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ABSTRACT

In a context of increased land and natural resources scarcity, the possibilities for local authorities and stakeholders of anticipating evolutions or testing the impact of envisaged developments through scenario simulation are new challenges.
PRECOS's approach integrates data pertaining to the fields of water and soil resources, agronomy, urbanization, land use and infrastructure etc. It is complemented by a socio-economic and regulatory analysis of the territory illustrating its constraints and stakes. A modular architecture articulates modeling software and spatial and temporal representations tools. It produces indicators in three core domains: soil degradation, water and soil resources and agricultural production.
As a territory representative of numerous situations of the Mediterranean Basin (urban pressures, overconsumption of spaces, degradation of the milieus), a demonstration in the Crau's area (Southeast of France) has allowed to validate a prototype of the approach and to test its feasibility in a real life situation. Results on the Crau area have shown that, since the beginning of the 16th century, irrigated grasslands are the cornerstones of the anthropic-system, illustrating how successfully men's multi-secular efforts have maintained a balance between environment and local development. But today the ecosystem services are jeopardized firstly by urban sprawl and secondly by climate change. Pre-diagnosis in regions of Emilia-Romagna (Italy) and Valencia (Spain) show that local end-users and policy-makers are interested by this approach. The modularity of indicator calculations and the availability of geo-databases indicate that PRECOS may be up scaled in other socio-economic contexts.

Key words: soil, water, resources, territory, urban sprawl, climate change.

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1. Introduction

Present crisis and transitions all have in common that they concern primary production fields (agriculture, raw materials), transformation activities (industry and crafts) and local economy (retail, general services and transport…) (Pachauri and Reisinger, 2007; IEA, 2008). They impact land use and resources (water, food and energy) and they are mutually interdependent. Thus the gradual awareness of the "crisis" dimension leads to a renewed approach of resources and regional areas' management systems (World Bank, 2007, 2009; FAO, 2009; Trolard and Dangeard, 2014). To face these challenges, efforts should focus on:

- Capacity building in relationship to territorial analysis at different organizational levels. Systemic analysis, life-cycle analysis (Day, 1981; Ayres, 1995; Ayres et al., 1998; von Bahr and Steen, 2004) and integrative concepts (biophysical, biological indicators, ecological footprint, virtual water…) (Bell and Morse, 2004; Graymore et al., 2008) already are a dominant trend of recent literature (Bouman et al., 1999; Crescenzi et al., 2007; Davodi, 2012);
- Reinforcing expertise provision in different but complementary disciplines, such as support for the shaping and monitoring of public policies, critical assessment and dissemination of references or devising innovations with attention to their social acceptability;
- Merging and/or adapting technological innovations from other sectors in order to develop new analysis or expertise tools for territorial development (*e.g.* energy network models to assess cumulative environmental impact of urbanization on carbon emission (Chen and Chen, 2012) or on river ecosystems (Chen et al., 2015)). Recent innovation in spatial metrology both in the fields of robotics and of information technologies and communication, now makes it possible to propose new management practices, assessment, monitoring and decision support tools (Xia Li and Gar-On Yeh, 2000; Waddel, 2002; Vohland and Barry, 2009…).

Cities, as they develop, have a tendency to degrade environmental assets, and impair the essential services provided by ecosystems. The difficulty resides in the evaluation of benefits provided by natural and agricultural areas. The changes thus introduced by urban development in the agro- and ecosystems increase the risks and retroactively impact the value of constructible land and of property because of regulation constraints (extension of non-constructible surfaces) and/or conditions attached to the safeguarding of investments (insurance, cost of loans….).

Cities are drivers for innovation (Glaeser, 2011) and urban growth is a productivity factor, enabling producers from rural areas, consumers and companies to access markets and the workforce to find employment. Hence, a first series of studies undertaken by ECOLOC (Club Sahel and OECD, 2001) has established that the concept of local economy ought to coincide with a tangible reality, for instance that of a pilot economic zone–- always open towards other areas, regions, countries, world –- but populated enough and with activities that are sufficient for having the potential for generating value and commercial exchanges.

Urbanization develops mainly at the expense of agricultural land at the outskirts of cities (Chakir and Madignier, 2006; Ruellan, 2010; Sapoval, 2011) and along coastal areas (Pageaud and Carré, 2009). For the moment, assessing the consequences of urban sprawl basically boils down to measuring surfaces consumed; it does not take into account the qualitative properties associated to soils and associated environmental functions before sealing.

To overcome such contradictions, it is necessary to identify the impacts of urban and agricultural policies over natural environments, to assess externalities and anticipate evolutions.

The PRECOS framework allows for simulating the likely evolution of indicators in the future and, in the light of various constraints, assessing the deterioration risks of local environmental assets and the lessening of decision makers' means and levers for potential action.

The main goal of this paper is to present the different elements of this approach highlighted by results obtained on the demonstration area, the Crau (South of France) with the prototype (Astuce & Tic, 2011) and some elements for structuring it in a framework (the PRECOS approach) applicable in other geo-socio contexts.

2. Methods

2.1 The basic concept

The basic idea is that urban sprawl cannot be considered separately from its immediate rural environment, *i.e.* its hinterland (Trolard et al., 2010, Trolard et al., 2013b). The circular causality chain DPSIR (Drivers - Pressure - State - Impact - Response) elaborated by the OECD (2003) is the working basis of the framework: human activities exert pressures over the environment and modify the quality and quantity of natural resources. Society reacts to these changes by adopting protection, limitation, confinement, depollution measures… and the cycle starts over again. The objective is of course to prompt a virtuous cycle.

2.2 Devising the software's architecture

The fields covered by the PRECOS approach comprise land occupation changes, soil sealing levels, agronomic qualification of soils, water geo-chemistry, fresh water needs according to the availability of resource and agricultural production requirements (Fig. 1a).

The selected models have already proven their efficiency in their respective fields. PRECOS integrates them all in an overall scheme (Fig. 1b), ensuring a global approach.

Both METRONAMICA (White and Engelen, 1993; White et al., 1997; Straatman et al., 2004) and URBANSIMUL (Géniaux, 2011) compute land occupation changes over time. In METRONAMICA, this transformation is achieved by the use of a cellular automaton coupled with a GIS, which constraints are defined by urbanization (distance to water, electricity networks, transport infrastructures...). URBANSIMUL uses probability tests of mutation of plots into urbanization based on tax data. The parameters, obtained from the analysis of the results of both software, measure and represent the territory of a land use conversion into another (natural, agricultural, urban and/or industrial areas and infrastructures), the share of coastline affected by urbanisation and fragmentation of natural areas.

