hazard** is a factor that can cause damage. Any environmental variable constitutes a hazard if too low or too high for optimal ecosystem performance. It becomes hazardous if it is in the range of values that generate negative impacts under on the ecosystem variable under study; According to an “external” definition of hazardous conditions, they are known before the simulation results are produced, e.g. by inspecting definition of extreme events commonly used in the literature; According to an “internal” definition, hazardous ranges of environmental variables are derived from the modelling results.
2. **EXPOSURE.** The exposure is the set of shocks and disturbances to which the system is subject with a certain probability. In our case, it is the degree and nature of environmental change (e.g. long periods under high temperature) to which the ecosystem is subject. Exposure is actually influenced by global change and climate variability, GHG concentrations and **non-climatic factors** (set of environmental, political, socio-economic, demographic and technical factors). Non-climatic factors are defined by the **non-climatic scenarios** (e.g. maize price scenarios).
3. **SENSITIVITY.** The sensitivity (also said **susceptibility**) is the degree to which a system is affected, positively or negatively, by climatic stimuli. The sensitivity of a system becomes particularly important when substantial changes in the system arises for low levels of climatic changes, whereas for strong stimuli (such as extreme events), the system recovery properties predominate, namely the **amplitude** and the **elasticity**. **Amplitude**, also called **ecological resilience**, is the maximum tolerated perturbation before changing the system so much that we are not able to come back to its reference state. It corresponds to the internal adaptation capacity of a system, defined as the recovery potential of an ecosystem (De Lange *et al.*, 2010). The recovery rate against small perturbations (“**engineering resilience**”, Holling, 1996), defined as the rate of return to the reference state (or dynamic) after a temporary disturbance (Grimm and Wissel, 1997) is also called **elasticity**. Together, sensitivity, ecological resilience and elasticity represent the ecosystem **stability**, and are mainly influenced by non-climatic factors.
4. **IMPACTS.** Impacts are principally driven by exposure of the system to climatic pressure and its stability properties. Among the impacts, we can distinguish **potential impacts** and **residual impacts**, which are all the impacts resulting from climate change before or after strategy application (*i.e.* adaptations or mitigations), respectively. The vulnerability is sometimes seen as the residual impacts of climate change after adaptation measures have been taken (e.g. FAO, 1996, IPCC, 2007).
5. **ADAPTIVE CAPACITY.** The concept of residual impacts uses the notion of **adaptive capacity**, *i.e.* the system ability to change in order to be less vulnerable. In the climate change context, it can be defined as the system ability to adjust to climate change (including climate variability and extreme phenomena), to moderate potential damages, to take advantage of opportunities or to cope with the consequences. Adaptive capacity is a direct function of non-climatic factors. **Vulnerability** is a function of impacts and adaptive capacity. Within the adaptation (and mitigation) capacity, we can distinguish **potential adaptation capacity** and **real adaptation capacity**, whether it is limited or not by non-climatic factors.



6. ADAPTATION AND MITIGATION STRATEGIES. **Mitigation** consists in reducing the sources or enhancing the sinks of GHG (Füssel and Klein, 2006), whereas **adaptation** policy is to reduce the negative and inevitable effects of climate change. The major prerequisite for such strategies is the adequacy of resources needed to implement them. Historically, mitigation has received more attention because, on one side, mitigation reduces the impact on the integrity of all the systems potentially sensitive to climate change. On the other hand, the potential of adaptation policies is very limited for some systems. For a more accurate comparison between adaptation and mitigation, the reader is referred to Füssel and Klein (2006). These two, yet different but intimately linked strategies, can influence a number of factors. Adaptation seeks primarily to influence stability, non-climatic factors and system exposure and thus the impact of climate change on specific systems, whereas mitigation mainly impacts the GHG concentrations in the atmosphere through reduction in emissions.

