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Combining narrative scenarios, local knowledge and land-use change modelling for integrating soil erosion in a global perspective

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1 **Combining narrative scenarios, local knowledge and land-use change** 2 **modelling for integrating soil erosion in a global perspective**

3 4 **Abstract**

5 Mediterranean soil resources are heavily affected by water erosion. There is a need for anticipating
6 the potential impact of land-use change at the catchment scale, considering a range of contrasted
7 possible changes, in order to prepare a relevant adaptation strategy. While participatory scenario
8 approaches are useful for unveiling the diversity of possible futures, their outputs generally take the
9 form of narratives that may be difficult to relate to biophysical models used for simulating soil and
10 water processes. We addressed this challenge by developing a methodology combining narrative
11 scenarios and land-use change modelling at the catchment scale, interacting with local stakeholders
12 who were involved throughout the research, in line with current Land System research. First, we built
13 contrasted scenarios, each with a narrative story and quantitative assumptions for key variables.
14 Then we drew up rules for translating narrative scenarios into spatially explicit maps based on expert
15 groups and local knowledge, simulating the evolution of land use over time. Third, we evaluated and
16 validated the final scenarios by conducting two workshops with scientists and local stakeholders.
17 Finally, we assessed the impact of these scenarios on agricultural production and erosion control.
18 This approach was implemented in the Tleta basin (Morocco), a 180 km² rural watershed, 10 km
19 from Tangiers and heavily affected by water erosion. As a result, we propose three contrasted
20 spatially explicit land-use change scenarios by 2040. Our work highlights the interest of combining
21 narrative storylines and land-use modelling when developing spatially explicit scenarios at the
22 catchment scale, incorporating the local knowledge of stakeholders. The combination of Land System
23 and ecosystem frameworks contributes to integrating the soil erosion issue in a more global
24 perspective, and lays the foundation for building sustainable strategies for Mediterranean
25 catchments affected by soil erosion.

26 **Keywords:** Narrative scenarios, LUCC modelling, Participation, Land System, Soil erosion, Morocco

1 **1. Introduction**

2 Soil degradation, and in particular soil loss due to water erosion, is a major threat to the future of the
3 Mediterranean basin (Lagacherie et al., 2018; Raclot et al., 2018). Soil losses lead to lower soil fertility
4 that can affect agricultural production (Panagos et al., 2018), and reduce water-supply capacity due
5 to siltation in reservoirs (Ben Slimane et al., 2016; Kondolf and Farahani, 2018). This phenomenon is
6 expected to increase in the future due to climate change (Lagacherie et al., 2018) and land-use
7 changes (Van Rompaey et al., 2007; Borrelli et al., 2013). Several recent studies on the combined
8 effects of climate and land-use changes on water erosion have shown that land use has a
9 predominant effect (Paroissien et al., 2015; Simonneaux et al., 2015; Luetzenburg et al., 2020),
10 although uncertainties attached to its evolution are clearly recognized. Anticipating future land-use
11 changes is therefore particularly important for mitigating and/or reducing their potential negative
12 effects on water erosion.

13 An approach commonly used in erosion-process modelling is to simulate purely technical land-use
14 change scenarios. These can involve a minor change in the value of one variable of the land-use
15 change model (Van Rompaey et al., 2007), or extreme scenarios involving several variables
16 simultaneously, but which have the disadvantage of being rather implausible (Ashagre et al., 2018).
17 This type of approach formulates clear-cut land-use change hypotheses, which are simple to quantify
18 and spatialize, and easy to use as input for biophysical models. [A second approach consists of
19 predicting a land-use scenario based on trends in land-use change observed in the past \(Maeda et al.,
20 2010; Ferreira et al., 2016; Zare et al., 2017\). This predictive approach is based on the assumption of
21 a continuation of past trends, without envisaging potential economic, political or social breakdowns.](#)
22 Conversely, participatory scenario approaches allow exploring different futures for a territory by
23 considering a wide range of driving factors that influence land-use change, and by formulating
24 assumptions related to their possible evolution. Although the driving factors to be considered are
25 case dependent, they usually cover economic, regulatory, social and technical dimensions, including
26 those driving changes in farming systems and practices (e.g., agricultural policy, agricultural
27 commodity markets, technological change, environmental regulation, water resources availability),
28 and factors determining the form of urban development, such as population growth, economic
29 development and income.

30 An increasing number of studies relies on the development of contrasted narrative scenarios, to
31 facilitate the exploration of potential land-use changes and their impact by experts and stakeholders
32 together (Rinaudo et al., 2013; Oteros-Rozas et al., 2015; Vacquie et al., 2015; Houet et al., 2017).
33 However, a direct use of such scenarios can be difficult when trying to transform them into spatial

1 and dynamic representations over time (Shackley and Deanwood, 2003; Kok et al., 2007; Alcamo,
2 2008), or as maps of land-use change that can be used as input for biophysical models. Translating
3 these narrative scenarios into spatially explicit maps requires a numerical description of the rates of
4 change in land use and, above all, of the constraints of their plausible locations at fine scales
5 (Mallampalli et al., 2016). There are several methods for achieving this numerical description,
6 including fuzzy set theory (Kok et al., 2014), pairwise comparison (Abildtrup et al., 2006; McDaniels et
7 al., 2012) and role-playing games (Castella et al., 2005; Lamarque et al., 2013). Yet, the translation of
8 narrative scenarios into quantified hypotheses that can be used in land-use and -cover change (LUCC)
9 modelling remains a challenge, particularly at catchment scale where local processes—such as
10 urbanization or agricultural management—interact with global drivers (Booth et al., 2016). Our paper
11 addresses this challenge by developing an empirical approach based on input from expert groups and
12 local knowledge. This provides the flexibility and specificity necessary for translating narratives with a
13 large set of drivers, into quantitative-input models that vary in space and in time (Vacquie et al.,
14 2015; Booth et al., 2016).

15 There are several LUCC models for a fine description of the processes involved. These range from
16 multi-agent systems describing social behaviour, such as LUDAS (Le et al., 2008), MP-MAS
17 (Schreinemachers and Berger, 2011), or cellular automata for urban growth (Guan et al., 2011), to
18 Markovian-type probabilistic models for describing heavy trends (Paegelow and Camacho, 2008;
19 Ruiz-Benito et al., 2010), including Clue-S (Verburg and Veldkamp, 2001), Dinamica (Maeda et al.,
20 2011), SPA-LUCC (Schirpke et al., 2012) and Land Change Modeler (Agujejad and Houet, 2008).
21 Improving LUCC predictions can be done by adding spatial constraints related to geomorphological or
22 anthropic factors, such as distance maps to fixed landscape elements, or crop aggregation criteria
23 (Castellazzi et al., 2007; Houet et al., 2010). When simulating land use, Brown et al. (2005) described
24 the constant tension between the desire for accurate prediction and the accuracy of the process. In
25 the case of a prescriptive approach, the goal is to obtain the closest map to the narrative scenarios;
26 in the second case, the explanatory approach, the main goal is to explain the underlying mechanisms
27 of change and, if so, the maps showing a path-dependency according to the process included and its
28 parameterization. These LUCC models are used with varying degrees of stakeholder involvement.
29 Historically, LUCC models were built in isolation, with stakeholders being involved primarily as end-
30 users (Kok et al., 2007). Gradually, however, stakeholder involvement increased, especially with the
31 “Storyline and Simulation approach” defined by Alcamo (2008), constructing participatory scenarios
32 that were translated into quantitative LUCC input (Houet et al., 2017). Today, Land System research
33 articulates around three pillars: scenarios, land-use change modelling, and participation (Castella et
34 al., 2007; Kok et al., 2007; Rounsevell et al., 2012; Houet and Gourmelon, 2014; Houet et al., 2016),

