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To cite this version:

Romain Lardy, Raphaël Martin, Bruno Bachelet, David Hill, Gianni Bellocchi. Ecosystem Climate Change Vulnerability Assessment Framework. International Congress on Environmental Modelling and Software (iEMSs), Jul 2012, Leipzig, Germany. pp.777-784. hal-02808983

HAL Id: hal-02808983
https://hal.inrae.fr/hal-02808983

Submitted on 6 Jun 2020

International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Ecosystem Climate Change Vulnerability Assessment Framework

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Abstract: Vulnerability is the degree to which human and environmental systems are likely to experience harm due to a perturbation or a stress. In the last years, it has become a central focus of the global change (including climate change). The climate change literature contains many explanations of vulnerability, stemming from the notion of sensitivity to more complex ideas, yet taking into account the exposure history of the system up to residual impacts of climate change after adaptation. This work addresses the issue of ecosystems vulnerability assessment by presenting a conceptual framework, as an attempt to generalize previous approaches. We present a model of concepts linked to climate change vulnerability, based on literature review, in which we detail the key concepts of adaptation and mitigation measures (and their respective capacity), ecosystem stability (sensitivity, ecological resilience and elasticity), exposure and impacts. An exemplary case-study is given to address the issue of vulnerability assessment for grassland ecosystems with the help of an impact model (ModVege). This paper emphasizes on the interest of using a design of experiment (DOE) accounting for different levels of uncertainties. It also demonstrates that a set of vulnerability indices, accounting for exposure, may be necessary to capture (if not all) most of the information.

Keywords: Climate change; Design of Experiment; Ecosystems; Grassland; Vulnerability

1. INTRODUCTION

An ever-increasing number of scientists and lay people state that they aim to provide a vulnerability analysis (also known as vulnerability assessment) as a process to define, identify and classify potential threats (vulnerabilities) in a system. In addition, vulnerability analysis is meant to anticipate the effectiveness of proposed countermeasures and to evaluate their actual effectiveness when they are used. On one hand, understanding what potentially unprecedented ecological and climatic change might do to human well-being and to the integrity and functioning of ecosystems is perceived as a central issue in a range of regional and national concerns (Ericksen [2008]). In addition, policy interest in vulnerability research has recently increased because climate change impacts are being observed (IPCC [2007]), and thus developing and implementing adaptation policy has become a priority (Hinkel [2011]). As a matter of fact, policymakers often ask which country, region or sector is most vulnerable in order to prioritise efforts that need to be undertaken with the aim to minimise risks and mitigate possible consequences (e.g. Füssel and Klein [2006]). Within the climate change scientific community, the concept of vulnerability is used in a variety of meanings, often not defined properly or even used without any definition (e.g. Ionescu et al. [2005]). As a result, a considerable diversity of methodologies is applied for assessing vulnerability (Eakin and Luers [2006]; Füssel and Klein [2006]). Moreover, through the history of vulnerability assessment, methodologies have grown in complexity with increasing numbers of subsystems, processes, drivers, feedbacks and types of impacts taken into account. Assessments have thus evolved from linear to complex chains of analysis while progressively including various feedbacks, moving from focusing on climate change as the only driver to taking into account other global environmental and socio-economic changes and considering a number of cross-cutting issues, such as uncertainties (McCarthy et al. [2001]).

One can generically define vulnerability as the degree to which a human or environmental system is likely to experience harm before being damaged (Turner et al. [2003]). In a climate change context (IPCC [2001]): “vulnerability is 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) and of the adaptive capacity”. This is the definition used in the paper, which is structured in seven sections. The next section documents the concepts behind ecosystem climate change vulnerability assessment. In this kind of studies, vulnerability is generally evaluated via model-based simulations under both current (baseline) and projected climate for future time slices. In order to illustrate the effectiveness of our approach to vulnerability assessment, we approached the issue through a grassland ecosystem model (ModVege, Jouven et al. [2006a]), which is presented in the third section. The fourth section details an array of vulnerability indices and the following section explains the design of experiment (DOE) used to account for uncertainties in an exemplary storyline (upland permanent grassland in central France). In section six, we analyze and discuss the results. In the concluding section, key results illustrate the value and limits of the methodology, and future research needs are addressed.