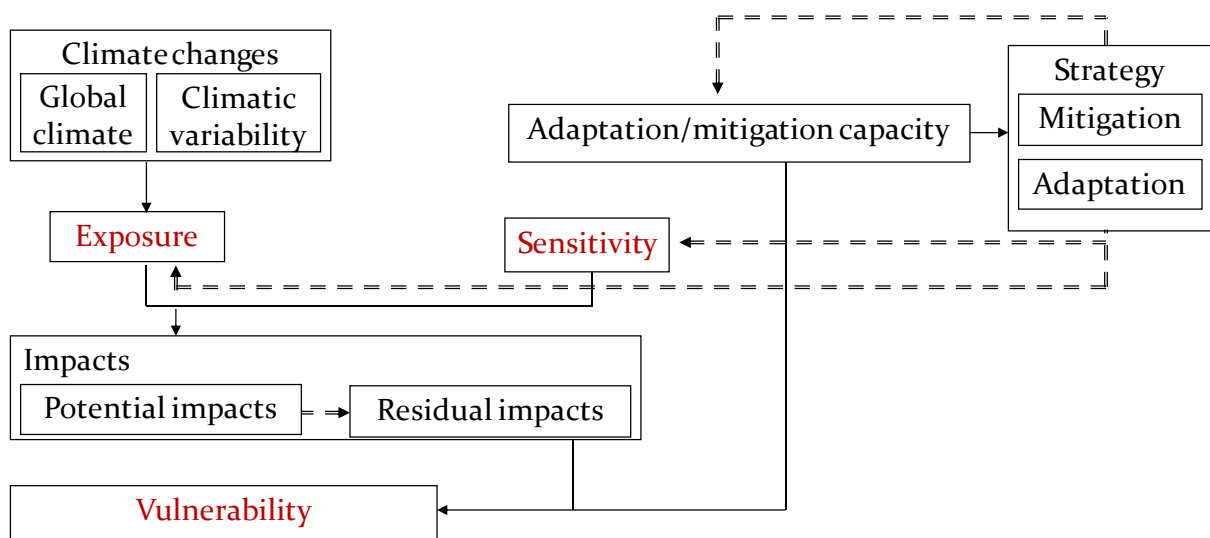


Figure 1. Conceptualization of vulnerability to climate change, after Lardy *et al.* (2012). Dashed arrows represent the feedbacks of mitigation and adaptation strategies onto climate change impacts.

3. Probabilistic vulnerability assessment

Vulnerability is defined in such a way that it includes both the elements of an impact assessment (*i.e.* sensitivity of a system to a hazard and exposure to hazardous conditions), and adaptive capacity to cope with potential impacts of climate change. A probabilistic framework has been developed for application to ecosystems in collaboration with the EU-FP7 CarboExtreme project.

This approach is based on a probabilistic risk assessment, which combines probability distribution functions (PDF) of climatic hazards (**exposure**) and of ecosystem processes **sensitivity** to those hazards. The PDF of climate change **impact** is then calculated from the probability of sensitivity conditional to exposure. In this way, the framework includes both the effects of variability (in climate) and of uncertainty (in model parameters and structure). **Adaptation** can further be considered to derive the probability distribution function of residual impacts after adaptation, which defines a probabilistic **vulnerability**.



As the system is less vulnerable to climate when less exposed to hazardous events and less sensitive to them, vulnerability analysis is the result of a three-step procedure in which exposure, sensitivity and impact are assessed (examples below).

1. Exposure

There is an interest to quantify the probability for ecosystems to incur potentially hazardous climate events. This can be done by quantifying precipitation and temperature hazardous events via agro-climatic metrics. The climate hazard can be appreciated by analyzing statistics of high values (e.g. 95th percentile). The example of Fig. 2 is generated from the probability distribution of two key agro-climatic indices (length of dry spell, mean number of heat waves over May-September) for different time slices and for an ensemble of climate models in Europe.

2. Sensitivity to climatic hazards

The sensitivity of an ecosystem process to a given change in a climatic variable may be evaluated through modeling. For instance, pasture production sensitivity to hazardous climatic conditions can be modeled by:

- i) Defining hazard conditions, e.g. low precipitation values. For instance, hazardous conditions may be defined as precipitation below the 25th percentile;
- ii) Studying simulated pasture production in response to the hazardous conditions. For instance, simulated variations in pasture production between future (e.g. 2079-2100) and past (e.g. 1999-2010) climate conditions associated with hazardous low precipitation values can be calculated.

Importantly, the sensitivity of the studied variable to a given climatic hazard may vary over time as a direct result of climate change (e.g. soil and vegetation degradation may result in a higher sensitivity to a low precipitation event).

Fig. 3 is an example of how the sensitivity of an ecosystem can be appreciated with respect to precipitation values. In this case, variations in gross primary productivity (*GPP*) between future (2079-2100) and past (1999-2010) climate conditions, as estimated by JSBACH model, are shown associated with low precipitation values. In particular, hazardous conditions were set to as precipitation below the 25th percentile. A negative sign shows that *GPP* is a smaller sink or a larger source under hazardous conditions; a positive sign shows that *GPP* is a larger sink or smaller source under hazardous conditions.