1 with a high degree of involvement by local actors throughout the process. To our knowledge, this
2 integrated approach of the Land System combining narrative scenarios, LUCC models and
3 stakeholder participation has not yet been used for analysing soil-erosion problems.

4 Our paper bridges this gap, describing a methodology that combines narrative scenarios and LUCC at
5 the catchment scale, in interaction with local stakeholders who are involved throughout the
6 research, for developing land-use scenarios that will serve as input for estimating future soil erosion.
7 We illustrate its potential use (1) as a concrete support for discussion with local stakeholders, and (2)
8 as input data for ecosystem service assessment at the catchment scale. This approach is applied to a
9 rural catchment in northern Morocco facing major soil losses. It enriches the corpus of Land System
10 studies, validating the relevance of our approach in a regional, socio-economic and environmental
11 context that is complementary to those of existing studies.

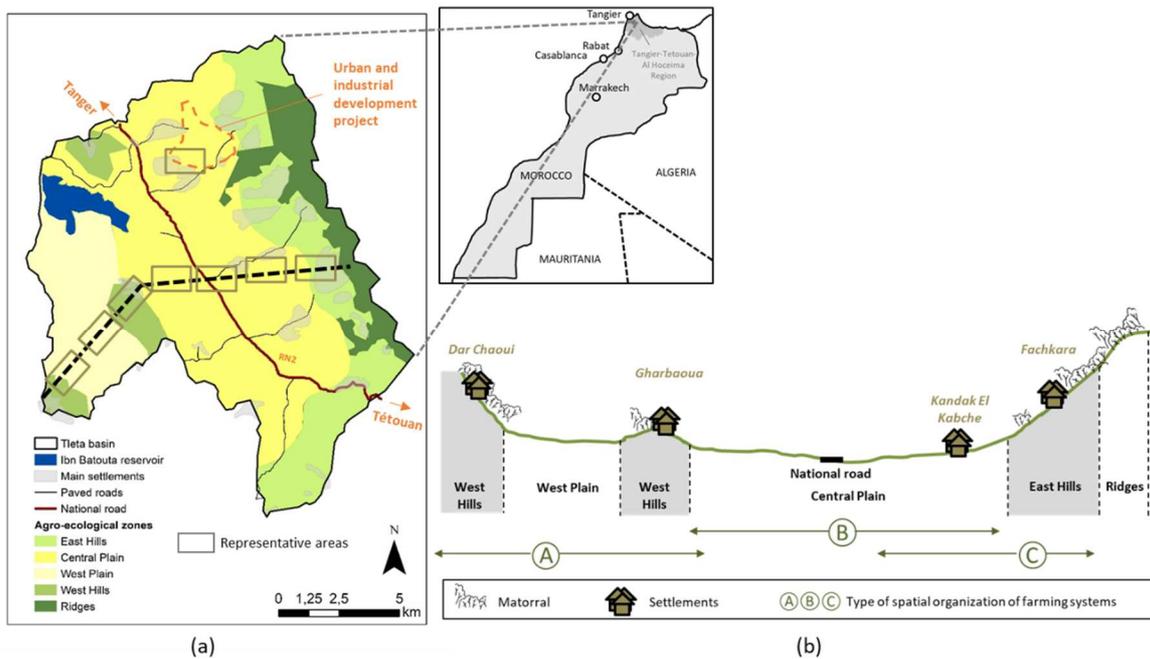
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13 2. Study area

14 In Morocco, water erosion affects more than ten million hectares, with a particularly high rate of
15 erosion in the catchment areas of the Western Rif where average soil loss is 35t/ha/year (REEM,
16 2015). (Croitoru and Sarraf, 2017) estimated the Moroccan crop-yield loss due to water erosion at
17 1.1 billion dirhams (100.8 million euros) by 2040. In addition, the loss of storage capacity through
18 silting up of reservoirs is currently 75 million m³ per year, leading to a commensurate decrease in
19 regulated volume for users (Croitoru and Sarraf, 2017). The total cumulative loss is estimated at 1.75
20 billion m³, or 10% of the total initial storage capacity behind Morocco's dams (Chentouf, 2016).

21 The Ibn Batouta dam, supplying drinking water to the city of Tangiers, illustrates this silting
22 phenomenon. Built in 1977, its storage capacity has dropped from 43.6 to 29.1 Mm³ between 1978
23 and 2013, a loss of 33%, due to the progressive deposition of soil by water erosion processes. Its
24 catchment area, the Tleta (180 km²), is essentially rural with farms oriented towards polyculture and
25 livestock farming (Fig. 1a). Due to scarce water resources, irrigation is almost non-existent in this
26 basin, which is mainly oriented towards rain-fed production of cereals, sorghum and vegetables,
27 mainly for self-consumption and livestock. A significant proportion of the basin (20%) is covered by
28 matorral (Mediterranean bush vegetation). Though soil- and water processes in the Tleta have been
29 extensively studied since the 1970s, investigating the influence of changes in agricultural land use
30 and practices on erosion processes (Hammouda, 2010; El Bazi, 2014; Kouatli, 2015; Sahraoui, 2015),
31 there has been almost no work to understand and analyse changes in human activities and resulting
32 land-use changes. Located 10 km from Tangiers, this basin shows accelerated changes in land use,
33 driven mainly by rapid urban growth. Recently, it saw strong industrial, commercial and residential

1 development on both sides of the national road traversing it, the development of new roads serving
 2 remote rural settlements, and the construction of a new industrial city in its northern part (Fig. 1b).
 3 Several new olive orchards and the arrival of agricultural investors from outside the basin further
 4 modified the agricultural landscape mosaic of this territory (Sabir et al., 2019).