2. CONCEPTUAL FRAMEWORK FOR VULNERABILITY ASSESSMENT

The diagram presented Figure 1 relies on the assumption that greenhouse gas (GHG) concentrations are the primary factor influencing the climate, and therefore GHG emissions into the atmosphere are a key motor in driving the climate change. Other natural factors such as variability in solar output and volcanic activity are not considered in our study. 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 and changes in the amount of variability.

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. wheat price scenarios).

Sensitivity 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**.

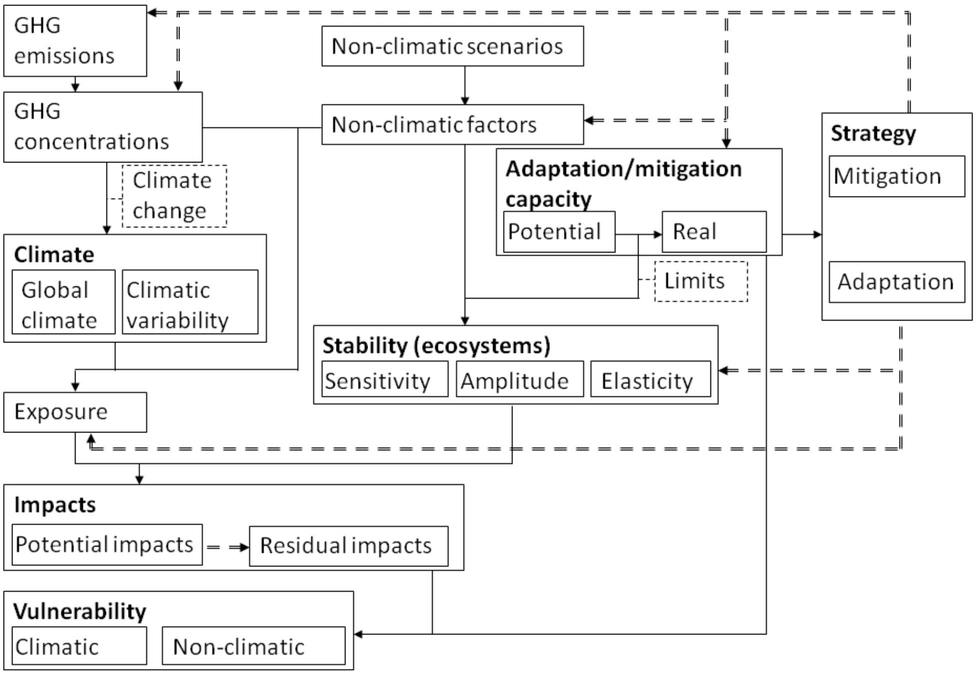

Figure 1. Conceptualization of vulnerability to climate change, based on Füssel and Klein [2006]. Dashed arrows represent the feedbacks of mitigation and adaptation strategies onto climate change impacts.

Together, sensitivity, ecological resilience and elasticity represent the ecosystem **stability,** and are mainly influenced by non-climatic factors. **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 adaptations (and mitigations), respectively. The vulnerability is sometimes seen as the residual impacts of climate change after adaptation measures have been taken (e.g. FAO [1996]).

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 thus 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.

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. In order to account for vulnerability with or without adaptation, we proposed a two-step approach (Lardy et al. [2011]). Firstly, we will realize a sensitivity analysis step, whose aim will be to estimate vulnerability without adaptation and to calculate response surfaces. A response surface is a model or approximation of the relationship between inputs and outputs in much simpler terms than the full simulation. In the next step, vulnerability is minimized under constraints of actual adaptation capacity. For the purpose of this paper, an exemplary case study is illustrated to assess vulnerability without adaptation.