3. Impact

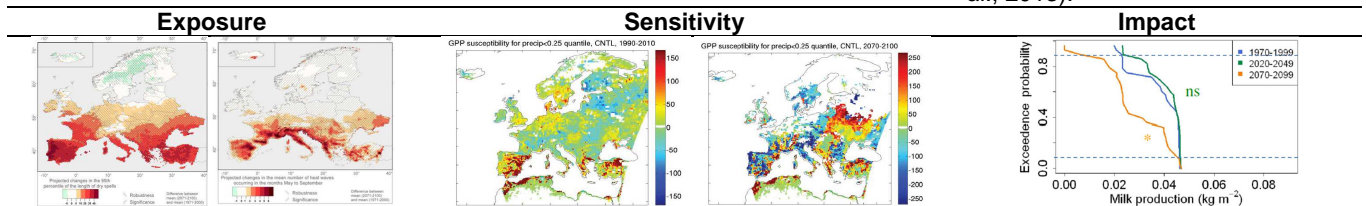
Multiple scenarios provide us with a range of possible changes in climate (*i.e.* exposure) and allow us to assess the response of ecosystems and changes in the services they provide (*i.e.* potential impacts). Standard analyses target mean annual impacts (e.g. yield levels) by comparing 30-year time slices of future and past conditions. Low and high percentiles (e.g. 10th and 90th) are also selected as options to represent impacts associated with worse and best years. They can be extracted from distribution functions as in the example of Fig. 4, which shows an increased risk of low summer milk production towards the end of the century compared to current conditions (for a pasture site in eastern France). This statistical approach shows that the 90th percentile for daily summer milk production per unit pasture area (kg m^{-2}) drops from 0.025 to 0.010 g at the end of the century compared to the reference time period.

Changes over time can be studied in this way for a given site. However, when comparing sites across regions, relative changes – e.g. (future mean yield – past mean yield) / past mean yield – need to be calculated in order to scale future changes in relation to their current value.

Figure 2. Projected changes of the differences in the 95th percentile of two climatic variables (left: length of dry spells; right: mean number of heat waves) from two time slices (past: 1971-2000; future: 2071-2100), as generated by an ensemble of models in Europe (from the EC-ENSEMBLES project, CMIP3) // // // Significant (P<0.05) \\ \\ \\ Robust (>2 models out of 3)

Figure 3. Gross primary productivity sensitivity (susceptibility) to low precipitation events as simulated by JSBACH model for control (left: 1990-2010) and future (right: 2070-2100) conditions.

Figure 4. Example of exceedence probabilities for an impact variable (summer milk production as affected by climate change) for a pasture site in eastern France under three 30-year time slices. Simulations were run with the Pasture Simulation model (PaSim) assuming a constant management during the course of the century. Horizontal lines indicate the 10th (bottom) and the 90th (top) percentile, respectively (Graux *et al.*, 2013).



4. Vulnerability indices

Lardy *et al.* (2012) documented a number of indices that have been developed to perform vulnerability assessment (Table 1).

Table 1. Summary of vulnerability indices. W is the state variable (e.g. productivity), W_0 is the threshold value, n is the number of elements (e.g. years), q is the number of elements below the threshold value. When calculated, the indices are weighted by exposure.

Index	Formulation	Notes
Proportional vulnerability (Foster <i>et al.</i> , 1984)	$V_0 = \frac{q}{n}$	It corresponds to the number of vulnerable individuals (years) in a population.
Vulnerability gap (Foster <i>et al.</i> , 1984)	$V_1 = \frac{1}{n} \sum_{i=1}^q \frac{(W_0 - W_i)}{W_0}$	It represents mean deficit in vulnerable individuals (years).
Vulnerability severity (Foster <i>et al.</i> , 1984)	$V_2 = \frac{1}{n} \sum_{i=1}^q \left(\frac{(W_0 - W_i)}{W_0} \right)^2$	The distance to threshold is used as a weight. More weight is given to the most vulnerable cases.
Most vulnerable individual	$V_\infty = 1 - \frac{\min_i W_i}{W_0}$	It is the relative distance to threshold of the most vulnerable case.
Luers <i>et al.</i> (2003)	$V_L = f \left(\frac{ \partial W / \partial X }{W / W_0} \right)$	The coefficient of variation is used for quantifying the sensitivity of the system.

Vulnerability is a relative notion, and absolute values attached to a vulnerability index are not meaningful (Downing *et al.*, 2001). Mostly, defining the vulnerability of a system requires identifying a threshold below or above which the system is considered to be damaged.

5. Comparing vulnerability assessment methodologies

1. Field scale

Lardy *et al.* (2011) have used this approach to derive response surfaces of pasture model sensitivity to a variety of climatic conditions and according to a range of simulation designs:

- The first design (“simple”) consists in merely simulating the pasture system over 30 years time slices for a given management and under fixed atmospheric CO₂ concentration;
- In the second design (“climate uncertainties”), a bootstrap method was used to check that the occurrence of individual climatic years is a random event (low correlation between successive years);
- In the third design (“Extreme events”), the frequency of hazardous conditions (e.g. number of arid years in a time slice configuration) was artificially increased in the 30-year time series;
- In the fourth design (“Management”), uncertainties in management were introduced by considering a Gaussian distribution for mowing dates.

Table 2. Vulnerability indices (see Table 1) calculated by Lardy *et al.* (2012) with different designs for ‘near future’ (NF: 2020-2049) and ‘far future’ (FF: 2070-2099). The values are relative to the “reference period” (RP: 1975-2004). The higher the index, the more vulnerable the system is. An upland permanent pasture in France was simulated (ModVégé model, Jouven *et al.*, 2006a, b) for three time slices of 30 years each. Future climate projections are based on the A1B emission scenario, as generated by the climate model ARPEGE (Déqué *et al.*, 1994) downscaled by “weather anomalies” method (Déqué, 2007).