5
 6 *Figure 1. The Tleta basin: (a) Agro-ecological zones, transects and representative areas studied;*
 7 *(b) Simplified cross-section of transects studied (adapted from Sabir et al., 2019)*

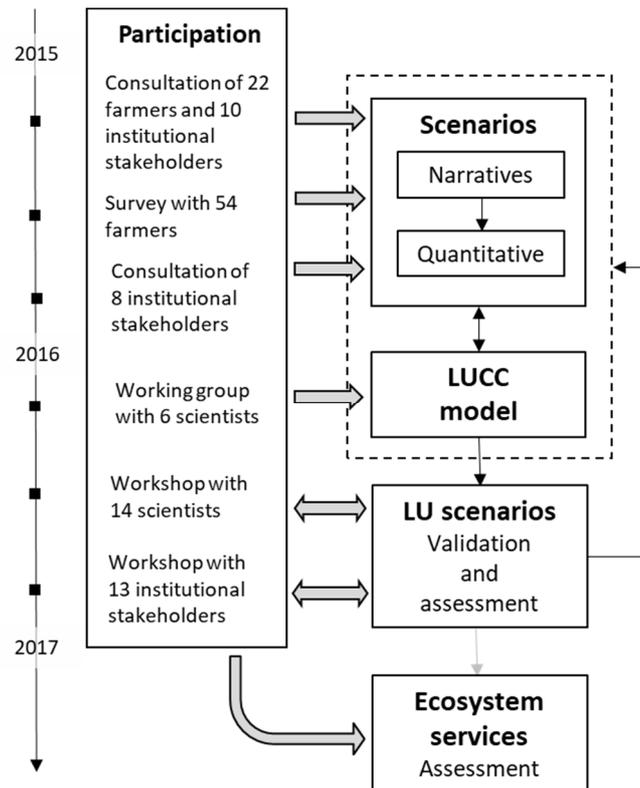
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9 3. Methodology

10 Consistent with Land System research (Kok et al., 2007; Rounsevell et al., 2012), our approach was
 11 structured around three closely linked key methodological components (Fig. 2): scenario
 12 development, land-use change modelling, and active stakeholders' participation in all phases.

13 The first step consisted in building scenarios, each consisting of a narrative story and quantitative
 14 variables. The second step was to simulate land use in time and space. The third step evaluated and
 15 validated the final land use (LU) scenarios by conducting workshops, first with a group of scientists
 16 and then, after reworking the LU scenarios, with a group of institutional actors. The workshops
 17 improved the plausibility of the assumptions of the narrative scenarios, and of the assumptions used
 18 for the land-use change model. Each step called upon local knowledge and/or scientific expertise,
 19 mobilized through surveys, interviews, and working-group meetings. Finally, following Ellis et al.
 20 (2019), we show how LU scenarios can be used for analysing spatially the resulting ecosystem

1 services, through assessing agricultural production and the erosion-control service associated with
2 each LU scenario.



3

4 *Figure 2. Overview of our approach to building and assessing land-use (LU) scenarios.*

5

6 **3.1.Scenarios: development of narratives**

7 Construction of the narrative scenarios took place in two phases, following Godet's (1994) scenario
8 method: analysis of the system (past and present situation) and elaboration of narratives.

9 **3.1.1. System analysis (past and present situation)**

10 This step consisted in an, as complete as possible, global and explanatory description of the current
11 system and of its past temporal dynamics, and in identifying all the factors influencing land-use
12 change. The objective was to develop a conceptual representation of the local socio-ecological
13 system, where policies, economic actors and natural components interact. This systemic approach
14 helped understanding the system dynamics, allowing the formulation of assumptions concerning its
15 future evolution. Sabir et al. (2019) described in detail the tools used for this step. Similar to Castella
16 et al. (2007), our approach combined the use of a regional/basin scale and a local scale. First, the
17 analysis was carried out at the scale of the Tleta basin, based on field observations of the landscape,
18 and on vegetation maps for the period 1977 to 2007 (Hammouda, 2010; El Bazi, 2014), census data,

1 and consultation of 10 institutional stakeholders and 22 farmers in the basin (Fig. 2). This resulted in
2 identifying five main agro-ecological zones in the basin, from west to east: Western hills, Western
3 plain, Central plain, Eastern hills and Ridges—the latter being entirely occupied by State forest for
4 which land use is considered to be stable over time—as well as their land use and past trends. This
5 identification was, however, limited in the understanding of underlying finer mechanisms of land-use
6 change.

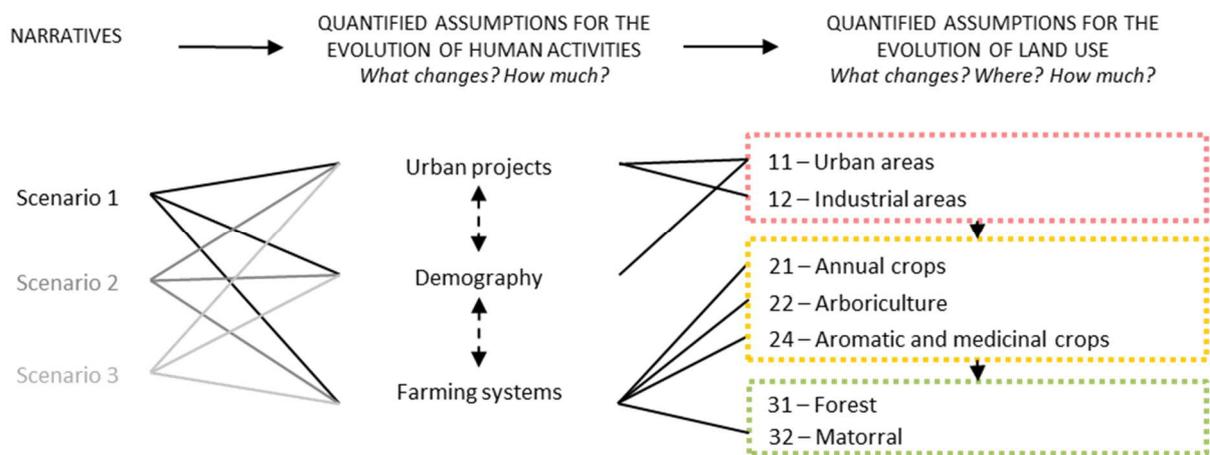
7 In a second step, a refined analysis was carried out at the scale of eight local representative areas
8 (rectangles of 1.5 by 1 km) in four agro-ecological zones, where land use is likely to change over time
9 (Fig. 1a). These representative areas are distributed along two transects in the northern part of the
10 basin, which is more affected by the economic development of the Tangiers area. We carried out a
11 detailed analysis of the historical evolution of land use in these eight representative areas, based on
12 digitizing of the plots and the observation of satellite images over the period 2003-2015. This analysis
13 identified and quantified the main changes in land use over this period (cultivation of matorral areas,
14 establishment of arboriculture, construction of buildings), serving as a basis for in-depth surveys with
15 56 farmers working plots in the representative areas, and providing quantified data on past land-use
16 changes. This finer analysis provided quantitative data on farming systems in 2015, their spatial
17 organization and their historic evolution, in relation to the observed land-use changes. This
18 highlighted contrasting land-use dynamics between the agro-ecological zones of the basin,
19 demographic dynamics, and the different forms of spatial organization of the basin's farming
20 systems.

