Meteorological risks as drivers of environmental innovation in agro-ecosystem management

Work Package 3 - Identification of vulnerable / resilient agro-ecosystems and zones

Deliverable 3.2 – Methodology to assess vulnerability of agro-ecosystems

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Introduction

This deliverable presents an original methodology to assess vulnerability of agro-ecosystems. This original approach has been developped in the framework of the MERINOVA project. It has been applied to two Belgian case-stydies : cropland vulnerability to heavy rain and grassland vulnerability to drought.

The form of the present deliverable is a full scientific paper that has been submitted to a special issue of the journal Mathematical Geosciences in Decembre 2016.

The article prestents the context of this part of the study and a litterature review (1. Introduction), a general presentation of the developped methodology and its fundamental principles (2. Methods), the application of the approach to the two case-studies, the results of this first application and the discussion of these results (3. Application) and conculsive remarcks (4. Conclusions).

Deliverable 3.2 – Methodology to assess vulnerability of agro-ecosystems

The MAVABEK methdod - MApping Vulnerabilty of Agroecosystems Based on Experts' Knowledge – article submitted to Mathematical geoscience

MERINOVA Project - Frédéric M. Vanwindekens, Anne Gobin, Yannick Curnel, Viviane Planchon

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A new approach for mapping vulnerability of agroecosystems based on experts' knowledge

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Abstract Climate change has an influence on the frequency and the intensity of extreme weather events. These events are highly impacting agroecosystems. At the regional scale, agroecosystems are diverse in terms of ecological environments and farming practices. These intrinsic properties have an influence on their vulnerability to extreme weather events. The link between extreme weather events and the vulnerability of agroecosystems is conceptualized by experts – including farmers, advisers, and agricultural scientists. Their knowledge is not easily taken into account in models. An transdisciplinary modelling approach was developed for combining Fuzzy Inference Systems and Geographical Information System tools for mapping vulnerability of agroecosystems based on experts' knowledge. The developed approach was applied for vulnerability assessment to two major Belgian agroecosysems : (a) cropland vulnerability to heavy rain and (b) grassland vulnerability to drought. The approach is flexible and the vulnerable zones constitute relevant information for analysing potential adaptation and resilience of agroecosystems.

Keywords Geographical Information System · Fuzzy Inference Systems · Heavy rain · Drought · Resilience · Climate change

Our appoach has been developed in the framework of the Belgian BELSPO project MERINOVA (SD/RI/03A, 2012–2016)

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1 Introduction

The frequency and impact of devastating weather-related events captured increasing interest of both the general public and politicians in Europe (Vicente-Serrano et al 2014). In August 2003, Europe recorded an unprecedented heat and subsequent drougth that led to a reduction in primary productivity (Ciais et al 2005). In recent years, most European countries have been affected by drought (EC 2010; Gudmundsson and Seneviratne 2016; Tallaksen et al 2015): dry summer of 2003 in a large part of central Europe, dry summers of 2005 and 2007 in southern Europe, dry spring of 2011 in northwerstern Europe. Based on climate modelling, Christensen and Christensen (2003) showed that an increase of excessive rainfall is very likely in many European countries and that severe flooding may become more frequent. In Belgium, excessive rainfall of up to 90 mm during 3 days in November 2010 triggered the worst flooding in 50 years (IRM 2010).

All of these natural hazards were caused by extreme weather events. Extreme weather events are meteorological phenomena that are at the extremes of the historical distribution (IPCC 2001). Since 44.4% of the European territory is managed by the agricultural sector (2012 grassland and cropland, source: Eurostat-lan_lcv_ovw), extreme weather events have significant impacts on agroecosystems, their functions and services, from local to global levels (Lesk et al 2016; Peltonen-Sainio et al 2016; Potopová et al 2016). The perspective of rising risk-exposure for farmers is exacerbated further by more limits to aid received for agricultural damage (amendments to EC Regulation1857/2006) and an overall reduction of direct income support from the CAP.