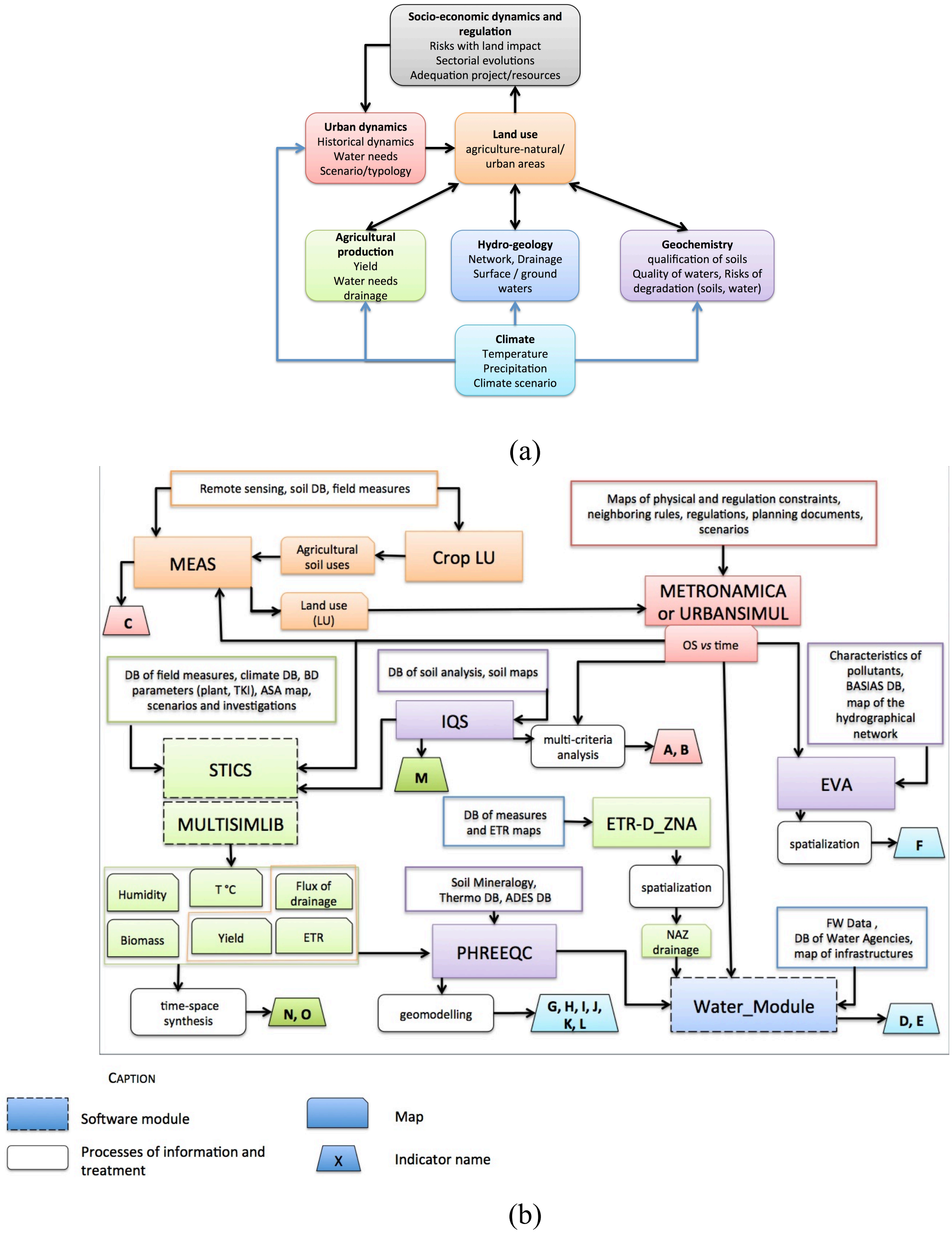


***Figure 1**: **(a)** Scheme of interconnections (black arrows) of the different domains considered in PRECOS approach; blue arrows indicated where climate parameters were explicitly taking into account and, **(b)** declination of this schema in the software architecture in Astuce & Tic's prototype.*

The method of Assessment of Soil Artificialisation (MEAS) (Astuce & Tic, 2011) takes into account the diversity and agronomic qualification of soils (SQI) (Balestrat et al., 2011), soil sealing and urban sprawl, including the fragmentation of agricultural lands. This approach is complemented by the EVA3 software (developed at Lausanne University) assessment of polluted sites and soils, which estimates the risk of soil contamination by industrial activities. MEAS and EVA produce spatially distributed typologies of artificial soil as well as input data for METRONAMICA or URBANSIMUL.

STICS (Brisson et al., 2003; Brisson, 2008) is a crop model that simulates crop biomass production, agricultural yields, water and nitrogen requirements, surface water flows and drainage (water percolation below the root zone). Calculations are made at the field plot level and aggregated on the territory with MultiSimLib model (Buis et al., 2011). The model is driven by climate parameters, which allows for taking into account climate change scenarios.

PHREEQC software (Parkhurst and Appelo, 1999) is a thermodynamical model for processing water chemistry data. It allows for the construction of geochemical indicators of water quality (potability, salinity, sodicity...) and the study of soil - solution interactions (geochemical changes, salinization, sodisation and stability of clays...).

For the spatial representations of data and results, specific visualization software (Mapinfo®, Arcview®, Arcgis®....) and a geo-modelling tool (gOcad®) have been implemented. gOcad® software, developed by oil and mining geologists (Mallet, 2002) is more specifically capable for mapping heterogeneous and incomplete data (mesh conditional objects, interpolation functions and specific kriging, 3D visualization...). It has been adjusted to the requirements of territorial data mapping such as land distributions, soil properties, the geometry of soil horizons and of the aquifer, groundwater quality, land uses... (Astuce & Tic, 2011). This software can produce thematic maps in 2D and 3D as well as spatial statistical analysis.

The above-mentioned software retain all the properties that might come in handy for subsequent in depth sector based studies. The constraint of building a tool around this system requires the pooling of scientific and technical expertise necessary to use it, define and produce the indicators. A Web portal presents the results in the form of maps, tables, curves or diagrams, which are accessible to end-users (e.g. decision-makers, stakeholders or local authorities), upon request, via key words.

2.3 Sources of data

Territorial data are abundant but also extremely scattered, very heterogeneous in space and/or time, albeit lacunar. At times, they can be accessed easily via open Web portals but quite often they only exist as paper records. The INSPIRE directive is currently driving many European regions to collect data, organise their regional databases around a homogeneous grid and make the information it contains available for free, especially when it belongs to the public domain (INSPIRE, 2007). Setting up a geo-database for the Crau plain involved quite a lot of information collection and computerization work. Data concern soil occupation, soils characteristics, geochemical qualities of soils and waters, climate, agricultural activities, demography, industrial sites characteristics, networks of water distribution. Different data production methods were implemented: extraction and assembling of information, layout, geo-referencing and digitization of documents, new data acquisition either via specific commands (*e.g.* remote sensing pictures), or by *in situ* measurements and laboratory analysis (*e.g.* soil thickness in grasslands, chemical composition of irrigation water…).