3. MODEL DESCRIPTION

ModVege (Jouven et al. [2006a]) is a multi-year mechanistic model which deals with the dynamics of production, structure and digestibility of managed permanent pastures. Designed to respond to various defoliation regimes, it is based on five assumptions. Firstly, the average value of the vegetation attributes (functional traits) explains the functioning of a permanent pasture (Louault et al. [2005]). Secondly, sward heterogeneity is modelled by the relative abundance of the structural plant components (Carrère et al. [2002]) (i.e. green leaves and sheath: Green Vegetative, dead leaves and sheath: Dry Vegetative, green stems and flowers: Green Reproductive, and dead stems and flowers: Dry Reproductive). Thirdly, like other grassland dynamic models, senescence, growth and leaf abscission are modelled by continuous fluxes, calculated at a daily time step. Fourthly, due to storage of plant reserves and their mobilization in plant organs, shoot growth is based on a light-utilization efficiency approach and modulated by a seasonal pattern (Volenec et al. [1996]). The last assumption is that the quality of green compartment, abscission and senescence are influenced by compartment ageing. The model was evaluated for upland grasslands in central France (Jouven et al. [2006b]).The use of this impact model is supported by its complexity (sufficient to reproduce climate variability impacts on a pasture, Jouven et al. [2006b]) and relatively limited input and computational requirements.

4. VULNERABILITY INDICES

In the international literature, vulnerability assessment is often more about a qualitative assessment and only in few cases based on quantitative indices. The current study addresses the index-based approach to vulnerability assessment by the concept of Luers et al. [2003], the generalized poverty measures of Foster et al. [1984], and extension of the latter ones (Table 1), which have been considered sufficiently sound for climate change studies and representative of the methods currently available . Vulnerability is a relative notion, and absolute values attached to a vulnerability index are not very meaningful (Downing et al. [2001]). Mostly, defining the vulnerability of a system requires identifying a threshold below or above which the system is damaged.

Our illustrative case shows the interest of the approach proposed by comparing the achievements of the different indices in Table 1. The growing potential dry matter (DM) which is an output of a grassland system was simulated by ModVege under present and future climate conditions, by taking 750 kg DM ha^{-1} as arbitrary threshold (W_0) below which the system is considered vulnerable. We took current climate conditions as reference (baseline), in order to calculate relative values for any given vulnerability index for future projections of climate-driven changes. The relative index is thus defined as the absolute index for future climate divided by the absolute index for the baseline. In some cases (e.g. Luer's index), the threshold value (W_0) assigned disappears in the relative index, which is thus only influenced by the reference climate.

Table 1. Summary of vulnerability indices. W is the state variable (i.e. productivity), W_0 is the threshold (i.e. 750 kg DM ha^{-1}), n the number of elements (e.g. number of years), q the number of elements below the threshold value. When calculated, the indices were weighted by exposure.

Index	Formula	Interpretation
Proportional vulnerability, Foster et al. [1984]	$V_0 = \frac{q}{n}$	It corresponds to the number of vulnerable individuals in a population (the years in this study).
Vulnerability gap, Foster et al. [1984]	$V_1 = \frac{1}{n}\left[\sum_{i=1}^{q} \frac{(W_0 - W_i)}{W_0}\right]$	It represents mean deficit in vulnerable individuals.
Vulnerability severity, Foster et al. [1984]	$V_2 = \frac{1}{n}\left[\sum_{i=1}^{q} \left(\frac{(W_0 - W_i)}{W_0}\right)^2\right]$	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 et al. [2003]	$V_L = f\left(\frac{\lvert \partial W/\partial X \rvert}{W/W_0}\right)$	The coefficient of variation is used for quantifying the sensitivity of the system.

5. DESIGN OF EXPERIMENTS

In order to comparatively assess different vulnerability indices, but also to account for different kinds of uncertainties, we designed an experiment to illustrate a range of cases. The design of experiment (DOE) used is the same as proposed in Lardy et al. [2011], for building models of design in order to propose a metamodel of agro-ecological models with their associated DOE.