Agroecosystems are socio-ecological systems managed by farmers. These systems are highly dependent on climate and meteorological events. Since these events are an important source of uncertainty for agroecosystems, extreme weather events could be a source of vulnerability. Vulnerability is a broad meaning concept that is used in various disciplines (Berry et al 2006, medecine, social sciences, environment). In a socio-ecological perspective, vulnerability of a socio-ecological system to climate change is considered as the degree to which this system is susceptible to suffer damage caused by climate change (IPCC 2001).

This study is focused on vulnerability of agroecosystems to extreme weather events. The degree of temporal overlap between extreme weather events and the sensitive periods of the agroecosystem in terms of farming calendar, crop development and seasonality may lead to different responses. Extreme weather events may lead to critical physical and/or physiological thresholds being exceeded during sensitive stages of the growing season. Extreme weather events affect crop production schedules, depending on the crop type and the sensitive periods in the cropping calendar. For example, most arable crops are susceptible to drought, particularly around the flowering period (Jaggard et al., 2007; Wheeler et al., 2000).

In Europe, ecological and meteorological data are widely collected and available for research and development activities. Vulnerability of agroecosystems to extreme weather events not only depends on ecological variables, but also on social and human variables like farmers' practices (Turner et al 2003). These variables are less easily taken into account in quantitative studies and models (Vanwindekens et al 2013). Farmers, advisers, agricultural scientists can be considered as experts of agroecosystems. They have the knowledge on how the influencing socio-ecological variables are affecting agroecosystems vulnerability and their mutual interaction (Uricchio et al 2004).

Mapping vulnerability of agroecosystems to climate change has been done at district scale with case studies in India (o'Brien et al 2004), in South Africa (Gbetibouo and Ringler 2009) and in Nordic Region (Carter et al 2009).

Current knowledge gaps related to the integration of experts' knowledge for assessing vulnerability of agroecosystems to extreme weather events, and corollary resilience and adaptive capacitiers need to be addressed. An original approach was developed to this aim, named 'mapping vulnerability of agroecosystems based on experts' knowledge' (MAVABEK) . This approach combines methodologies drawn from different disciplines: qualitative interviews, cognitive mapping, a fuzzy inference system and a geographical information system. The outputs of the MAVABEK approach are maps showing the most vulnerable areas to extreme weather events. It also identified the various factors underlying vulnerability and provided a useful tool for looking at potential sources of resilience within agricultural systems.

The second section of this paper consists of the presentation of the developed approach in detail. The third section consists of the application of the MAVABEK approach to the assessment of the vulnerability of two major Belgian agroecosysems : (a) cropland vulnerability to heavy rain and (b) grassland vulnerability to drought. The results are presented and discussed in this section. The fifth section consists of the conclusions of the paper.

2 Methods

The MAVABEK approach aimed to (i) highlight key ecological, economic and social factors and (ii) their respective influence on agroecosystems vulnerability to extreme weather events. Expert knowledge was simulated using a coupling of a Fuzzy Inference System (FIS) and a Geographical Information System (GIS). The MAVABEK approach consisted in four major steps: : (1) qualitative data collection; (2) cognitive mapping; (3) vulnerability assessment; and, (4) coupling with a GIS.

The MAVABEK approach was applied on two case studies in Belgium: (1) vulnerability to heavy rain; and, (2) vulnerability to drought.

2.1 Qualitative data are collected during open-ended interviews

The expert knowledge was collected by surveying stakeholders of the studied agricultural system(s): farmers, advisers, and researchers. The sample of stakeholders constituted key persons having a systemic conception of the studied system(s) and being able to clearly express the conception they have of this system.

The interview process was guided by topics linked to the agricultural systems and its vulnerability. Each interview was divided in three broad open-ended questions: (i) What kind of vulnerability characterizes the studied system (ecological, economic, social) ? (ii) What are the key factors influencing the vulnerability of studied system ? and (iii) How do these key factors affect the vulnerability of this system ?