Design \ Index	Most vulnerable individual		Luers' index		Proportional vulnerability		Vulnerability gap		Vulnerability severity	
	NF	FF	NF	FF	NF	FF	NF	FF	NF	FF
Simple	1.62	2.76	1.66	2.23	2.13	2.63	3.14	7.64	4.49	20.37
Climate	1.57	3.00	1.42	2.33	1.92	2.58	2.98	8.35	4.38	23.58
Extreme events	1.62	2.77	1.67	2.22	2.16	2.64	3.16	7.64	4.48	20.22
Management	1.45	2.45	1.67	2.19	2.06	2.55	3.08	7.42	4.12	18.65

Vulnerability indices were calculated for each design (Table 2). As expected, given the constant CO₂ concentration, climate change had negative impacts on the pasture system studied (thereby changing the vulnerability index). This is due to decreased grassland productivity, though with slightly reduced inter-annual variability. Simulations accounting for extreme events frequency uncertainties did not show differences compared with the “simple” design, probably due to the low responsiveness of the model to extreme events. Accounting for climate years order uncertainties (design 2) globally increased vulnerability values. This shows that uncertainties on climate scenarios, climate models and regionalization techniques should be accounted in climate change vulnerability assessment studies. Whatever index is considered, uncertainties on management (*i.e.* mowing dates) tend to reduce vulnerability. This means that the sensitivity and the uncertainties on cutting dates should be accounted for in an impact assessment, but also when looking for adaptation options.

Including a range of indices in vulnerability assessment is important because each of them contains complementary information. For instance, the most vulnerable individual index

informs us that the productivity of the most vulnerable year is expected to be up to three times lower in the far future than at present (design 2), whereas vulnerability severity informs about how severely the system is expected to be damaged. At the same time, thanks to the vulnerability gap, we know that average missing biomass for vulnerable cases may increase up to eight times, whereas the number of vulnerable cases increases by 2 to 2.5 for NF and FF period, respectively (proportional vulnerability). The Luers' index (calculated here using the coefficient of variation as sensitivity measure) is a kind of average index, which combines information on global productivity with the variability of the system. It also has the advantage of being threshold-independent when using the coefficient of variation (but still dependent on the reference period chosen), and as such does not require decisions regarding thresholds.

2. European, pixel-based scale

In order to have a large-scale application example of different vulnerability indices, a complex mechanistic grassland model was employed to run pixel-based simulations of European grasslands. The simulations were run on 170 x 278 grid points at 0.25 x 0.25 degree resolution, spanning from 29.125 to 71.375 latitude North and from 23.875 longitude West to 45.375 longitude East.

This example is illustrative of the type of outcome that can be achieved by vulnerability assessment in the case of regional analyses.

Weather data were supplied by Christian Beer (Max-Planck Institute for Biogeochemistry, Jena, Germany) within the frame of EU-FP7 CARBO-Extreme, arranged in two groups. In the period from 1901 to 2010, hourly weather inputs were reconstructed from observational data, mainly based on 0.5° resolution of daily values supplied by EU-FP6 WATCH (<http://www.eu-watch.org>) and ERA-Interim tool (<http://www.ecmwf.int/research/era/do/get/era-interim>), and downscaled to 0.25° via CRU CL 2.0 (http://www.cru.uea.ac.uk/~timm/grid/CRU_CL_2_0.html). For 2011-2100, the A1B emission scenario (IPCC, 2007) was adopted with its assumptions about future energies (balanced emphasis on all energy sources) and world demography (moderate population and high income growth) to generate weather data from an ensemble of regional climate models (based on EU-FP6 ENSEMBLES, <http://www.ensembles-eu.org>).

The average annual concentration of CO₂ in the atmosphere (the same for all Europe) was also used as input (thus ignoring seasonal to hourly dynamics). Values were reconstructed for the period 1901-2010, based on the recovery of ice cores and the analysis of atmospheric observations as carried out by the National Oceanic and Atmospheric Administration (<http://www.noaa.gov>). From 2011 onwards, annual average CO₂ concentrations for the SRES A1B storyline (IPCC, 2007) were used.