21 3.1.2. *Elaboration of narratives*

22 Nine main factors of change were identified from the previous stage (Sabir et al., 2019), five on the
23 global/national scale (national agricultural policy and the Green Morocco plan; influx of external
24 capital invested in the land; economic development of Tangiers; political choices of the State in terms
25 of land-use planning; climate change) and four on the basin scale (availability of water resources for
26 irrigation; technical innovations; rural-development choices; land-use planning choices). Several
27 evolution hypotheses were formulated for each of these factors, based on additional interviews with
28 eight key institutional stakeholders in the basin, involved in land-use planning, agriculture, forestry,
29 water and soil management (Table 1.A.) and consultation of planning documents (Royaume du
30 Maroc, 2006; Omrane, 2010; Fahs-Anjra, 2015). We then combined these hypotheses, in order to
31 write contrasted narratives describing possible future land-use scenarios for the Tleta basin
32 (Table 1.C.).

33 **3.2. Scenarios: quantifying land-use change hypotheses**

1 The narratives were broken down into quantified assumptions for simulation by the land-use change
 2 model. These hypotheses were based on the consultation of local stakeholders and scientific experts,
 3 on the analysis of data from surveys conducted in 2015 among 56 farmers in the basin (Sabir et al.,
 4 2019), on census data (HCP, 2007) and on key planning documents. This part of the work was carried
 5 out in two steps (Fig. 3). First, we formulated hypotheses on the evolution of human activities (urban
 6 projects, demography, agricultural production systems) consistent with each narrative scenario. This
 7 was done by answering two questions: What changes? and How much? In a second step, each
 8 change in human activities was linked to the types of land use concerned, using the Corine Land
 9 Cover nomenclature expanded to a supplementary level of detail for specific land use, such as
 10 including aromatic and medicinal crops, for which assumptions were also formulated according to
 11 three questions: What changes? Where? How much?



12

13 *Figure 3. Approach for translating narrative scenarios into quantified and spatially explicit*
 14 *hypotheses.*

15

- 16 - Assumptions related to urban projects were mainly based on planning documents (Royaume
 17 du Maroc, 2006, 2011; Omrane, 2010; Fahs-Anjra, 2015), considering different construction
 18 phases of the new town and the industrial areas. Concerning diffuse (unplanned)
 19 urbanization, we assumed a continuation of trends observed over 2003-2015 in
 20 representative areas on either side of the national road (Sabir et al., 2019). These data
 21 helped estimating, for each scenario, the areas for construction of the new town and
 22 industrial zones, as well as their location.
- 23 - The quantified demographic assumptions were based on different growth rates per
 24 settlement over the period 1994-2004 (local census data). Population growth rates differ
 25 between scenarios according to each agro-ecological zone.

1 - The hypotheses related to evolving farming systems were based on data from surveys
2 conducted in 2015 among 56 farmers in the basin (Sabir et al., 2019). First, our hypotheses
3 for evolution of the urban and industrial areas were used for evaluating the available
4 agricultural area in each agro-ecological zone. Then, the number of farms was assessed as a
5 function of the population. To simplify, we considered only three types of spatial farm
6 organization (Fig. 1b): Type A for those located both on the Eastern hills and in the Central
7 plain with a 50%/50% distribution of their agricultural area; Type B for those entirely located
8 in the Central plain; and Type C for those located both on the Western hills and in the
9 Western plain with a 10%/90% distribution of their agricultural area. The number of farms
10 was considered proportional to the population of settlements (Eastern hills settlements for
11 Type A, Central plain settlements for Type B, and Western hills settlements for Type C).
12 Finally, we selected, for each agro-ecological zone and each scenario, a 'typical' farming
13 system observed in 2015 that would become the 'average' farming system of the agro-
14 ecological zone in 2040. The distribution of crops within each agro-ecological zone is thus
15 based on the crop rotation of these 'typical' farming systems.

16 The results of this scenario quantification step were the proportions of the different land-use types in
17 2040, for each agro-ecological zone that served to calibrate the LUCC model.

18 **3.3. Land-use change modelling**

19 The approach chosen for simulating land-use changes was defined in an *ad-hoc* manner, according to
20 the constraints of spatio-temporal scales and the characteristics of the land uses to be simulated. As
21 the maps had to be produced over spatial and temporal scales of 180 km² and 25 years, respectively,
22 only the major evolutionary trends were simulated, without considering annual crop rotation. We
23 also had to simulate diffusive processes, such as urban sprawl. Consequently, for running the
24 simulations we preferred a Markov-type formalism combined with a cellular automaton [Markov-CA
25 model (Guan et al., 2011)] rather than a multi-agent system, the latter being more case-specific and
26 less user-friendly.

27 Considering the tension emphasized by Brown et al (2005) and presented above, our method is at an
28 intermediate stage between a prescriptive approach reflecting narratives, and an explanatory
29 approach considering annual dynamics of urban expansion and land change. Consideration of the
30 prescriptive approach in LUCC helped stakeholders to project themselves into possible futures; the
31 explanatory approach helped simulating specific processes, such as urban sprawl constrained by
32 geomorphological factors, creating the possibility of modifying system behaviour. By fitting the LUCC
33 model parameters to land demand, we constrained the path-dependency of the model.

1 Spatialization criteria for land cover were constrained by geomorphological and pedological criteria,
2 and by the distance to hydrographic networks. Each constraint map was based on expert knowledge
3 in pedology, agronomy, hydrology, economics, forestry, and land-use change modelling, being a
4 linear combination of several spatial criteria. For example, the location of olive groves was
5 constrained by clayey soil and steep slopes, the constraint map being 1 for clayey areas on steep
6 slopes (no olive trees) and 0 for everything else (olive crop possible). Note that for the same land use,
7 the constraint maps can be expressed differently depending on the narrative scenarios. Constraint
8 maps are presented in Appendix B.

9 The grain of the model is the agricultural plot, a polygon of varying shape delimiting a homogeneous
10 agronomic unit defined by a planted crop managed in a specific manner by farmers. The mean area
11 of agricultural plots was defined from representative areas of the agro-ecological zones (Fig. 1a).
12 Basin segmentation used a simple Dirichlet (Voronoi) tessellation, considering different mean values
13 of plot area in each agro-ecological zone (Holland et al., 2007), as digitization of the whole basin was
14 not possible. The matorral and forest areas were also divided in multiple polygons, to anticipate their
15 future modification according to the narrative scenarios. All distance maps were defined according to
16 plot centroids. As the average plot size remained constant over the period 2003-2015, we decided to
17 keep the same segmentation during the model simulations.

18 The proposed model, based on plot scale and annual time steps, is a function of two sequential
19 processes. First, we defined a Markovian land-use transition process according to a transition matrix
20 that controls temporal changes between land-uses; and then we defined a diffusion process of urban
21 areas according to a cellular automaton governed by local neighbourhood rules between plots.
22 Contrary to the study by Guan et al. (2011), for which only the cellular automaton was constrained,
23 both processes were modified by specific constraint maps.