Interviews were recorded and fully transcribed in computer text files. These text files were used to produce a first qualitative model of the systems.

2.2 Cognitive maps is used to model experts' knowledge on agroecosystems vulnerabilty

The second step had an intermediary position and preceded the core of the modelling approach. It aimed to build a first qualitative model of experts' knowledge, and connecting relevant information in a cognitive map.

A cognitive map is a network of nodes and directed edges, i.e. a directed graph used for showing causal relationships based on actors' descriptions (Axelrod and Arbor 1976). Cognitive mapping is a tool commonly used for qualitative modelling complex socio-ecological systems (Fairweather 2010; Özesmi and Özesmi 2004; Vanwindekens et al 2013, 2014). Some main advantages of this technique are its relative simplicity, its flexibility and its capacity to encompass complexity of modeled systems.

Cognitive mapping is proposed for showing causal relationships based on actor's descriptions of agroecosystems vulnerability. The practical method for building cognitive maps is left relatively free : coding transcription files using a Computer Assisted Qualitative Data Analysis approach (e.g. the Cognitive Mapping approach for Assessing Systems Of Practices, CMASOP, in Vanwindekens et al 2013) ; mapping directly with actors, during the interview ; mapping based on the transcription of the interviews.

For each analysed couple of agroecosystems/extreme weather event, a cognitive map was composed by variables that had a perceived influence on agroecosystems vulnerability regarding to the extreme weather event. The variables were linked to each other by relationships that (i) were causal ; (ii) were oriented and (ii) could be weighted regarding their importance.

The output of this second step, a cognitive map, was used as principal source of information for building the model to evaluate the agroecosystem vulnerability to extreme weather events.

2.3 Vulnerability of agroecosystem is assessed with a Fuzzy Inference System

The third step was the core of the MAVABEK approach and represented the model of the vulnerability of agroecosystems. The modelling approach is based on a Fuzzy Inference System (FIS). The R-package "sets" (Meyer and Hornik 2009) was used for this purpose.

2.3.1 Fuzzy rules

The experts' knowledge in the cognitive map was used for editing a series of rules that qualitatively described the influence of key factors on the vulnerability of the system. Each rule had the following form :

$$\textbf{IF}\ (var1\ \textbf{is}\ldots)\ \textbf{AND IF}\ (var2\ \textbf{is}\ldots)\ \textbf{THEN}\ (vulnerability\ \textbf{is}\ldots)$$

where

- *var1*, *var2*, are the key factors
- *vulnerability* is the element to be evaluate
- ... are the levels of the variables, e.g. in a five-point scale: *very low*, *low*, *medium*, *high*, *very high*
- boolean operations between elements of the rule can be **AND** or **OR**

2.3.2 Others Fuzzy Inference System's parameters

The Fuzzy Inference System required some further technical parameters. The following ones was used in the MAVABEK approach :

- the universe was defined from 0 to 1 by a step of 0.01 (figure 1)
- the memberships function of the five-point fuzzy classes were fuzzy cone with a radius (base) of 0.2 universe unit(figure 1)
- the fuzzy inference method used was the common Mamdani's direct method
- the conclusions of each rule were aggregated using the maximum operators
- the aggregated conclusion of the FIS was defuzzified using the centroid method

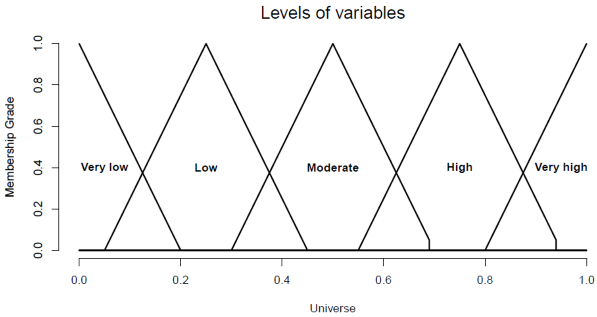

Fig. 1 Fuzzy cones defined the memberships of a quantitative value (universe) to a five-point class of each variable