To illustrate the results that can be achieved by the different indices, a low productivity upland permanent pasture in France (Theix, 45° 43' North, 03° 01' East, 850 m a.s.l.) was simulated for three climatic periods of 30 years each: "Reference" period (1975-2004), "Near future" period (2020-2049), "Far future" period (2070-2099). Future climate projections are based on the A1B emission scenario (Nakiçenoviç et al. [2000]). The soil was characterized by water holding capacity of 200 mm. Grassland management was simplified to a single cut on the 15th of June each year. The impact variable of interest is the growing potential of the grassland, which is calculated as 1.5 x simulated biomass at 1100 ℃-day (or at the cutting event if earlier). It represents the estimable annual production of meadow. A methodology was employed to assess the uncertainties associated with climate and management.

The first design ("simple") consists in merely simulating the system over 30 years for given management and environmental conditions.

In the second design ("climate uncertainties"), climatic years are representative of a period, and correlations between achievements at year N and year N-1 are negligible compared to the membership of any year to the period considered. So, the occurrence of individual years is a random event. A simplification introduced in the design is that it does not account for the transient increase of atmospheric CO_2 concentration over years (as prescribed by the emission scenario adopted). We generated 10 000 climates produced by bootstrapping without replacement.

In the third design, we considered that in the initial climatic data, Extreme Events (EE) could be more frequent than predicted. So, the 30-year series was simulated by replacing one to three years by an EE year. EE year was defined as the most arid year of the period, based on the De Martonne-Gottman aridity index (De Martonne [1942]). For vulnerability assessment, it was necessary to weigh up with the relevance of the occurrence probability of extreme events in the climate series, i.e. that probability of 1, 2, 3 or 4 EE occurrences over 30 years was, respectively, 0.5, 0.4, 0.09 and 0.01.

The fourth design considers the possibility of a slightly different management (e.g., changes in the mowing dates) compared to the original one. To account for these uncertainties, the DOE allows for ±9 days of difference to the originally scheduled dates, with a known distribution (Gaussian in this case).

6. RESULTS AND DISCUSSION

We launched simulations thanks to the OpenMOLE workflow engine (http://www.simexplorer.org/wiki/OpenMOLE), and then vulnerability indices were calculated for different designs (Table 2). By neglecting CO_2 effect, climate change increases vulnerability of the system studied. This is due to decreased grassland productivity, though with slightly reduced inter-annual variability. Simulations accounting for EE frequency uncertainties did not show differences compared with the “simple” design, probably due to the low responsiveness of ModVege to EE. Accounting for climate years order uncertainties (design 2) globally increases 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 tend to reduce vulnerability. This means that the sensitivity and the uncertainties on cutting dates should be accounted for vulnerability assessment, but also when looking for adaptation options. Indeed, adaptation aims at reducing vulnerability through a robust solution (reflected by a lower sensitivity of the system to climate perturbations). However, whatever the source of uncertainty is, a common trend is clearly observed, i.e. an increase of vulnerability of the perennial pasture system investigated. If cases should arise where different indices would not produce similar results (or in the absence of clear trends), not accounting for some uncertainties associated with climate, management and environmental conditions can result in flawed conclusions.

Table 2. Vulnerability indices calculated 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.

Index Design	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

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 gives us information 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, and as such does not require decisions regarding thresholds. Otherwise, in a full range assessment of vulnerability, a sensitivity analysis to the threshold value should be performed to check for robustness of the results.

7. CONCLUSION

This study details the key concepts of ecosystem vulnerability to climate change, which includes adaptation and mitigation capacity, ecosystem stability (sensitivity, ecological resilience and elasticity), exposure and impacts. It is a proof of concept of our approach to vulnerability assessment that will eventually be extended to serve future studies with more complete biogeochemical models (e.g. the Pasture Simulation model, as in Graux et al. 2012). In this illustrative study, the ModVege model was applied on upland permanent grassland in France to show the suitability of a complementary set of quantitative indices for vulnerability assessment. Indeed, either weighted by the exposure probability, one single index may not give a full picture of the system vulnerability. The study also emphasizes the benefit of using a well-thought design of experiment (DOE) to account for different levels of uncertainty associated with the system under study. Note that we could combine all previous approaches, in order to account for all uncertainties. The main issue would the DOE size. A Latin Hypercube Design could be a suitable way to reduce the number of needed simulations (McKay et al. [1979]). In synthesis, three main issues make the novelty of our approach (compared to published literature): an improved conceptualization of vulnerability, a combined use of multiple vulnerability indices to get better insights about vulnerability, and the use of DOE to account for uncertainties associated to vulnerability assessment.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreements n° 226701 (CARBO-Extreme, http://www.carboextreme.eu) and n° 266018 (ANIMALCHANGE, http://www.animalchange.eu). The authors thank Juliette Bloor for model development and Haizou Li for Java implementation of ModVege.