2.4 Indicators

The PRECOS approach combines heterogeneous data to produce indicators in three domains: soil degradation, water and soil resources and agriculture production. Today PRECOS is operational and set up to generate 15 indicators (Table 1). The modularity of the software's architecture allows for adding or selecting pertinent indicators as function of the local characteristics of the area under consideration.

Table 1: *List of indicators produced by PRECOS's approach*

	Indicators	Definition
A	Land occupation	Typology of soil occupations: 30 classes categorised as urban and non-urban environments, surface texture and specific classes (resulting of merge of previous defined classes) for METRONAMICA software, which is able to calculate only with 15 classes.
B	Fragmentation of habitats	Measure the discontinuities in natural areas.
C	Soil sealing	Soil-sealing ratio in % per surface unit.
D	Aquifer evolution	Variation of the aquifer's water volume and flows.
E	Drinking water supply	Supply / demand balance checks per infrastructure (drilling point and connection to the fresh water supply networks).
F	Pollution risk	Vulnerability of industrial activity: potential of dangerous substances per site, mobilisation potential of environmental assets: air, soil, surface water and groundwater, exposure of assets in need of protection.
G	Water drinkability	Estimation of the risk of non-drinkability from physical and chemical characteristics of waters.
H	Risk of water salination	Calculation depending of the Ionic force and / or electrical conductivity of waters.
I	Risk of soil salination	Estimation of the risks of precipitation of soluble sodium salts, gypsum and salts more soluble than gypsum.
J	Risk of soil acidification 1 (calculated with water data)	Calculation of the water saturation index compared to calcite precipitation.
K	Risk of soil acidification 2 (calculated with soil data)	Calculation of the "active lime" contents in soils.
L	Risk of soil sodicity	Calculation of Sodium Adsorption Ratio (SAR) as an indicator of

		soil structure degradation.
M	Soil agronomic qualification index	Assessing the qualification of soils for agriculture use.
N	Agriculture production	Calculation of yields and biomass products of the different crops.
O	Drainage	Quantification and localisation of waters drained per surface unit.

2.5 The scenarios' construction method

The PRECOS approach makes a distinction between « constraints » such as climate, economic climate upon which local actors have little influence and "levers" on which actors can exert some degree of influence such as zoning, land acquisition… (Trolard et al., 2013b). The medium-term was chosen for the scenarios because it is a time horizon where preventive and adaptive actions are still possible. By providing an "*a minima*" representation of pressures and some notion of additional costs incurred for coping with them, these scenarios can help stakeholders to remain under the threshold beyond which damages to strategic resources will be irreversible. Indeed, in a space with limited resources, pressures are to a large extent predetermined and respond, at this horizon, to rather rigid dynamics determined by geography, regulation, demography, real estate market logics, infrastructure and economic activities.

Table 2: *Standard questionnaire used for the test cases*

Domains	**Questions or needs**
Socio-economic context	Rough description of the main economic sectors focusing on agriculture, industry and urbanization
Local vulnerability	Are urban sprawl and/or soil sealing problems in your area? Is it exerting pressure over other sectors, *e.g.* the consumption of fertile land for food production? Can you identify a hot spot area where to study these relations and related problems and solutions? Is climate change affecting local resources, and main economic sectors? Which are the main climate related problems for agriculture, urban areas and industries? (General and rough answers also.)
State of the art of current tools	Are there similar tools already available in your territory? Which tool managing water use, soil use, soil quality, urban development, *e.g.* irrigation advice or water use in industry and urban areas? Who is the owner? Who is running it? Is the result for free? Are they considering an inter-sectorial approach or are they only sector based? Is the local government feeling the need to have a tool, which is able to integrate all sectors using land and water resources? (General and rough answers also with a simplified table.)
Territorial data	PRECOS needs to use mainly geographical data, *e.g.* data on soil and water quality, water use, land use, urban trends, hydrology etc. Are these data easily available? Who is the owner? What is the overall spatial resolution? Are they free? (General and rough answers also with a simplified table)

Main vulnerability and linked indicators	Astuce & Tic (A&T) is the first version of PRECOS approach. The prototype is able to release a list of indicators, which were specifically required in the demonstration area, the Crau area. Which are important locally and which one are missing? Are they obtainable using current available data?
Conclusion	Mainly state the reason for which the application of PRECOS can be important.

This kind of simulation made by iteration does not take into account major events likely to change drastically the land occupation (*e.g.* natural hazard, political decision). However, the PRECOS approach can re-initialize its tools in such a way that if needed, this new occurrence might be included and accordingly a new simulation achieved.

2.6 Up-scaling of the PRECOS approach in other contexts

To assess whether the PRECOS approach could be deployed in different geo- and socio-economic contexts typical situations where urban sprawl and climate change may critically jeopardize local resources were identified and explored. This involved extensive discussions, interviews and exchanges with local decision-makers, stakeholders, engineers and researchers in Italy, Spain and France and the completion of a questionnaire (Table 2).

3. Demonstration area: the Crau plain

Covering a surface of approximately 600 km^2, the Crau plain is delineated by the Alpilles in the North, the Rhone River in the West, the Mediterranean Sea in the South, and in the East, the Etang de Berre and the La-Fare-les-Oliviers short mountain chain (Fig. 2). The climate is meditarranean (rainfall is less than 600 mm $year^{-1}$), the tree cover quasi non-existent and the Mistral wind blows regularly with great violence.