24 For each plot, the (first order) Markovian process consists in defining a land-use class according to a
25 probability that is assumed only to depend on the previous class. All transition probabilities of land-
26 use classes from one year to the next were estimated from the transitions over the period 2015-
27 2040. Due to a lack of data on such land use, small-scale aggregation of land use other than urban
28 areas was not considered in the model.

29 To realize the cellular automata, all distances between plots were estimated at the start of
30 simulation. Then, for each year, the evolution of urban spots was defined as follows: For each
31 urbanized plot, all adjacent plots were collected within a certain radius for which the constraint map
32 is 1; then, a certain proportion of the collected plots was changed into urbanized plots at the next
33 time step.

1 Thus, for each scenario and, if possible, each agro-ecological zone, a transition matrix was defined
2 between all land uses, generating a set of constraint maps for establishing each land use (including
3 urban areas), and setting the radius and proportion of the cell automaton. All parameters were
4 calibrated *a posteriori* to obtain, at the end of the simulation, the final land-use proportions defined
5 in the quantitative scenario descriptions. The model was built with R (R Core Team, 2018) using
6 specific libraries for spatial data, such as raster, maptools, rgdal, rgeos, or gdistance.

7 **3.4. Participation**

8 Construction of the narrative scenarios (3.1), and their breakdown into quantified and spatially
9 explicit hypotheses (3.2), relied on local knowledge through interviews with farmers and institutional
10 stakeholders (Fig. 2), as well as on scientific expertise acquired during several joint missions in the
11 basin and the creation of a multidisciplinary working group for construction of the scenarios.

12 The resulting scenarios were submitted to debate and evaluated in two participatory workshops
13 (Appendix A). The first, at Rabat in May 2016, brought together 14 scientists specialized in the
14 Western Rif and/or erosion management of rain-fed agrosystems of Morocco. The second workshop,
15 held in Tangiers in November 2016, included 13 key institutional stakeholders of the basin
16 (Table 1.A.). The workshops were held over one day in three main sessions. After a short
17 introduction, the first session presented the Tleta basin in 2015 and its past dynamics. The second
18 session presented the LU scenarios. After each LU scenario presentation, the participants were
19 invited to assess its expected impact on the agricultural economy, the state of the environment and
20 the social dimension, by completing a questionnaire and then sharing their assessment during a
21 round table discussion. A synthesis session closed the workshop, summarizing the main conclusions.
22 Each participant was then invited to choose which scenario he or she would prefer—if he or she had
23 to support one—and which one seemed most likely, and to evaluate the approach and tools used
24 (narratives, land-use maps, quantitative data).

25 A description of the basin in 2015 and of the scenarios had been sent to the participants one week
26 before each workshop, as synthetic accounts of two pages each for the scientific experts, and as
27 fictitious press articles for the institutional stakeholders. We used four A0 posters for presentations
28 during the workshop, including the main hypotheses of basin evolution, the land-use map, photos of
29 typical landscapes, and a few quantified key variables (population, number of farms, etc.).

30 The workshops helped verifying the relevance and improving the plausibility of our assumptions for
31 the narratives, and further adjusted the quantitative data and the land-use change model.
32 Concerning the method, the first workshop showed that it was difficult for some participants to

1 project themselves into the future solely on the basis of posters. To improve this point, fictitious
2 press articles were used for the second workshop.

3 The first workshop also helped improving the plausibility of the LU scenarios for the second
4 workshop: the time horizon was shifted from 2030 to 2040; detailed historical statistical data for all
5 settlements in the basin were analysed for defining past trends; a detailed analysis of the spatial
6 distribution of farming systems in the different agro-ecological zones improved the understanding of
7 their past evolution; and it improved the description of the assumptions common to all three
8 scenarios. These changes led to improvements in the narrative scenarios and maps produced for the
9 second workshop. The second workshop was used for validating the plausibility and consistency of
10 the founding assumptions of the scenarios, and for improving a few land-use change assumptions.
11 The latter concerned the hypotheses of both settlement expansion by agro-ecological zone, and of
12 the conversion of crops back to matorral, which were integrated into the latest simulations.

13 **3.5. Using land-use scenarios for assessing future erosion control and agricultural production**

14 Land-use scenarios are meant to evaluate changes in terms of potential soil erosion, but also in terms
15 of future agricultural production. Here, we simply test the direct use of land-use scenarios for
16 estimating their potential effects on two types of services: erosion control and agricultural
17 production.

18 *3.5.1. Erosion control*

19 We used a simplified approach for capturing the potential effect of land-use change on soil erosion.
20 For this, we used the Cover-Management factor (C-factor) that reflects the influence of land use and
21 management on the risk of soil erosion within the Universal Soil Loss Equation (USLE)¹. The C-factor
22 accounts for how land cover, crop types and crop management cause soil loss to vary from those
23 losses occurring in bare fallow areas.

24 On the Tleta, we estimated C-factor values for six main land-use types based on Wischmeier and
25 Smith (1978): aromatic and medicinal plants (0.003), forests (0.11), matorral (0.18), arboriculture
26 (0.28), annual crops (0.38), urban areas (0), considering that practices for a type of land use are
27 constant over time. As a first estimate, the analysis of variations in C-factor values due to changes in
28 land use provides an indication of the potential evolution of the level of erosion control service at the
29 catchment level for each scenario x :

¹ The C-factor is one the five factors that are used to estimate the risk of soil erosion within the USLE (Wischmeier and Smith, 1978). We used it for estimating the effect (positive or negative) of land use changes on the erosion process, not for estimating resulting soil loss that would require the use of a soil erosion model.

1
$$I_{Er}^x = - \sum_i C_i \times (S_i^x - S_i^{Ref})$$

2 with C_i the value of the C-factor for land-use type i , S_i^x the area occupied by land-use type i in 2040
 3 in scenario x , and S_i^{Ref} the area occupied by land-use type i in 2015.

4 **3.5.2. Agricultural production**

5 We estimated the value of agricultural production with a market price approach at basin scale for the
 6 2015 and 2040 land-use scenarios, prices and yields remaining equal. All agricultural production was
 7 valued at selling prices, whether sold or self-consumed. The annual agricultural production was
 8 estimated as a function of the area S by agricultural land-use type (LU maps), the proportion α_{ij} of
 9 each crop j in the area of the main types of agricultural land-use type i (survey results and local
 10 agricultural statistics), the yields r_j (farm survey data and local agricultural statistics), and selling
 11 prices p_j (FAOSTAT data: average producer prices over the period 2007-2016). Comparison of the
 12 value of agricultural production of 2040 land use with land use of the reference year (2015) provided
 13 a rough estimate of changes in the level of service for each scenario x at the catchment scale:

14
$$I_{Ag}^x = \sum_i (S_i^x - S_i^{Ref}) \sum_j \alpha_{ij} r_j p_j$$

15

16 **4. Results**

17 **4.1. Three contrasted land-use scenarios**

18 We constructed three contrasted LU scenarios for the Tleta basin until 2040. The assumptions for the
 19 evolution of driving factors are detailed in Appendix C (Table 1.C).