REFERENCES

Carrère, P., Force, C., Soussana, J.-F., Louault, F., Dumont, B., Baumont, R., Design of a spatial model of perennial grassland grazed by a herd of ruminants: the vegetation sub-model. *Grassland Science in Europe 7*, 282–283, 2002.

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

De Martonne, E., Nouvelle carte mondiale de l'indice d'aridité. *Annales de Géographie* 51, 242–250, 1942.

Downing, T.E., Butterfield, R., Cohen, S., Huq, S., Moss, R., Rahman, A., Sokona, Y., Stephen, L., Vulnerability Indices: Climate Change Impacts and Adaptation, *UNEP Policy Series*, UNEP, Nairobi., 91 pp., 2001.

Eakin, H., Luers, A.L., Assessing the vulnerability of social-environmental systems, *Annual Review of Environment and Resources*, *31*, 365–394, 2006.

Ericksen, P.J., What is the vulnerability of a food system to global environmental change?, *Ecology and Society*, 13(2):14, 18pp., 2008.

FAO (Food and Agriculture Organization*), Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and* *plant physiological processes*, John Wiley & Sons Ltd, 1996.

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

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

Graux, A.-I., Lardy, R., Bellocchi, G., Soussana, J.-F., Global warming potential of French grassland-based dairy livestock systems under climate change. *Regional and Environmental Change*, doi:10.1007/s10113-012-0289-2, 2012.

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

Hinkel, J., Indicators of vulnerability and adaptive capacity: Towards a clarification of the science-policy interface. *Global Environmental Change 21*, 198–208, 2011

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

Ionescu, C., Klein, R., Kumar, K.K., Hinkel, J., Klein, R., Towards a formal framework of vulnerability to climate change. NEWATER Working Paper 2 and FAVAIA Working Paper 1, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 2005.

IPCC (Intergovernmental Panel on Climate Change), Impacts, adaptation, and vulnerability climate change 2001*. Third Assessment Report of the IPCC*. UniversityPress, Cambridge, UK. 1032 p., 2001.

IPCC, Summary for policymakers. In: Palutikof, J., van der Linden, P., Hanson, C. (Eds.), Climate change 2007: impacts, adaptation and vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom, 7–22, 2007.

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

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

Lardy, R., Bellocchi, G., Bachelet B., Hill, D.R.C., Climate change vulnerability assessment with constrained design of experiments, using a model driven engineering approach. ESM'2011, *The European Simulation and Modelling Conference 2011*, Oct. 24–24, Guimarães, Portugal, 2011.

Louault, F. Pillar, V.D. Aufrère, J. Garnier, E., Soussana, J.-F., Plant traits and functional types in response to reduced disturbance in semi-natural grassland". *Journal of Vegetation Science 16*, 151–160, 2005.

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

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S., *Climate change 2001: impacts, adaptation and vulnerability*. Cambridge University Press, Cambridge, United Kingdom, 2001.

McKay, M. D., Beckman, R. J., Conover, W. J., A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics 21*, 239–245, 1979.

Nakićenović, N., Greenhouse gas emissions scenarios. *Technological Forecasting and Social Change, 65*, 149–166, 2000.

Turner B.L. II, Kasperson, R.E., Matson, P.A., Mccarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America 100*(14), 8074–8079, 2003.

Volenec, J.J., Ourry, A., Joern, B.C., A role for nitrogen reserves in forage regrowth and stress tolerance. *Physiologia Plantarum 97*, 185–193, 1996.