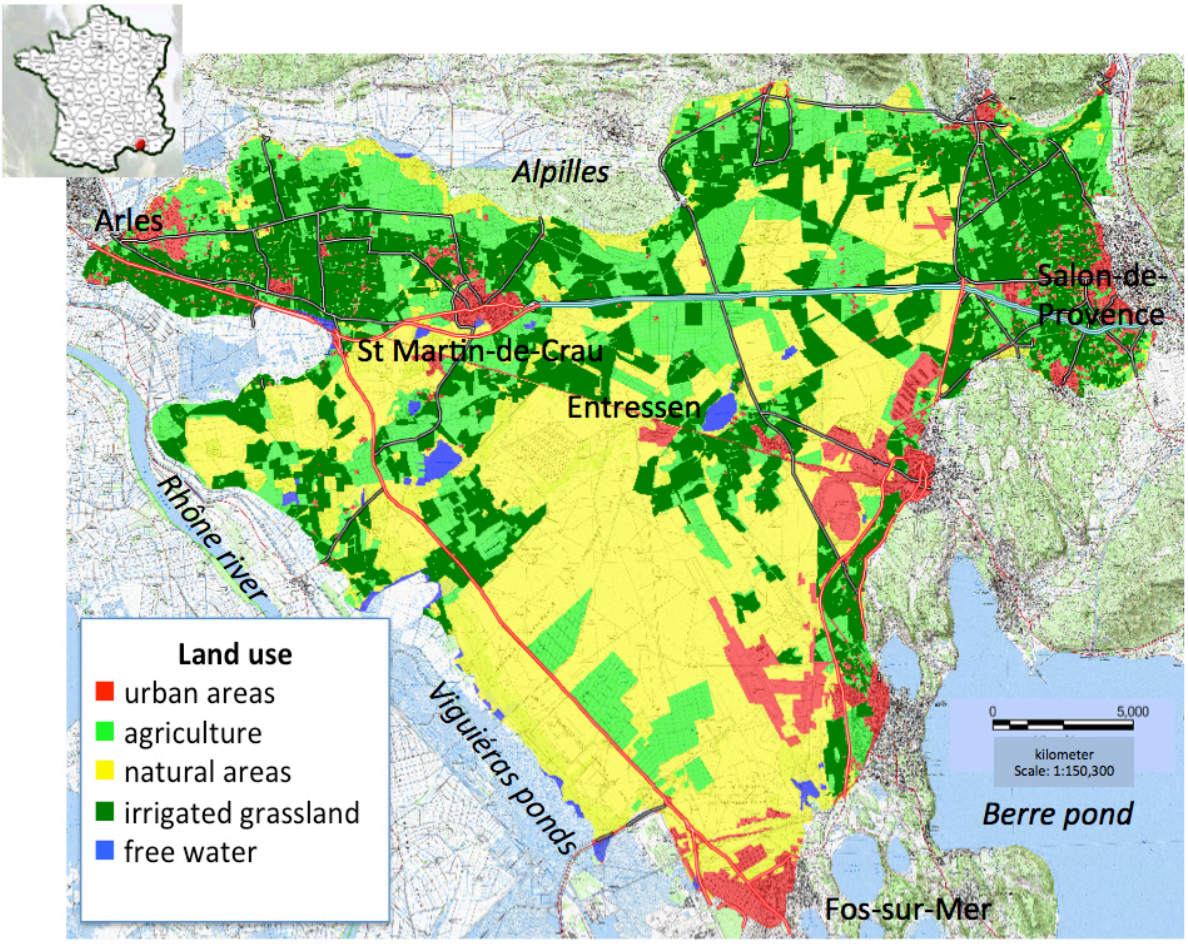


***Figure 2**: Map of the Crau territory*

The natural Crau landscape is a steppe of 9,200 ha called the « dry Crau »; its ecosystem is unique (forming a natural, cultural and economic exception at local, regional and European levels), with exemplary endemic organisms of special conservation interest (Wolff et al., 2013).

The Crau's irrigation system dates back to the 16th century. Thus for over 400 years, through gravity irrigation, the system brought the Durance water and silt over the Crau's gravel. It covers nowadays a surface of 12,500 ha mainly devoted to producing "Crau hay", a PDO (Protected Designation of Origin) and sheep rearing, especially that of the PGI (Protected Geographical Indication) labelled the "Sisteron lamb" and "Merinos from Arles". Locally, part of the pastoral land has been given over to intensive orchards and greenhouse vegetable production, most of the irrigation water for these activities being provided by directly pumping into the aquifer or by drip irrigation (Bonfillon, 2008). These irrigation waters contribute over 75% the Crau's groundwater recharge and supply drinking water to approximately 280,000 people as well as to the large industries established at the south of the area.

***Table 3:** Socio-economic scenarios, climate and water use constraints tested on Crau with PRECOS approach*

Scenario 0	Called "trend" scenario is the scenario that translates the weight of existing constraints over the area and population. The evolution of indicators is obtained by the linear extrapolation up to 2030 of the historical socio-economical evolutions registered over the 1997-2009 period.
Scenario 1	Called the "industrial consolidation and diversification" scenario, assumes a strong industrial development in the South of the area, with as hypothesis that the maritime Great Marseille harbour is the epicentre. This leads to the extension of industrial areas receiving high-risk activities and increases soil sealing.
Scenario 2	Called the "development of services and residential activities" scenario, assumes an important development in services activities in the North, along the Arles – Salon-de-Provence axis, and a stagnation of industrial activities in the South. This scenario examines especially the difficulty to combine development constraints, existing regulatory frameworks in such risk prone areas, with high land-consumptive activities such as logistics and residential activities dedicated to the tourism.
Climate and water use constraints	Climate scenario A1b over 2025-2035 period calculated with reference data (temperature, precipitation) over 2001-2010 period. Estimation of reduction of water resource for irrigation of 30%.

In the Crau area, the constraints appear particularly strong given that four factors currently guide the regional planning choices: (i) a demographic pressure that is not counterbalanced by a socio-economic dynamic growth; (ii) competition for access to land and local resources in an area marked by important physical constraints and vulnerabilities and a particularly high exposure to risks; (iii) the pervasiveness of very international economic activities with weak regional links but strong environmental footprint and an investment backlog in infrastructure (transport, energy) that increase the areas' marginalization from the main global trade routes and (iv) a legislative and regulatory framework that is supposed to offer in theory a high level of protection but only provides in practice, a low level of safety. This points towards a more rational use of resources (soils, water) (Trolard and Dangeard, 2014).

The regional climate change in Crau, as defined by IPCC's A1b scenario (Pachauri and Reisinger, 2007) and on the basis of long-term meteorological records (Olioso et al., 2013a), consists in: (i) a temperature increase well established since 1980 with a rate of 0.5°C every 10 years; (ii) no significant change in annual precipitation since the beginning of the 19th century; (iii) a recent increase of reference evapotranspiration *ETo*, computed using the FAO56-PM method (Allen et al., 1998) around 1.5 – 2 mm year^{-1}. A decrease of water resources for agriculture is to be expected from now to 2030, caused by a new allocation of water resources, due to the increasing competition between (i) maintaining a sufficient flow of water in dry periods and (ii) satisfying the demand for energy production, industrial and touristic needs.

Scenarios for Crau area were defined in Table 3. The situation of reference for the all the variables is defined by the values of the year 2009. The calibration of the dynamics of the models' parameters was made with reference to the land occupation's evolution between 1997 and 2009 calculated on a yearly basis. The objective of these simulations is to produce likely land occupation maps for the medium term, *i.e.* the 2030 time horizon by monitoring the dynamics of the indicators.