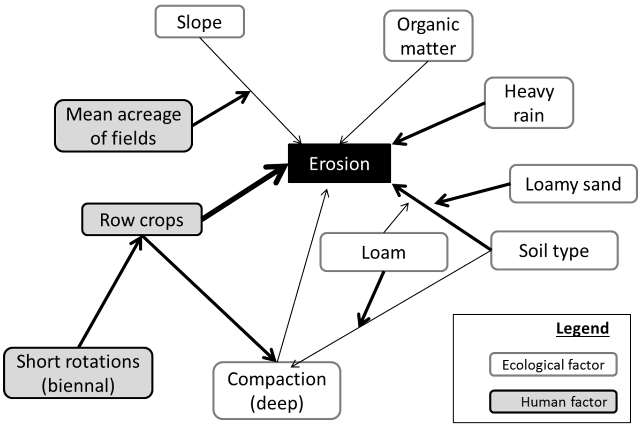

Fig. 2 Cognitive map of the vulnerability of belgian agroecosystem to heavy rain (erosion)

2.3.3 Type of inputs and practical application

Practically, inputs of the FIS were quantitative values for each of the key variables. These values were linear scaled to match with the universe of the FIS between 0 and 1 by 0.01 (Eq. 1).

$$X_{isc} = \frac{X_i}{max(X)} \tag{1}$$

A vector of scaled values were evaluated as input to the FIS. The FIS return a quantitative value of the universe between 0 and 1 which equalled an assessment of the agroecosystem vulnerability.

2.4 Coupling Fuzzy Inference System and Geographical Information System

Agroecosystems are complex entities and their intrinsic properties are varying in space. This variability induces the variability of their vulnerability. In order to incorporate this variability and to assess vulnerability of agroecosystems at various spatial scales (local, regional, national), the FIS module was coupled with a Geographical Information System (GIS) using R (R Core Team 2015a) and a cohort of packages for data and spatial analyses : gdata (Warnes et al 2015), grid (R Core Team 2015b), tidyr (Wickham 2014), plyr (Wickham 2011), sp (Pebesma and Bivand 2005), raster (Hijmans 2015), lattice (Sarkar 2008), rgdal (Bivand et al 2015).

This step involved the availability of spatial data across the assessed areas. The data were processed in the following steps :

– the projection of all spatial data was uniformized ;
– rasters were used as is and shapefiles were rasterized ;
– the resolution of the desired grid was defined and the resolution of inputs (rasters) were adapted accordingly ;
– cells with at least one NA (not available) data were removed from the grid (e.g. cities, roads).

For each cell of the grid, related variables were extracted and used as input of the FIS. The output of the FIS enabled the evaluation of agroecosystem vulnerability for each cell. The results of the FIS were used to reproduce a vulnerability raster. This vulnerabilty raster formed a principal output of the MAVABEK approach : a map of the vulnerability of the agroecosystem.

3 Application

The developed approach has been applied to two case-studies for assessing Belgian agroecosystems' vulnerability : erosion due to heavy rain and drought in grassland-based livestock farming systems. The practical details of these applications and the results are presented in the two following sections.

3.1 Vulnerability to heay rain (erosion)

3.1.1 Survey and Cognitive map

Two soil scientists were interviewed for describing the vulnerability of agroecosystems due to heavy rain. These two in-depth interviews were augmented with shared knowledge from farmers' focus groups. The interviews were at the basis of the global cognitive map (fig. 2). The influencing factors covered two main categories: farming practices (human factors) and environmental variables (ecological factors). The ecological factors were the slope and various soil characteristics (organic matter, texture). The main influencing farming practices were the presence of row crops, the rotation and the mean acreage of fields.