20 **4.1.1 Scenario 1 “Urban and industrial development”**

21 The first scenario assumes that, due to the proximity of Tangiers, the Tleta basin continues its
 22 economic and industrial development. The Central plain is urbanizing very rapidly around the new
 23 town and the national road. The agricultural area decreases, and remaining farms use simplified crop
 24 rotation. In the Eastern hills, the decrease in settlement population continues, small farms remain,
 25 and the clearing of matorral plots is necessary to compensate in part for the loss of urbanized plots
 26 on the plain. The western part of the basin remains isolated and little affected by urbanization.

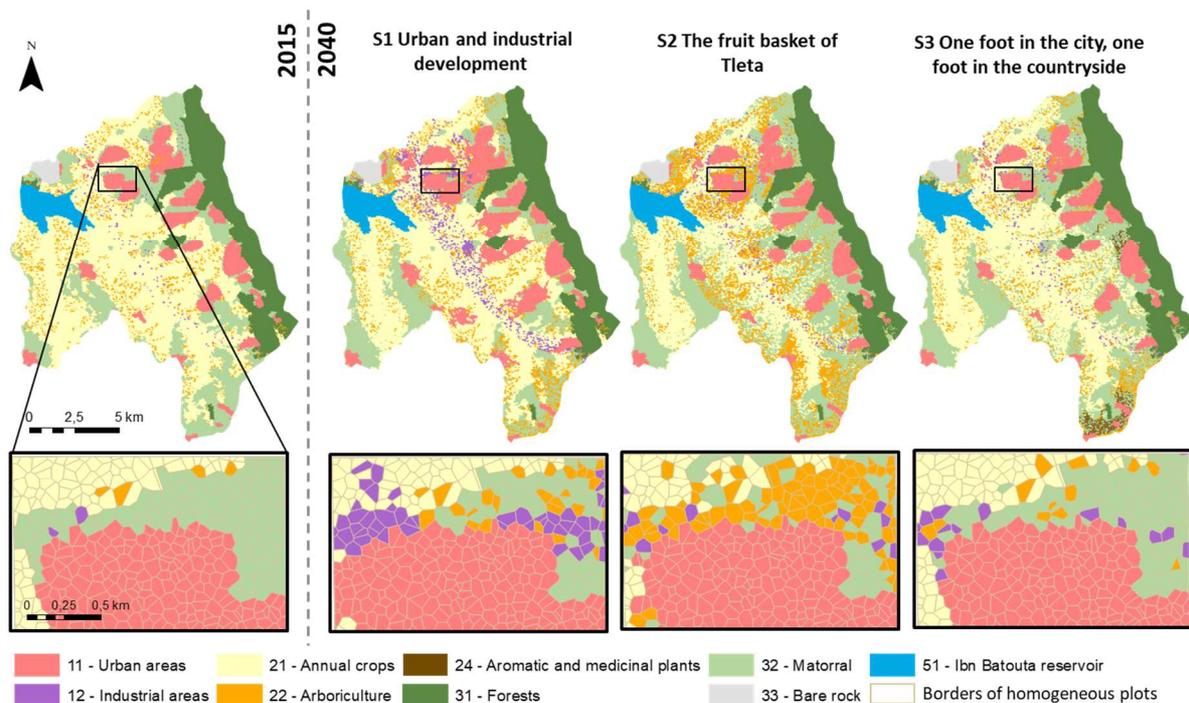
27 **Scenario 2 “The fruit basket of Tleta”**

1 The second scenario assumes that industrial development of the basin has not been as successful as
 2 expected. In this context, the State supports many agricultural development projects targeting rain-
 3 fed arboriculture (olive-, fig- and walnut trees) and the related value chain. In the Central plain, larger
 4 farms are gradually created, specializing in arboriculture. On the Eastern hills, small farms strongly
 5 oriented towards arboriculture are maintained. The western part of the basin remains isolated and
 6 little impacted by agricultural development projects.

7 *Scenario 3 “One foot in the city, one foot in the countryside”*

8 The third scenario assumes that gradual development of the new town benefits the surrounding
 9 settlements; many inhabitants of the rural areas have found work in or around it. The income
 10 generated is reinvested in the development of small-scale agricultural activities. Cooperatives are set
 11 up to launch the production of local products, such as honey, goat cheese, prickly pears and aromatic
 12 plants. The farms located on the Eastern hills are the key players in this development. In the Central
 13 plain, the farms remain on a more traditional model. The western part of the basin stays isolated and
 14 little affected by these changes.

15 Figure 4 shows the 2040 land-use maps corresponding to these different scenarios, after using the
 16 rules for translating narrative scenarios into spatially explicit maps by agro-ecological zones
 17 (Table 2.C). The annual maps are presented in Appendix D.



18

19 *Figure 4. Land-use maps in 2015 and 2040 by scenario: basin scale and zoom on a representative*
 20 *area.*

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Figure 5 highlights differentiated land-use changes by agro-ecological zone. For example, there are relatively few differences between the scenarios for the Western plain, whereas land-use is more contrasted between scenarios for the Central plain and the Eastern hills. In particular, we observe a doubling of urban areas in the Central plain for S1, a strong increase in arboriculture in the Central plain for S2, and the development of aromatic and medicinal plants in the Eastern hills for S3.