4. Results and discussion

4.1 Urban sprawl impact measures

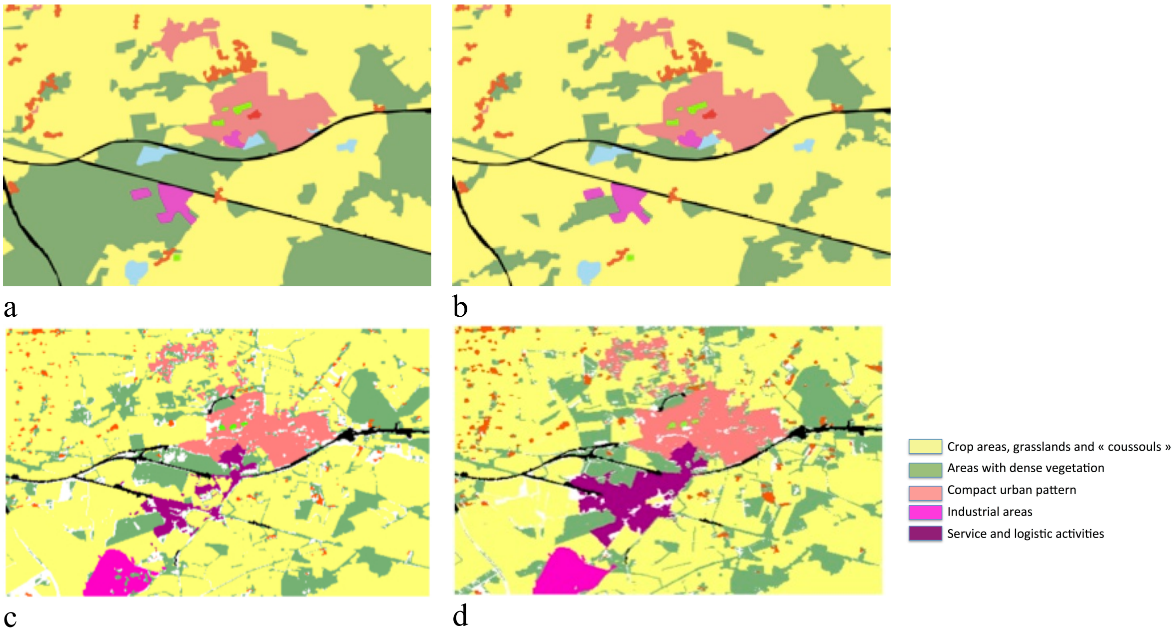


Figure 3: *Land use maps: it shows (a, b) how urban development is reflected in the Corine Land Cover mapping and (c, d) how it appears when the PRECOS approach is applied for one of the municipalities of the Crau area in 1997 and 2009 respectively (from Trolard et al., 2013b).*

During the 1997–2009 period over than 1,600 ha of irrigated grasslands and natural areas were lost to urban sprawl and the implementation of environmental measures is undermined by the “fait accompli” (Fig. 3).

Evidence for this was obtained by devising extremely fine land occupation maps of the Crau area between 1997 and 2009 (spatial resolution of 0.6 m to 20 m depending on the location in the area) (Fig. 3 c, d). Indeed, the data from CORINE Land Cover, as already observed by other authors (Pageaud and Carré, 2009), do not meet the needs of urban planning. This can be ascribed to the low resolution of the mesh used by CORINE Land Cover and to the fact that the classification of land uses is not stable over time. This makes it impossible to superimpose maps drawn on two different dates (Fig. 3a, b). The study covering the entire Crau area thus shows that between 1997 and 2009, urban sprawl has affected approximately 2,300 ha. Similar observations were made in Italy (Biasoli et al., 2006), more largely in Mediterranean region (Salvati, 2014) and in Asia (Zhang et al., 2007). Observations in the Emilia-Romagna region in Italy have shown that over the 6-year period (2003-2008) urbanization led to a loss of crop production potential equivalent to the daily caloric requirements of more than 440,000 people (Malucelli et al., 2014). In addition, the National Strategy for Sustainable Development for 2010 - 2013 has highlighted as one of its objectives the need to ensure that the land sealing rhythm, which is currently superior to demographic dynamics, must be better controlled especially by endeavoring to locate the new infrastructures on lands already artificialized (DIDD, 2010).

4.2 Multi-secular irrigated agriculture: a factor of sustainability and a source of ecosystem services

Thanks to Adam de Craponne's canals built in the Crau area, in the 16th century, the multi-secular irrigation system warrants a lasting resilience of the biophysical environment. This is demonstrated by the integrated analysis of the agronomical, pedological, land use and biogeochemical soil and water data (Trolard et al., 2013a).

The geochemical study shows that the Durance waters used for irrigation do not have any aggressive effect on the soil mineral components and instead, meet most of mineral nutrients necessary to the Crau's hay. A comparative balance between the concentration of mineral elements exported by the Crau's hay and the rates of mineral matters found in the irrigation waters only reveals a slight deficit for potassium and phosphorus (Table 4) (Bourrié et al., 2012).

Table 4: *Balance of mineral element fluxes brought by the irrigation water compared to the needs of Crau's hay for the first cut.*

Element	Ca^{2+}	PO_4^{3-}	Mg^{2+}	Na^{+}	SO_4^{2-}	K^{+}
Balance*	1.41	-0.02	0.30	0.31	0.47	-0.14

*in mol m^{-2}

In the Crau plain, irrigated agriculture for over 400 years, has contributed to four essential ecosystems services: (i) soil conservation; (ii) biomass production; (iii) aquifer recharge and (iv) wetland preservation.

4.3 Soil conservation

Irrigation has two consequences. It brings silt, thus changing the soils' granulometry. It changes soils' acido-basic properties because of the geochemical interactions between waters and soils. The Durance irrigation waters protect soil against its natural trend towards acidification caused by rainwater. When rain enters the topsoil, its acid properties are enforced because it equilibrates with pCO_2 of soil atmosphere, which is much larger than pCO_2 of external atmosphere; it operates then as a strong solvent. In the Crau area, irrigation waters contain dissolved calcium carbonate because of their transfer from the Alps through limestones, and their pH is of 8.3. This makes them less aggressive towards soils minerals and even instead, makes them rather encrusting depending on the degree of concentration of water by evaporation, which depends itself on climatic conditions.