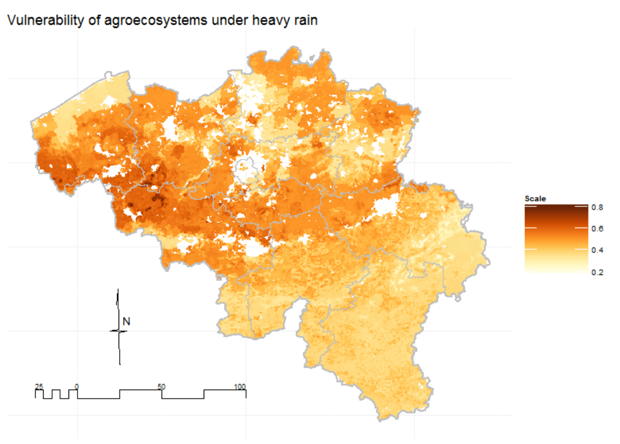

Fig. 3 Vulnerability of Belgian agroecosystems to heavy rain (resolution=500m)

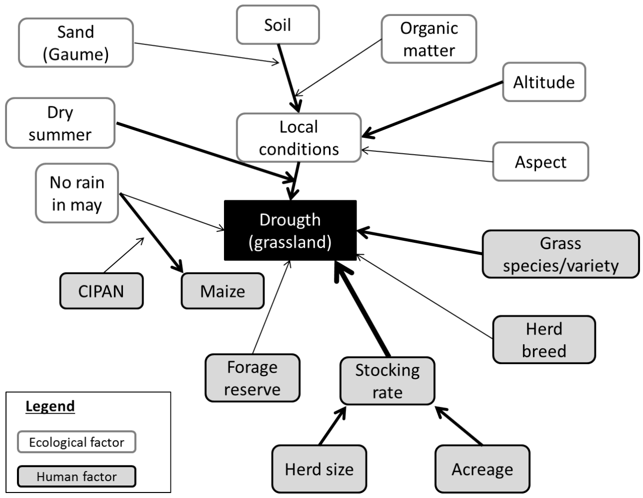

Fig. 4 Cognitive map of the vulnerability of belgian grassland-based farming systems to drought. CIPAN is a french-abbreviation for "catch crop".

3.1.2 Influencing variables and Fuzzy rules

Based on expert's cognitive map, three variables have been chosen as inputs of the MAVABEK approach :

– the part of row crops (maize, potato, sugar beet) in the Utilized Agricultural Area (UAA) (%), data at municipality level from IACS parcel information ;
– the slope (%) from National Geographic Institute of Belgium ;
– the erodibility of soil ([-]) (Panagos et al 2014, data available from European Soil Data Centre).

The values of these variables were mapped in appendix. The variables were scaled subsequently according to Eq. 1. Their mutual influence and their impact on vulnerability of agroecosystems have been set up using the rules in table 1.

3.1.3 Vulnerability assessment

Based on these variables and fuzzy rules, the FIS-based approach was used for evaluating the vulnerability of Belgian agroecosystems to heavy rain. As all data were geolocated, the MAVABEK approach enabled the assessment of the vulnerability for each cell of a raster. In addition, various resolutions were tested: 10000m, 5000m, 2000m, 1000m and 500m to evaluate the optimal resolution in relation to information present in the resulting map and in relation to computation time.

The output of the MAVABEK approach was a map of the relative vulnerability of Belgian agroecosystems to heavy rain (500m resolution map, figure 3).

3.2 Vulnerability to drought

3.2.1 Survey and Cognitive map

Three grassland scientists were interviewed for describing the vulnerability of grassland-based agroecosystems to drought. These three in-depth interviews were augmented with shared knowledge from farmers' focus groups. The interviews were at the basis of the global cognitive map (fig. 2). Various influencing factors were taken into account for describing this part of vulnerability. The main contributing factors were linked (i) to local ecological conditions (soil type, topography, location in the landscape) and (ii) to farming practices and farm specificities : stocking rate, grass species, forage reserve, . . .