The soil properties needed to input the grassland model were retrieved from the Harmonized World Soil Database (<http://www.fao.org/nr/land/soils/harmonized-world-soil-database>) and aggregated to comply with weather data

Grassland management data were from the protocol developed within EU-FP7 GHG-Europe (<http://www.ghg-europe.eu>), based on results from EU-FP6 Nitro-Europe (<http://www.nitroeurope.eu>). By using country and region based statistical data (available for the year 2010), three intensification levels (extensive, intermediate and intensive) were generated. Cutting dates were made climate-dependent by using thermal sums on a base of 5 °C (from the 1st of January), that is, 900 °C-days for Low, 500 °C-days for Medium, and 500 °C-day and 1200 °C-day for High (two cuts). No cutting was done if such thresholds were not met. Nitrogen fertilization took place three days after cutting. Grazing started 30 days after

the last cutting event and lasted until the end of year or at the first occurrence of five or more consecutive ice days. Likely to cutting events, grazing did not take place if the required sums of temperatures were not met. Starting with statistical data for 2010, transformation rules were applied to generate past and future management:

- 1901-1950. For each intensification level, low-type management is used with no mineral fertilization, (which mean that only legume fraction differs between intensity levels);
- 1951-2010. Over this period, the grassland management was progressively intensified up to achieve the values of 2010 based on regional and national statistics: the amount of N fertilization and animal stocking rate were linearly increased, cutting date was gradually anticipated towards 500 °C-d from 900 °C-d (a second cutting event occurred since 1981);
- 2010-2100. The management of 2010 was kept constant over this period.

Some European countries were ignored due to missing or poor quality statistical data.

The biogeochemical model PaSim (<https://www1.clermont.inra.fr/urep/modeles/pasim.htm>) was implemented on a pixel basis and run to simulate grasslands over Europe. Using the basic parameterization of the model for permanent grasslands, the exercise consisted of simulating three climate time slices in the late 20th century and the 21st century: 1980-2009, reference period; 2020-2049, near future; 2070-2099, far future. More details are given by Lardy (2013) with a pattern of results on testing the use of vulnerability indices on a variety of outputs.

The example sketched in Fig. 5 shows the spatial pattern of Luers index, calculated for 2070-2099 on the harvested dry biomass estimated by PaSim for three intensification scenarios. 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 absence of values characterise high vulnerable zones. 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 21th century are shown to reduce the vulnerability of intensively managed European grasslands (Fig. 5C). The results obtained suggest instead that an increased vulnerability is on average expected with intermediate level of management (Fig. 5B). However, it is 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.

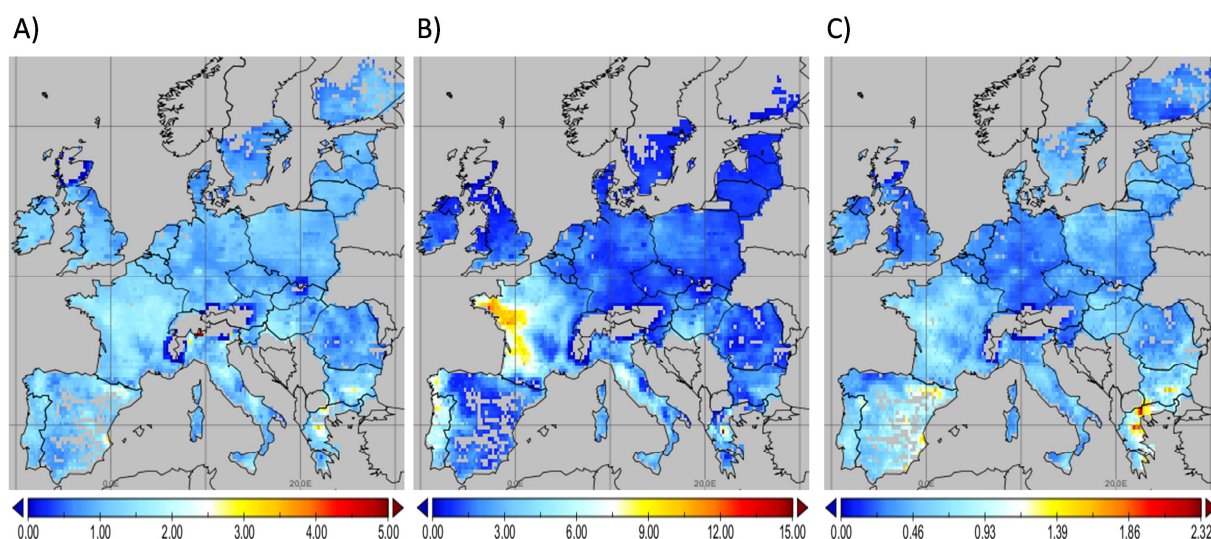


Figure 5. Luers vulnerability index for harvested dry biomass in far future (2070-2099) for: A) extensive management, B) intermediate management, C) intensive management. Index values were normalized over the reference period (1980-2009). They were calculated using until two levels neighbour pixels, in which each pixel value is 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. The higher the vulnerability index, the higher is the vulnerability of grassland systems to changes in climate.

These results do not account of the many sources of uncertainties associated with the grassland management, emission scenarios, climate and impact modelling. They are exemplary of the type of achievement that can be attained in vulnerability analysis based on the use of synthetic indices on a regional perspective.