4.4 Biomass production

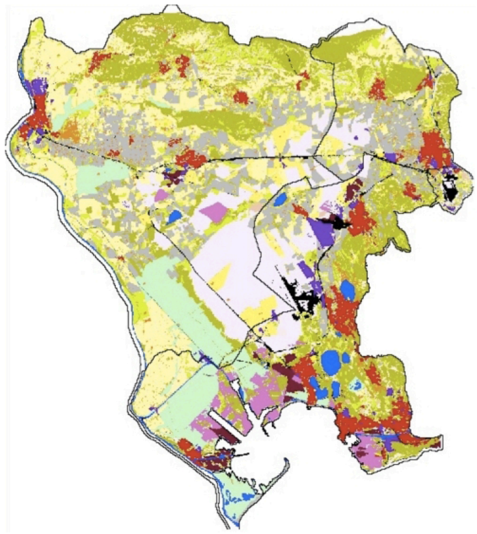
Two parameters are critical for determining the grassland's yield: the soils' characteristics and the water turns, *i.e.* time between two irrigations and water quantity per irrigation (Astuce & Tic, 2011). The average yields vary between 7.8 t ha^{-1} and 9.7 t ha^{-1} (Comité du Foin de Crau, personal communication). The highest yields are obtained on hydromorphic soils or on soils, which have the thickest HA horizon, *i.e.* soils with the highest water holding capacity. The productivity is also dependent on the water turns: the greater the intervals, the lower the yields.

4.5 Aquifer recharge

The large permeability of the aquifer in the Crau (10^{-3} to 10^{-2} m s^{-1}) and massive inflows of water by irrigation (about 20,000 m^3 ha^{-1} $year^{-1}$) define a highly dynamic regime of the aquifer. Thus even though irrigated grasslands occupy less than 20% of the Crau plain's surface, they contribute to over 75% to the aquifer's water replenishment. The sporadic but regular charging, which comes from irrigated grasslands, actively supports the groundwater levels observed. In the North the piezometrical variations under some irrigated areas can reach 10 m (Baillieux et al. 2015). Water charging by irrigation is smaller in grasslands on hydromorphic soils and the average recharge of water is 1,337 mm $year^{-1}$, while on other types of soils it is over 1,700 mm $year^{-1}$. As the average thickness of the aquifer is between 10 and 40 m, the operational capacity to use the underground water resources is highly dependent on the conduct of the gravity irrigation of grasslands.

4.6 Wetland conservation

Gravity irrigation for agriculture has a predominant influence on surrounding wetlands. It maintains the overflow of groundwater upstream from the aquifer. These waters then reappear under the form of resurgences feeding the surrounding ponds (Entressen and Des Aulnes) and wetlands, known for their large ecological diversity (Vigueirat pond), 1,000 ha of which are classified as a biosphere reserve. Gravity irrigation thus maintains a hydrostatic balance preventing the salted aquifer to ingress from the South (Fig. 2).



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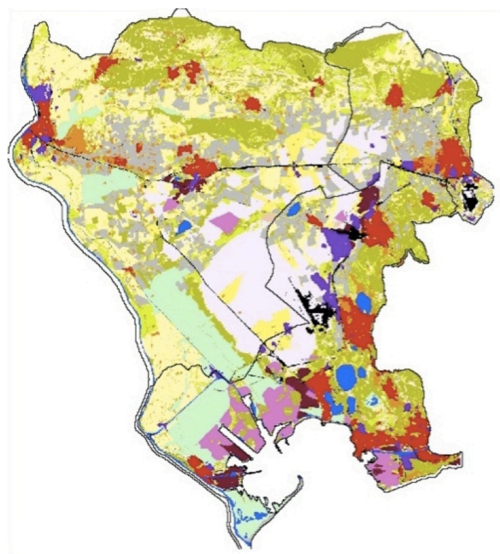

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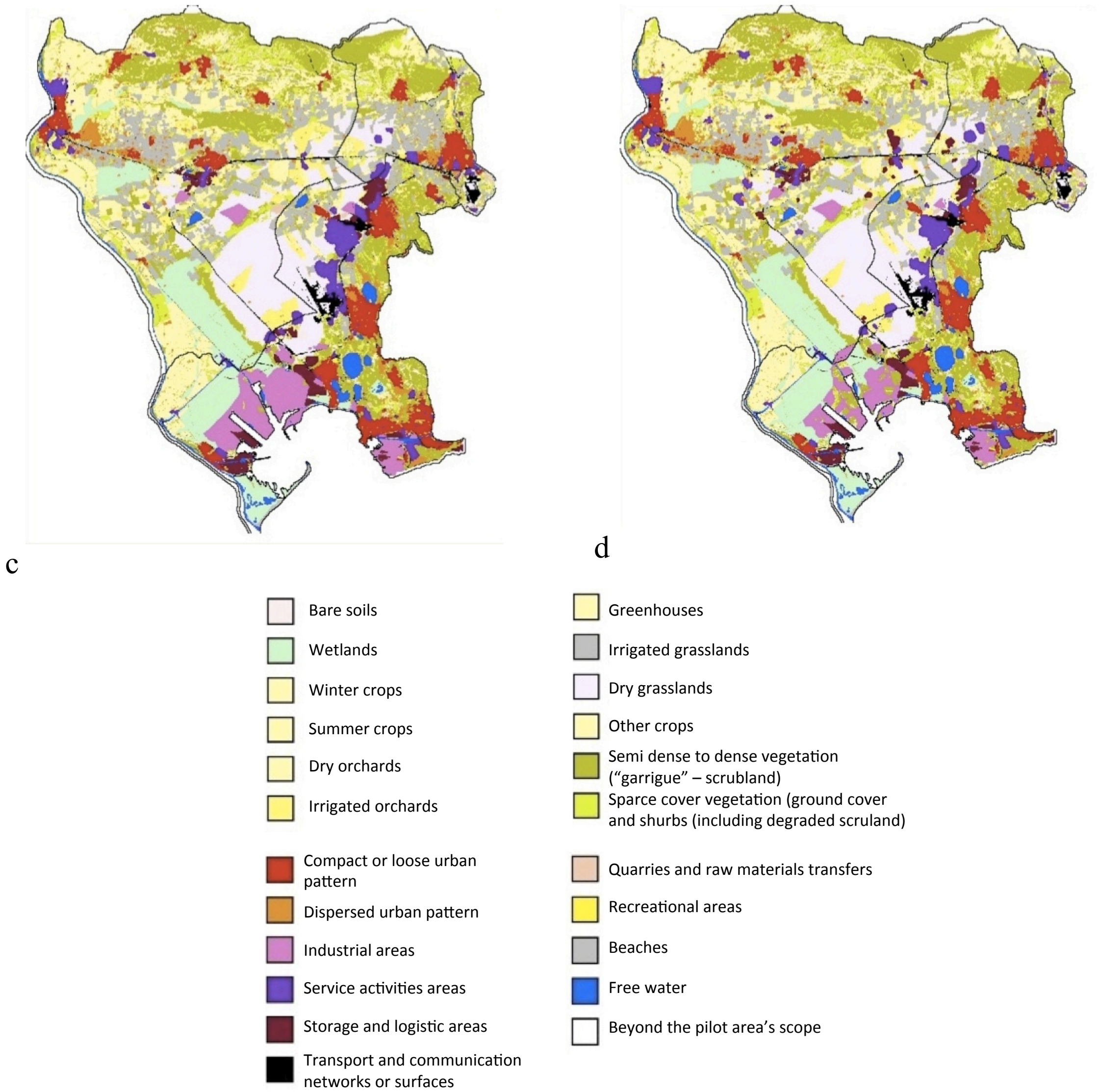

Figure 4: *Prediction of land occupation change in 2030 as function of the different scenarios. (a) reference 2009, (b) 2030 – scenario 0, (c) 2030 – scenario 1 and (d) 2030 – scenario 2.*

Furthermore, the supply of calcium by irrigation water percolating through the soil and sub-soil down to the aquifer contributes to the groundwater's high quality, by precipitating the excess of phosphate in the form of apatite (calcium phosphate) preventing any eutrophication of the aquatic systems (Bourrié et al., 2012).