3.2.2 Influencing variables and Fuzzy rules

According to experts'interviews, and constrained by data availability, three variables were chosen as inputs for the second case-study :

– the total available water capacity (*i.e.* field capacity minus wilting point), from the b-CGMS model (Buffet et al 1999) ;
– the stocking rate (number of bovines per hectare of forage area) at municipality level, from Statistics Belgium (available online at http://www.atlas-belgique.be) ;
– the share of permanent and temporary grassland in the total agricultural area, from Statistics Belgium (available online at http://www.atlas-belgique.be).

The values of these variables were mapped in online supplementary materials (appendix). The variables were scaled according to Eq. 1. Their mutual influence

Table 1 Set of fuzzy rules for the heavy rain case study. *factor k* is the erodibility of soil, *rowcrops* is the part of row crops (mainly maize, potatoes, suger beets) in the utilized agricultural area (UAA).

IF	factor k	**is**	very low	**OR IF**	rowcrops	**is**	very low	**THEN**	vulnerability	**is**	very low
IF	factor k	**is**	low	**OR IF**	rowcrops	**is**	low	**THEN**	vulnerability	**is**	low
IF	factor k	**is**	low	**AND IF**	rowcrops	**is**	low	**THEN**	vulnerability	**is**	very low
IF	factor k	**is**	moderate	**OR IF**	rowcrops	**is**	moderate	**THEN**	vulnerability	**is**	moderate
IF	factor k	**is**	high	**OR IF**	rowcrops	**is**	high	**THEN**	vulnerability	**is**	high
IF	factor k	**is**	high	**AND IF**	rowcrops	**is**	high	**THEN**	vulnerability	**is**	very high
IF	factor k	**is**	very high	**OR IF**	rowcrops	**is**	very high	**THEN**	vulnerability	**is**	very high
IF	slope	**is**	very low					**THEN**	vulnerability	**is**	very low

Table 2 Set of fuzzy rules for the drought case study. *tawc* is the total available water content, *livestock* is the stocking rate of livestock,*grassland* is the part of grassland in the UAA.

IF	tawc	**is**	very high	**OR IF**	livestock	**is**	very low	**THEN**	vulnerability	**is**	very low
IF	tawc	**is**	high					**THEN**	vulnerability	**is**	low
IF	tawc	**is**	high	**AND IF**	livestock	**is**	low	**THEN**	vulnerability	**is**	very low
IF	tawc	**is**	moderate	**OR IF**	livestock	**is**	low	**THEN**	vulnerability	**is**	moderate
IF	tawc	**is**	low	**OR IF**	livestock	**is**	(high OR moderate)	**THEN**	vulnerability	**is**	high
IF	tawc	**is**	low	**AND IF**	livestock	**is**	high	**THEN**	vulnerability	**is**	very high
IF	tawc	**is**	very low	**OR IF**	livestock	**is**	very high	**THEN**	vulnerability	**is**	very high
IF	grassland	**is**	very low					**THEN**	vulnerability	**is**	very low

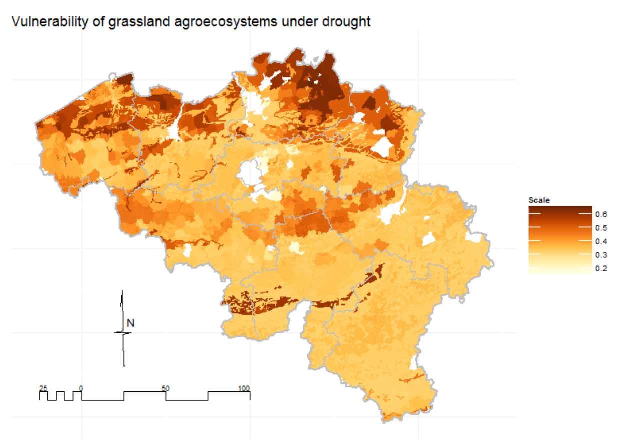

Fig. 5 Vulnerability of Belgian grassland agroecosystems to drought

and their impact on vulnerability of agroecosystems were set up using the rules in table 2.