6. Implementation of vulnerability analysis

In AnimalChange, the implementation of vulnerability assessment will be grounded to the general definitions of this deliverable. Impact variables, vulnerability indices and weather metrics to be analysed will be defined in detail via an exchange with involved partners (notably, INRA, CEA DLO, ILRI, EMBRAPA, IIASA, UP, FAO). Vulnerability analysis is meant to be run on a set of impact variables, as simulated by a core of ecosystem models, such as:

- Grassland-specific model: PaSim (INRA)
- Global model, adapted to grasslands: ORCHIDEE-PaSim (CEA)
- Crop model: CERES-EGC (INRA)
- Crop model with extension at different scales: EPIC-GLOBIOM (IIASA)

A vulnerability analysis may be implemented based on any impact variable. Application in the AnimalChange project will be limited to productivity outputs at the scale of simulation defined by task 5.1. Maps of vulnerability indices will be generated, with the complement of probability distributions of production losses at selected areas. Moreover, the comparison of multiple climate and impact models will provide an estimate of the uncertainty associated with using alternative modelling solutions.

To characterize climate change hazards, an initial set of climatic hazard metrics will include the three indicators in Table 3. Dry spells are based on precipitation only and are indicative prolonged periods of dry weather. However, they are not as severe as a drought and may appear interspersed with occasional large rain events (>100 mm). Heat waves address the issue of prolonged periods of excessively hot weather. The aridity index combines

temperature and precipitation values. An altered pattern of these two climatic variables may mean an expansion of aridity conditions. This metric indicates the relative dryness of an area and thus summarises the agricultural production potential that can be attained.

Table 3. Short list of hazard indicators. P : daily precipitation (mm), T_{max} : maximum daily temperature, P_y : yearly precipitation total (°C), T_y : mean annual temperature (°C), p_a =precipitation total of the driest month, T_a : mean temperature of the driest month (°C).

Indicator	Quantile	Metric	Reference
Dry spell length	25%	Maximum number of consecutive days in a year with $P = 0$	after Barnett <i>et al.</i> (2006)
Number of heat waves	75%	Number of minimum seven consecutive days when $T_{max} >$ average T_{max} (baseline period) + 3 °C	after Barnett <i>et al.</i> (2006)
De Martonne-Gottmann aridity index (b)	25%	$b = \frac{1}{2} \cdot \left(\frac{P_y}{T_y + 10} + 12 \cdot \frac{p_a}{T_a + 10} \right)$	De Martonne (1942)*

$b < 5$: extreme aridity, $5 \leq b \leq 14$: aridity, $15 \leq b \leq 19$: semi-aridity, $20 \leq b \leq 29$: sub-humidity, $30 \leq b \leq 59$: humidity, $b > 59$: strong humidity.

Sensitivity will be assessed against low precipitation (<25th percentile) and high mean annual (or seasonal) temperature (>75th percentile) values. Aridity will also be assessed against high values (<25th percentile).

Synthetic indices for vulnerability assessment will also be provided as a complement to probabilistic assessment of sensitivity and exposure. This will help communicate the results of vulnerability assessment to stakeholders. As a basis, the index by Luers *et al.* (2003), as in Table 1, will be calculated on 30-year time slices of future climate relative to baseline, according to ‘simple’ evaluation strategy (Table 2). Other options (alternative indices and evaluation strategies) will be considered as options for specific use by some of the modelling teams.

The procedure will be first run without either adaptation or mitigation, and will be repeated by including adaptation/mitigation options (in interaction with WP8).

A software tool for computation of vulnerability indices is described in Annex I. More operational details about vulnerability analysis are provided with the proceedings of MS63 (“Numerical methods for project vulnerability analyses with guidelines for use”).

7. Annex I – Software for computation of vulnerability indices

An application written in Java language was developed to calculate vulnerability indices using a three-tab interface divided into **Initialization**, **Results** and **Charts**. The programme uses Java Swing library for creating configurable menus, toolbars and pop-ups, and the chart library JFreeChart to generate charts. The tool is at a far developed stage and is being used in demonstrations yet some of the functionalities are still being worked on.

The **Initialization** tab (Fig. 6, left) has commands to load data from CSV/ASCII files (each line in a file containing the probability of the sequence, e.g. grassland yields over a period of 30 years and the different values that compose the sequence) files by **Add File** (Fig. 6, middle). The other tabs are activated by clicking on **Compute** (Fig. 6, right).