4.7 Perspectives to 2030 in the Crau area

At the 2030 time horizon and whatever the scenario, simulations show an increase of the territory's vulnerability and significant alterations of ecosystem services provided by agriculture.

Results show that urban sprawl will happen at the expense of protected natural areas, cropped lands and irrigated grasslands (Table 5, Fig. 4). Land surface lost to urbanization ranges between 4,377 ha for scenario 0 ("trend" scenario) and 7,358 ha for scenario 2, the most space-consuming scenario. In all cases urban sprawl impacts over 50% of the most fertile lands in the region, defined by the agronomic qualification index (Fig. 5). Generally, these lands correspond to the oldest irrigated grasslands where soils are the result of over 400 years of cumulated silt deposits.

Table 5: *Estimate of surface areas that will be used up by urbanization between 2010 and 2030 by type of land occupation as function of the three scenarios. The surfaces are expressed in hectares and in % of the total surface of the considered soil occupation.*

Type of Soil Occupation	**Scenario 0**		**Scenario 1**		**Scenario 2**	
	/ha	/%	/ha	/%	/ha	/%
Irrigated grasslands	1,065	6.8	1,308	8.3	1,826	11.5
Great field crops	23	0.2	43	0.4	62	0.6
Other crops	38	0.9	64	1.5	222	5.2
Dry meadow	113	0.9	585	4.6	563	4.4
Natural areas*	1,341	3.9	2,863	8.4	1,813	5.3
Wetlands	173	1.8	694	7.4	293	3.1
Orchards	147	2.3	332	5.3	798	12.7
Bare soil	1,473	21.0	1,916	27.3	1,778	25.3
TOTAL	4,376		7,805		7,356	

* out of wetlands

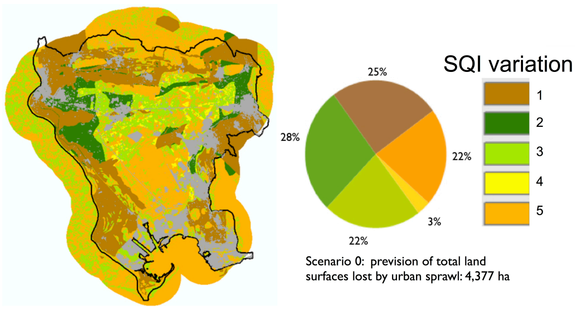

Figure 5*: Qualification and quantification of soils loosed to urban sprawl: results obtained for 2030 with the scenario 0. Soil Qualification Index (SQI): 1. Hydromorphic soils; 2. Soils with 50 cm HA horizon; 3. Soils with 35 cm HA horizon; 4. Soils with 10 cm HA horizon; 5. Fersialitic soils.*

For agriculture production, results show that climate change without any water irrigation restriction will have a rather positive effect on grassland yields (increase of about 11%) and an increase of approximately 1 t ha^{-1} of dry matter would be expected. However such positive increase of yield would be crushed by the reduction of water quantities allocated to irrigation (-30% in our scenarios). Globally, no significant yield change is expected. In all cases, gross agricultural production will decrease, due to the loss of agricultural land to urban sprawl in 2030 (Table 6), and consequently the income of farmers.

Table 6: *Inputs and withdrawals of groundwater as function of land occupation and water allocations in 2009 and prediction for the scenario 2 in 2030.*

Land occupation	**Inputs (mm $year^{-1}$)**	
	Reference 2009	Prediction 2030 – scenario 2

Occupation by default	10.0	10.0
Coussouls and sparse vegetation	32.8	-7.6
Irrigated grasslands	2,020.0	1,464.0
Summer crops (*e.g.* sunflower)	86.4	125.0
Winter crops (*e.g.* wheat)	63.6	54.6
Wetlands*	-316.0	-491.0
Orchards	-316.0	-434.5
Water allocation	**Withdrawals (millions of m^3 $year^{-1}$)**	
	Reference 2009	Prediction 2030 – scenario 2
Drinking water	24.8	32.2
Industrial water	7.6	7.6
Agricultural water	27.0	21.8

* the negative drainage values mean that on the concerned surfaces, real evapotranspiration is more important than the sum of inputs (rainfall + irrigation)

In addition, simulations of the water table level for 2030 show an important drawdown explained by the conjunction of an anticipated decrease of irrigated grassland surface in the range of 11%, a decline of about 30% of irrigation water quantities from Durance River and 30% increase of drinking water requirements (Fig. 6).

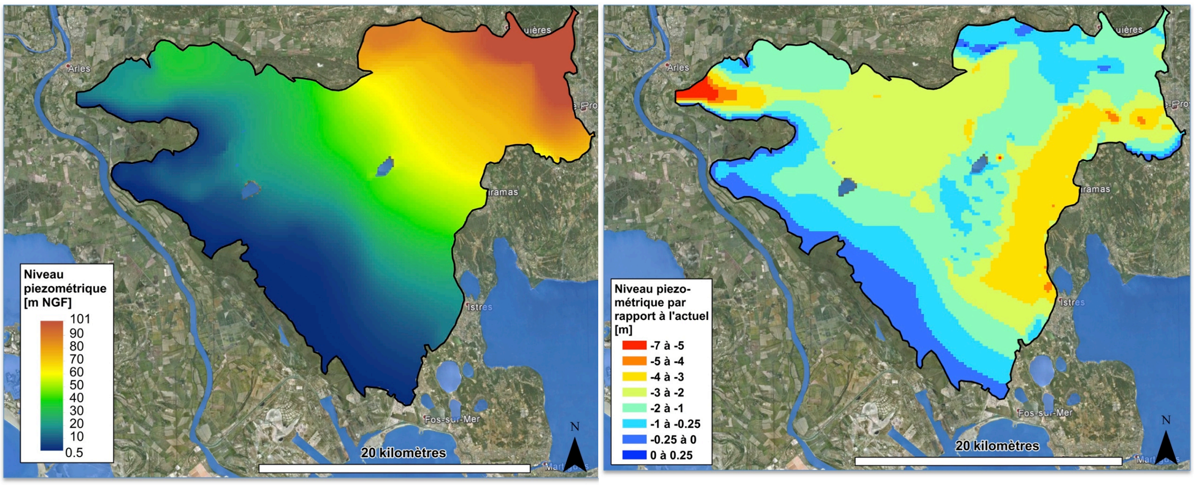

***Figure 6**: Piezometric level in permanent regime in reference state 2009 (a) and prediction of the evolution of the water table in permanent regime in 2030 with the scenario 2 (b) (from Olioso et al., 2013b and Baillieux et al., 2015).*

The main consequence for industry and cities would be water shortage, with a predicted lowering of the groundwater table ranging from 2 to 9 m. If infrastructures must be built to bring pressurised water from the East of Provence, the additional cost will be huge.