3.2.3 Vulnerability assessment

The output of the application of the MAVABEK approach to this case study is a map of relative vulnerability of Belgian grassland agroecosystems to drought (500m resolution map, figure 5).

3.3 Discussion of results

The MAVABEK approach for assessing agroecosystems vulnerability offers an original combination of strength in terms of (i) anchorage of the modelling process in experts' knowledge ; (ii) flexibility of the type of influencing variables that could constitute inputs to the model ; and (iii) information on the model's outputs that are visual and accessible for a wide public (specialist and non-specialist).

Complex systems have to be studied as a whole for effective understanding (Bossel 2001). Experts, including main actors, are best qualified for understanding but also expressing and explaining the complexity of the vulnerability of the agroecosystem to extreme weather events. It has been shown for various complex systems linked to a diversity of socio-ecological systems : sustainabilty at community scale (Rajaram and Das 2010) or practices in grassland based farming systems (Vanwindekens et al 2013).

As shown in previous studies Nelson et al (2010), the vulnerability is better assessed using holistic approaches, taken into account variables from diverse fields and directly linked to rural communities's prosperity, e.g. incomes. This kind of holistic variables can be included as inputs of the modelling approach. In this paper, the two applications of the MAVABEK approach were focused on the ecological part of vulnerability. Further applications would included more holistic variables in order to assess the resilience of agroecosystems, including socio-economic indicators.

Another originality of the MAVABEK approach is the indirect establishment of rules, which are not directly expressed by experts. On the one hand, it is easier for experts to describe their systems in an open-ended way than to establish a long list of fuzzy rules. On the other hand, this indirect way implies the generation of fuzzy rules by the researcher itself, which can lead to some misundestanding. An improvement of the MAVABEK approach could be the use of a step involving the coding of experts' interviews when producing cognitive maps like in Vanwindekens et al (2013). This improvement would objectivate fuzzy rules by linking them to experts' quotes describing each relevant rule.

As shortcommings of the present study, our two applications of the MAVABEK use only a limited number of variables and a short list of rules collected during a limited number of interviews. Another weakness of our case-studies is the narrow conceptual vision of 'vulnerability', approaching the only 'susceptibility'. Further applications would involve a betted explanation of the different aspects of vulnerability to a wider pannel of experts. This will allow to consider more social-ecological variables and, therefore, assess adaptive capacity and resilience of studied agroecosystem to climate change (Folke et al 2010).

We consider the strenght of the MAVABEK approach twofold : (i) its implementation in R and (ii) its combination with a Geographical Information System. These properties allow sequential assessement of a large amount of points and subsequent mapping of the results of geolocalized data. This kind of output has the advantage to contain a large amount of information, but also to remain simple and informative for main actors e.g. farmers, researchers, administrations. The flexibility of the MAVABEK approach allows increasing the number of rules. Compared to previous works (Carter et al 2009; Gbetibouo and Ringler 2009; o'Brien et al 2004), our approach is dealing with data of various nature: continuous raster, statistics at district or regional scale and even categorical data.

If mapping vulnerability shows a clear added-value in terms of clarity and communication, maps can be seen as the panacea by actors and lead to rapid decisions (Preston et al 2011). We consider that maps are able to reveal vulnerable parts of the landscape, but have to be critically reviewed by actors and taken into account with other tools (*e.g.* cognitivie maps, interviews and other modelling approaches).

4 Conclusions

This paper presents a transdisciplinary approach for assessing the vulnerability of agroecosystems and its applications in the case of extreme weather events. We showed that basic elements and tools can be used for modelling complex systems and interactions with their environment based on experts' knowledge. Outputs of the MAVABEK approach, maps of vulnerability and cognitive maps, can be seen as relevant informative communication tools for discussing vulnerability of agroecosystems, or wider socio-ecological systems. Perspective of the MAVABEK approach is to use these outputs as inputs of a further step in order to identify, in a participative way with actors and stakeholders, farming practices that could decrease vulnerability and enhance resilience of the entire agroecosystem. The developped approch could be extended easily to other regions and provides for a participative geo-information system that supports decision-making related to vulnerability and resilience of agroecosystems to extreme weather.