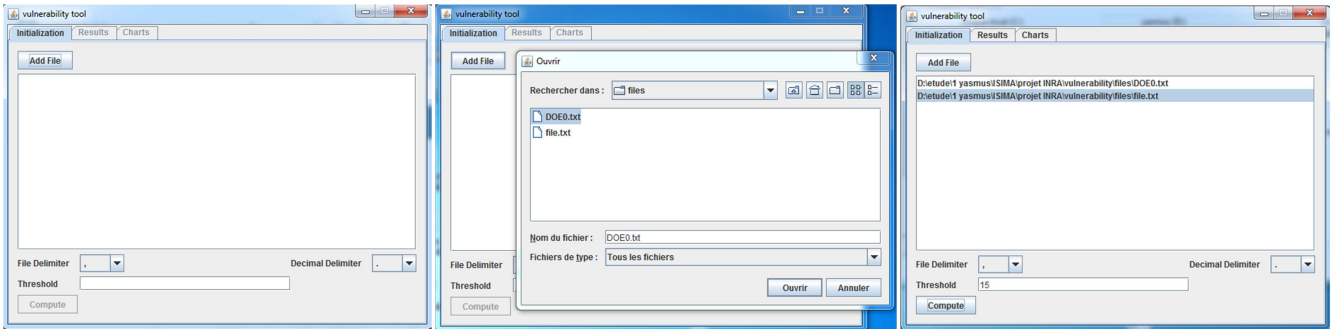


Figure 6. Initialization tab (left) with file load (middle) and activation of tabs Results and Charts (right).

Fig. 7 shows the tab **Results** implemented by two **JTable** components displaying five vulnerability indices, either as-is (**Table 1**) or after normalization with respect to a reference period (**Table 2**). A button **Export** allows saving results to an Excel-format file.

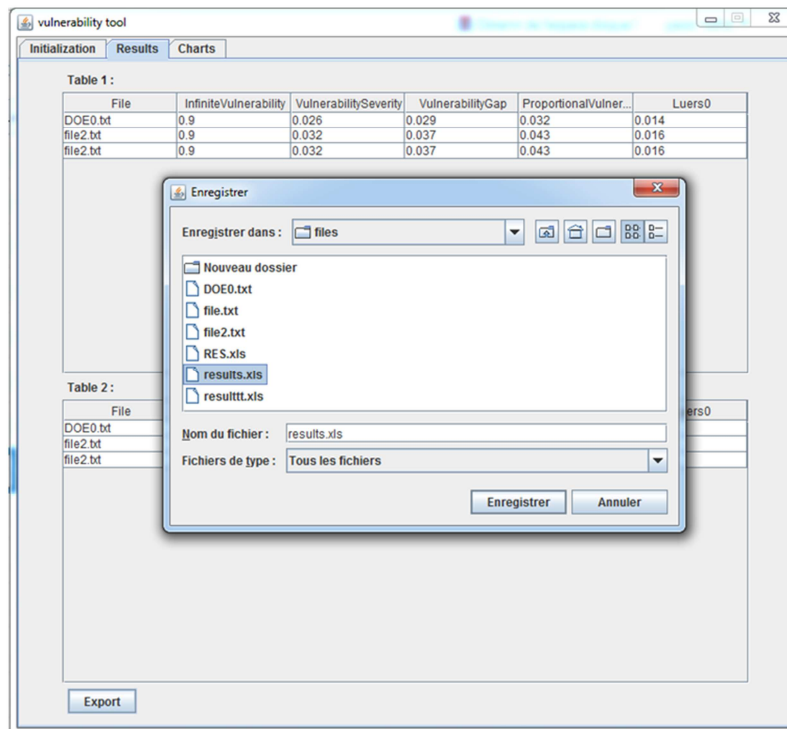


Figure 7. Results tab and the export option sub-tab.

In order to help the user to visualize results, a third tab, called **Charts**, was developed. As presented in the screenshot of Fig. 8, it contains two components: a histogram and a radar-type visualization.

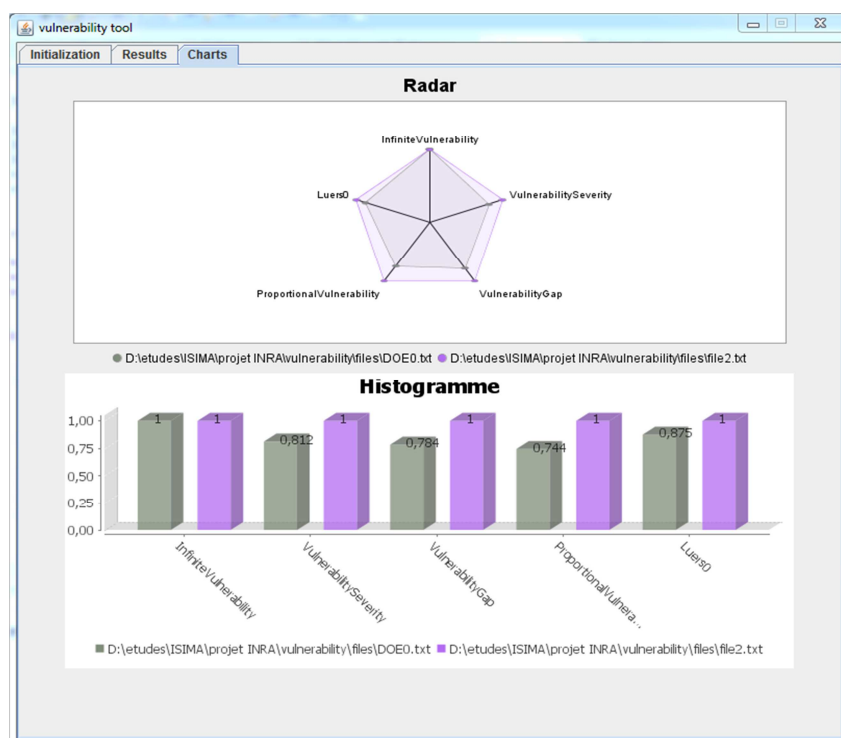


Figure 8. Charts tab.