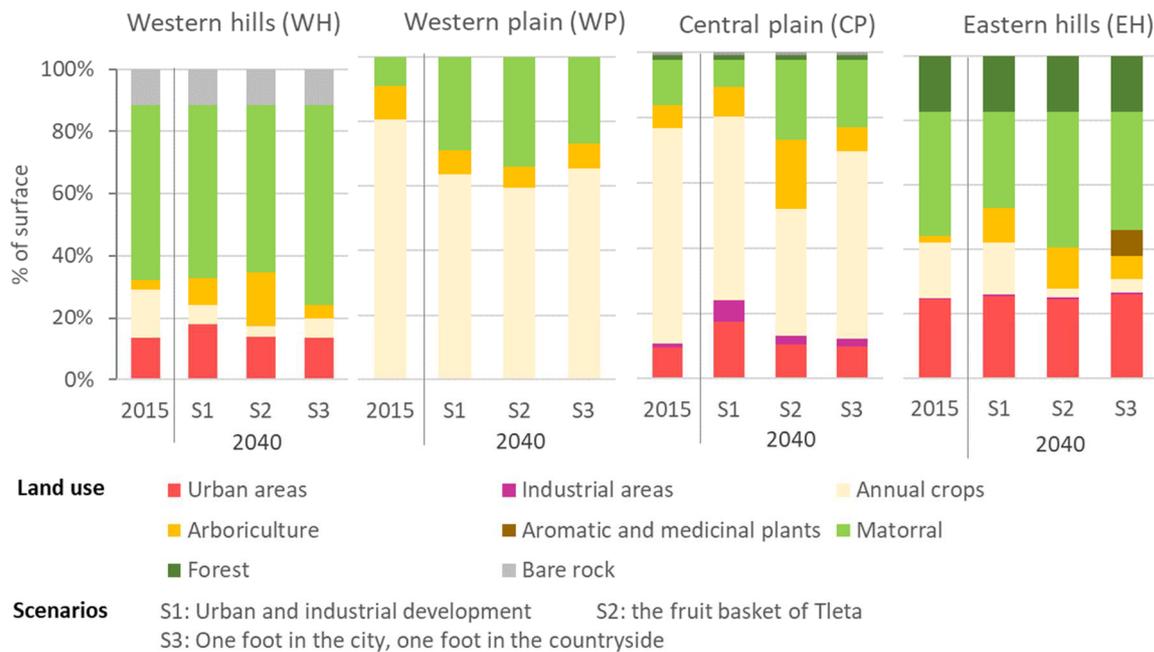


Figure 5. Land use in 2015 and for the three 2040 land-use scenarios by agro-ecological zone.

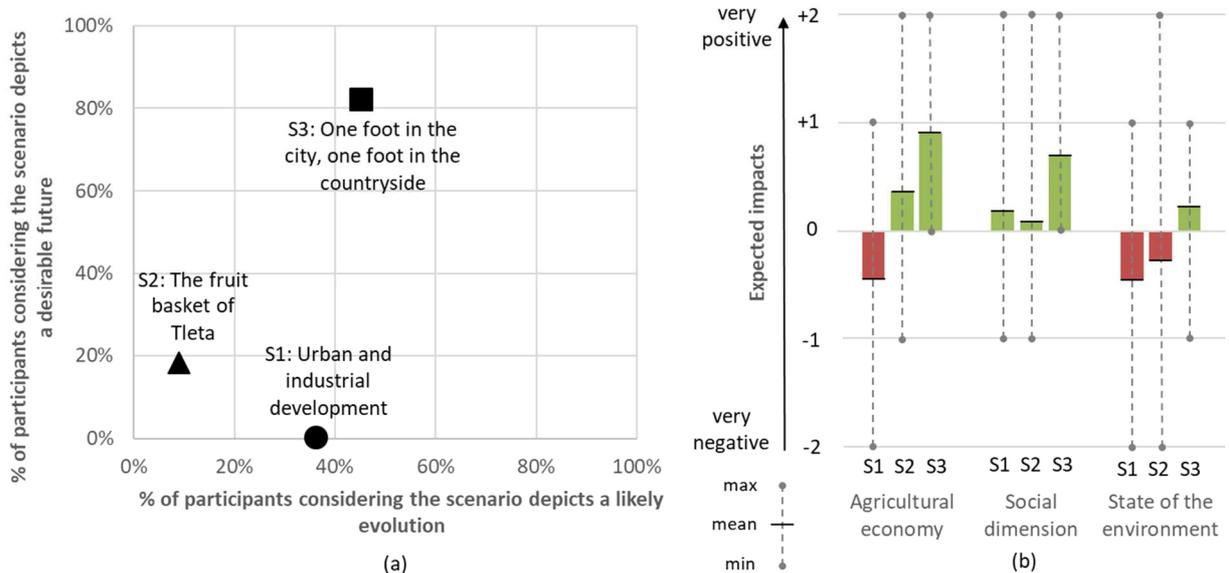
Figure 4 shows a salt-and-pepper effect affecting land use, due to assumptions of the model that do not consider possible aggregation at this scale. Some hypotheses of the model, such as space segmentation by tessellation, or absence of spatial aggregation of some land uses, could be improved by digitizing and classifying the entire basin using aerial images, and making spatial analyses of the land-use patterns. Adding more constraint to the model should limit the risk of equifinality for the calibration procedure of the explanatory model part.

4.2. Evaluation by institutional stakeholders

The three LU scenarios were presented and discussed during the second workshop for institutional stakeholders with different views and interests.

First, the participants commented on which LU scenario was considered most likely, and which they would choose if they were to support one (Fig. 6). The discussions between stakeholders provided

1 opportunities for exchanging viewpoints and expressing fears regarding the proposed scenarios. This
 2 helped assessing the degree of plausibility of the LU scenarios: S1 and S3 were considered by far the
 3 most plausible, compared to S2 (Fig. 6a). They also discussed the LU scenarios in terms of desirability,
 4 in particular with regard to three impact criteria: on the agricultural economy, on the state of the
 5 environment, and on the social dimension. Although perception of the impacts differed depending
 6 on the actors, scenario S3 was the preferred one for most actors, and also the one considered—on
 7 average—to have the most positive effects on the agricultural economy, the social dimension and
 8 the state of the environment (Fig. 6b). On the contrary, for S1 the participants anticipated mostly
 9 negative effects on the agricultural economy and the state of the environment.



10

11 *Figure 6. Evaluation of land-use scenarios by institutional stakeholders (N=11):*
 12 *(a) desirability and plausibility; (b) expected economic, social and environmental impacts*
 13 *(rating ranging from -2 = very negative to +2 = very positive)*

14

15 Second, a process evaluation after the workshops showed that most (82%) participants considered
 16 the workshops as useful for their daily work. Overall, they found the tools proposed during the
 17 workshops useful for exploring possible agriculture and landscape futures on the Tleta, especially the
 18 narratives (73% of the participants) and the land-use maps (73%). The salt-and-pepper effect of some
 19 land uses on the maps was not discussed. The quantitative data—though essential to the research
 20 team for the transition from scenarios to maps—were considered relatively less useful (36%). As a
 21 result, our approach created a win-win situation: for the research team that was interested in
 22 deriving scenarios and learn more about the Tleta basin, but also for the participants who got to
 23 know other stakeholders, exchanged knowledge, and took new information back home. The
 24 stakeholders also expressed a strong demand for the description of the scenarios to be accompanied

1 by a complete evaluation of their social, economic and environmental impacts, in order to better
2 position themselves on their desirability. This points at the fact that land-use change scenarios,
3 though designed to simulate future water erosion processes, will also have contrasted effects on
4 economic, social and environmental conditions.