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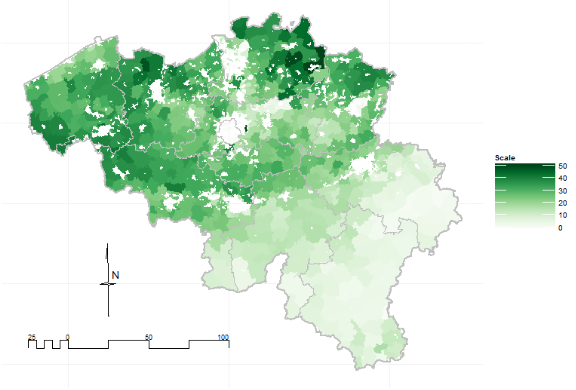
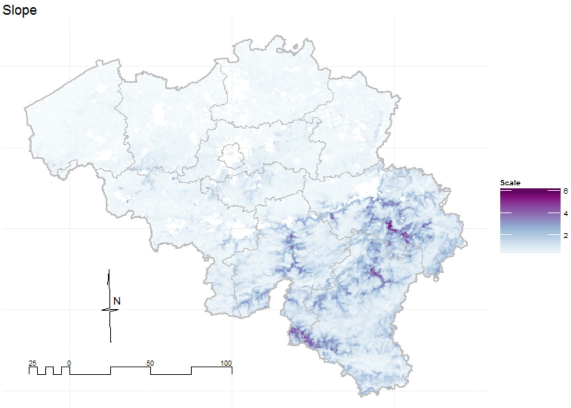
Appendix A: Variables

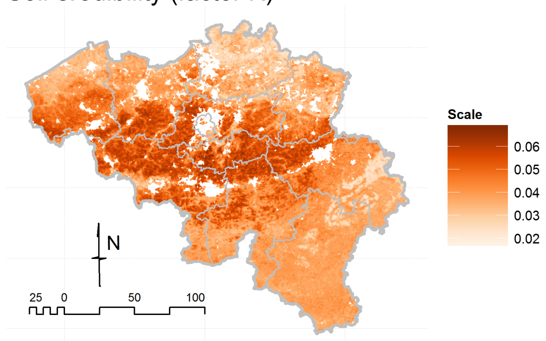
Row crops in the UAA (%)



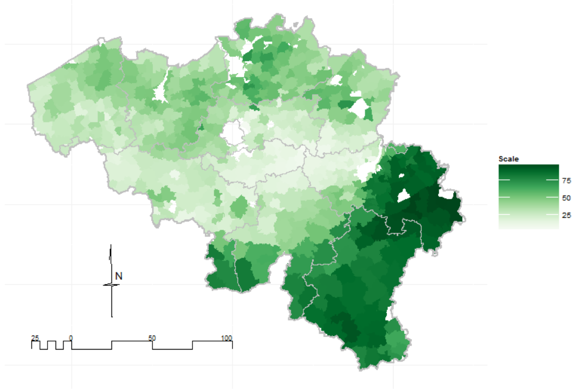
Slope



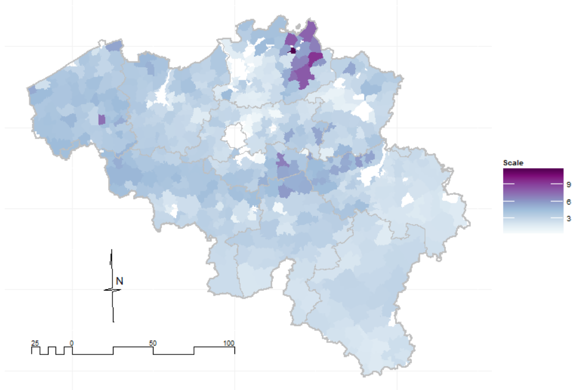
Soil erodibility (factor K)



Part of grassland



Stocking rate



Total Available Water Content