8. References

Barnett, C., Hossel, J., Perry, M., Procter, C., Hughes, G., 2006. A handbook of climate trends across Scotland. Scotland and Northern Ireland Forum for Environmental Research, SNIFFER Project CC03, Edinburgh, United Kingdom.

De Lange, H.J., Sala, S., Vighi, M., Faber, J.H., 2010. Ecological vulnerability in risk assessment – A review and perspectives. *Science of the Total Environment*, 408, 3871-3879.

De Martonne, E., 1942. Nouvelle carte mondiale de l'indice d'aridité. *Annales de Géographie*, 51, 242-250. (in French)

Déqué, M., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values. *Global and Planetary Change*, 57, 16-26.

Déqué, M., Dreveton, C., Braun, A., Cariolle, D., 1994. The ARPEGE / IFS atmospheremodel: a contribution to the French community climate modelling. *Climate Dynamics*, 10, 249-266.

Downing, T.E., Butterfield, R., Cohen, S., Huq, S., Moss, R., Rahman, A., Sokona, Y., Stephen, L., 2001. Vulnerability indices: climate change impacts and adaptation. UNEP Policy Series, UNEP, Nairobi, 91 pp.

FAO, 1996. Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes. John Wiley & Sons Ltd., Chichester, United Kingdom.

Foster, J., Greer, J., Thorbecke, E., 1984. A class of decomposable poverty measures. *Econometrica*, 52, 761-766.

Füssel, H.M., Klein, R.J.T., 2006. Climate change vulnerability assessments: an evolution of conceptual thinking, *Climatic Change*, 75, 301-329.

Graux, A.-I., Bellocchi, G., Lardy, R., Soussana, J.-F., 2013. Ensemble modelling of climate change risks and opportunities for managed grasslands in France. *Agricultural and Forest Meteorology*, 170, 114-131.

Grimm, V., Wissel, C., 1997. Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion. *Oecologia*, 109, 323–334.

Holling, C.S., 1996. Engineering resilience vs. ecological resilience. *Engineering within ecological constraints*. National Academy, Washington, DC, 31-43.

IPCC, 2001. Impacts, adaptation, and vulnerability climate change 2001. Third Assessment Report of the Intergovernmental Panel on Climate Change. University Press, Cambridge, United Kingdom.

IPCC, 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, 976 p.

Jouven, M., Carrere, P., Baumont, R., 2006a. Model predicting dynamics of biomass, structure and digestibility of herbage in managed permanent pastures. 1. Model description". *Grass and Forage Science*, 61, 112-124.

Jouven, M., Carrere, P., Baumont, R., 2006b. Model predicting dynamics of biomass, structure and digestibility of herbage in managed permanent pastures. 2. Model evaluation. *Grass and Forage Science*, 61, 125-133.

Lardy, R., 2013. Calcul intensif pour l'évaluation de la vulnérabilité en utilisant une approche d'Ingénierie Dirigée par les Modèles - Application à la vulnérabilité des prairies au changement climatique sous contraintes de plans d'expériences. PhD Thesis, Blaise Pascal University, Clermont-Ferrand, France (in press). (in French)

Lardy, R., Bellocchi, G., Bachelet, B., Hill, D.R.C., 2011. Climate change vulnerability assessment with constrained design of experiments, using a model driven engineering approach. In: Novais, P., Machado, J., Analide, C., Abelhapp, A. (Eds.), *The European Simulation and Modelling Conference ESM@'2011*, 24-26 October, Guimarães, Portugal, 354-446.

Lardy, R., Martin, R., Bachelet, B., Hill, D.R.C., Bellocchi, G., 2012. Ecosystem climate change vulnerability assessment framework. In Seppelt, R., Voinov, A.A., Lange, S., Bankamp, D. (Eds.) *iEMSs 2012 International Congress on Environmental Modelling and Software: "Managing Resources of a Limited Planet, Sixth Biennial Meeting"*. International Environmental Modelling and Software Society, 1-5 July, Leipzig, Germany, 777-784.



Luers, A.L., Lobell, D.B., Sklar, L.S., Addams, C.L., Matson, P.A., 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. *Global Environmental Change*, 13, 255-267.

Van Oijen, M., Beer, C., Cramer, W., Rammig, A., Reichstein, M., Rolinski, S., Soussana, J.-F., 2013. A novel probabilistic risk analysis to determine the vulnerability of ecosystems to extreme climatic events. *Environmental Research Letters*, 8, 015032.