The reduction of the aquifer expansion would have other drastic consequences with: (i) a possible progression inland of sea water ingress in the south of the territory and (ii) depriving of wetlands of their fresh water supply entailing "catastrophic" impacts on local biotopes and associated biocenosis.

4.8 Applying the PRECOS approach in other contexts: first step

When looking at urban governance system typologies (Metrex, 2010), it is possible to observe that several broad geographical and resource conditions will be favourable for integrated approaches such as PRECOS: (i) important rural surfaces devoted to agricultural production and /or proximity of protected natural areas; (ii) strong urban sprawl whether or not linked to urban growth; (3) the proximity of environmentally taxing industrial (or commercial) installations or infrastructure (Seveso installations, logistic platforms, mines etc.) and (iv) specific developments, constraints or triggers related to the socio-economic or regulatory context.

Table 7: *Main vulnerability and linked indicators (* A&T = Astuce & Tic prototype)*

	A&T* indicators	**Crau**	**Emilia-Romagna**	**Valencia**
A	Land occupation	yes	yes	yes
B	Fragmentation of habitats	yes	May be	yes
C	Soil sealing	yes	yes	yes
D	Aquifer evolution	yes	no	no
E	Drinking water supply	yes	no	no
F	Pollution risk	yes	May be, not easy	yes
G	Water drinkability	yes	no	yes
H	Risk of water salinity	yes	no	no
I	Risk of soil salinization	yes	no	yes
J	Risk of soil acidification (soil data)	yes	no	no
K	Risk of soil acidification (water data)	yes	no	no
L	Risk of soil sodicity	yes	no	yes
M	Soil agronomic qualification index	yes	yes	yes
N	Agricultural production	yes	yes	yes
O	Drainage	yes	yes	yes
	Locally important indicators not included in A&T			
1	Carbon stock		yes	yes
2	Run off modification		yes	yes
3	Land capability		yes	yes
4	Air quality		Data not ready	-
5	Brown soil		yes	-
6	Eutrophisation		-	yes

Consultations with potential end-users in regions of Emilia Romagna in Italy and Valencia in Spain have shown that the PRECOS approach can be deployed by using existing data and by organizing, at local level, a consortium of skills able to analyze the results. Table 7 shows that in these new test areas, indicators proposed by the PRECOS approach can be produced. If the local situation requires consideration of new indicators, the modularity of the processing chain allows for adding new modules and interfaces in the workflow.

The consortium had the opportunity to apply the first stages of the PRECOS approach in Emilia-Romagna, an Italian region identified as likely to encounter serious climate and resource pressures in the future. PRECOS has been identified as useful for policy makers, cautioning authorities and developers when planning for future land and water uses... The province of Modena was one of the areas earmarked as well adapted to the introduction of the PRECOS approach. Indeed, in this province, urban sprawl problems are rendered even more acute, because of on-going post-earthquake reconstruction operations especially those in connection to large scale transport infrastructure developments. Several studies have already shown the extension of the risks of soil sealing and climate change in the region (*e.g.* consequences and costs of runoff during extreme events, damages to the water network, soil degradation…) (Burrato et al., 2012; Ceccarelli et al., 2014; Salvati, 2014; Ungaro et al., 2014). Moreover, policy and decision-makers are quite aware of this especially considering the weight of high quality agriculture productions in the local economy.

In Valencia region, taking into account the complex scenario of future regional development with an increase of risks due to the climate change and a difficult balance between environment and economic growth (*e.g.* García, 2010; Rico-Amoros et al., 2009; Vicente Serrano et al., 2004; Luis et al., 2000), the PRECOS approach could play a significant role supporting decision-makers and politicians to make better decisions. The current lack of comprehensive tools capable of merging and managing different sources of geo-referenced data (social, economic, environmental) and of turning them into useful information for decision-makers has been emphasised.

5. Conclusions

Building on and elaborating from Astuce & Tic prototype, the European consortium in charge of PRECOS established that the approach could be deployed beyond the Crau pilot demonstration area and was likely to meet the needs of a variety of local situations.

The Crau area was chosen because it is representative of critical situations deriving from global changes, urban pressures and climate change that are apparent in a number of places in the world. Conducting this experimental approach on the Crau area has shown that up to the beginning of the 16th century local planning was developed around the Crau irrigation network. Irrigated grasslands were the cornerstones of the anthropic-system and an example of how successful men's multi-secular efforts were to maintain a balance with the environment.

The PRECOS integrated approach provides a global vision of urbanization and climate change' manifold impacts on all ecosystem services; it identifies *hic et nunc* the more vulnerable and risk-prone areas and takes into account the inter-relationships between all their components.

Method wise, the treatment or acquisition of new data and the integration of multi-sector information is pooled within a chain of modeling modules that generate pertinent and factual indicators for a given area and offer the possibility of following their dynamics in real time. Medium term scenarios then analyze the dynamics of these indicators overtime and lead to a virtual representation of what future adaptations could lead in terms of "*a minima*" pressures and potential additional costs before their cumulated impacts drive the area to tipping points. The representation tools make it possible to visualize these results in terms of time-space and also provide supporting documents for stakeholders' consultations, discussions or negotiations.

Pre-diagnosis made in regions of Emilia-Romagna (Italy) and Valencia (Spain) show that local end-users and policy-makers are interested by this approach. The modularity of indicator calculations and the availability of geo-databases indicate that PRECOS may be up scaled in other socio-environmental contexts. Moreover, on one hand, the efforts to build up regional databases following standardized guidelines defined at international level and, on the other hand, the development projects of the use of digital technologies in local communities mean that the data is becoming more accessible and free. In addition, the modular software architecture allows PRECOS (i) to evolve with advances in modeling sectors considered here; (Ii) to interchange a simulation module by an equivalent and more appropriate to the local context (iii) to integrate new features and compute new indicators based on the needs of stakeholders and policy-makers. PRECOS is a valuable tool to turn this data into actionable information for territorial management.

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