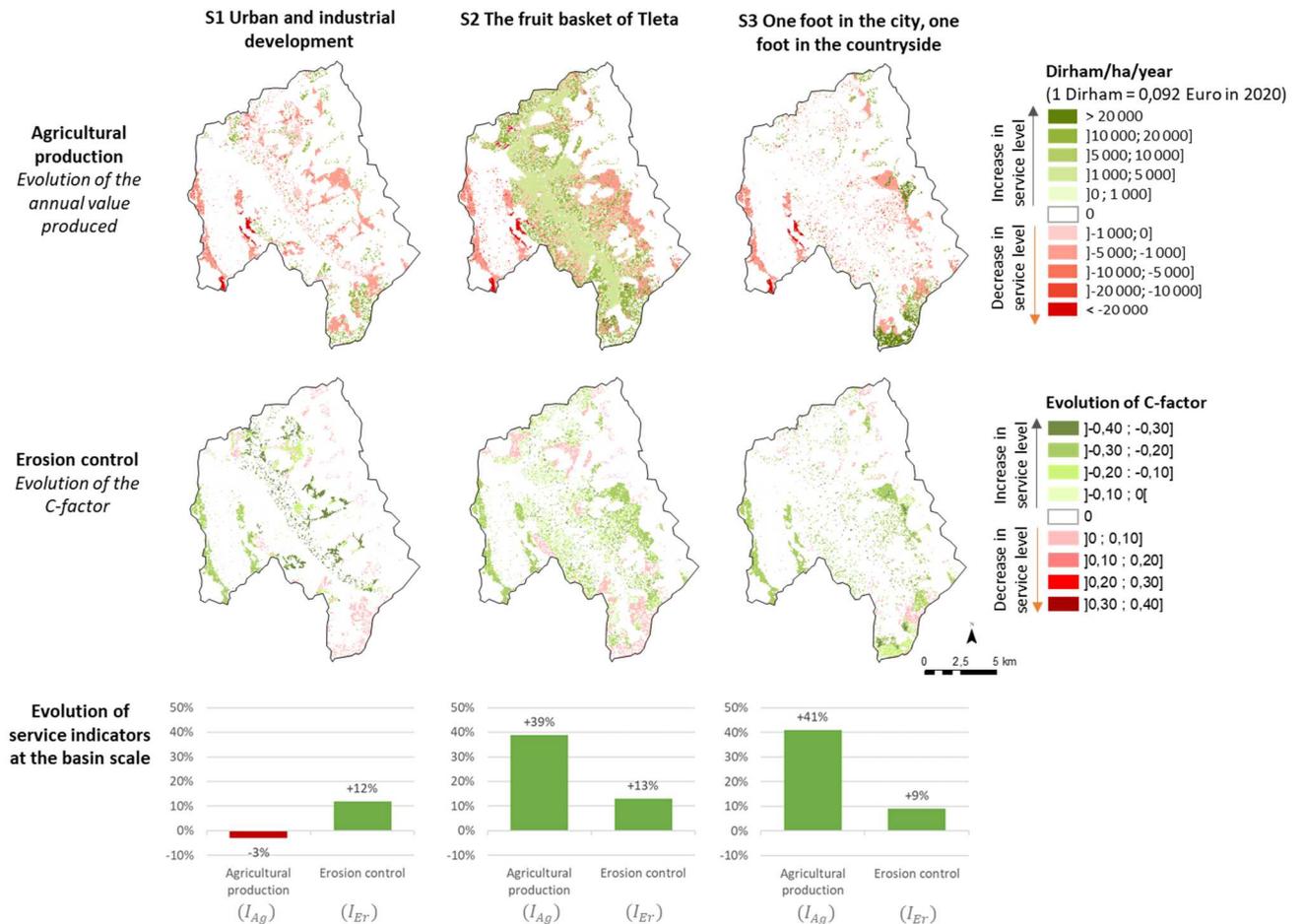
5 **4.3. Expected impact on agricultural production and erosion control**

6 The use of LU scenarios provided rough estimates of their impact on erosion control and on
7 agricultural production. At the basin scale, the three LU scenarios may lead to a 9 to 13%
8 improvement in the erosion-control service, with different spatial changes between scenarios
9 (Fig. 7). The impact on agricultural production, however, is stronger: at the basin scale, scenarios S2
10 and S3 lead to a strong increase in the value of agricultural production (+39% and +41%,
11 respectively), while S1 leads to a decrease (-3%). Spatially, however, the effects of S2 and S3 are
12 quite different, with a diffuse increase in value in the Central plain for S2, and a much more localized
13 increase in certain sectors of the Eastern hills for S3. The salt-and-pepper effect observed did not
14 affect the calculated impact at basin scale.

15 This first estimate of scenario impact shows that S2 and S3 both improve the level of erosion-control
16 service and the value of agricultural production. These two scenarios lead respectively to an increase
17 in the share of arboriculture and of aromatic and medicinal plants in the agricultural area: these two
18 crop types increase the value of agricultural production produced per hectare and have lower C-
19 factor values compared to annual crops. The spatially explicit results, however, show distinct
20 evolution patterns according to agro-ecological zone. While S2 favours a diffuse improvement of
21 services in the Central plain, S3 leads to an improvement in more localized sectors of the Eastern
22 hills. In other words, the results highlight trade-offs not between services, but between agro-
23 ecological zones.

24 However, these initial estimates remain rough, and can be improved in a number of ways. First, our
25 estimate of the effect of land-use changes on erosion only relies on the evolution of the C-factor,
26 which does not consider the real complexity of the processes. Moreover, the effect of land sealing
27 due to urbanization is badly captured with this factor, which ignores downstream erosion processes
28 due to the fact that land sealing can amplify urban runoff.

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2 *Figure 7. Change in agricultural production and erosion control services from 2015 to 2040 for the*
3 *three LU scenarios*

4

5 **5. Discussion and conclusions**

6 Through a Land System approach, based on a combination of narrative scenarios, land-use change
7 modelling, and the consultation and participation of local stakeholders, we built three contrasted and
8 spatially explicit 2040 LU scenarios at the Tleta catchment scale, and then analysed the preferences
9 of institutional stakeholders for these possible futures. The addition of an ecosystem services
10 framework illustrates how LU scenarios can be used for assessing the consequences for agricultural
11 production and erosion control. [To our knowledge, this is the first study that uses such an integrated](#)
12 [approach of the Land System combining narrative scenarios, LUCC models and stakeholder](#)
13 [participation for analysing soil-erosion problems.](#)

14 There are several perspectives for the operational use of this work. The first step will be to present
15 the results of the evaluation of the impacts of the scenarios on the levels of services to the
16 institutional actors, who expressed this need during the second workshop. This will not only allow an

1 assessment of the socio-cultural preferences for the different levels of services (Martin-Lopez et al.,
2 2012), but also ensure the continued involvement of stakeholders by improving their understanding
3 of the impacts of the different scenarios.

4 The second step will then be to involve these same actors in the implementation of the Moroccan
5 Sustainable Development Strategy 2030 (Royaume du Maroc, 2017) at their catchment scale.
6 Following Houet et al. (2017), engaging stakeholders with various opinions contributes to a common
7 vision of the possible futures for their catchment. This common understanding is likely to provide
8 sound future foundations for defining a shared strategy to control erosion and optimize the life span
9 of dams and reservoirs, while improving agricultural production, alleviating poverty and mitigating
10 climate change. This work will consist in mobilizing the entire framework presented in this article
11 with a normative objective, thus contributing to the sustainability-science agenda. This normative
12 approach, advocated by Rounsevell et al. (2012) and Nielsen et al. (2019), will provide a better link
13 between Land System research and the sustainability agenda, contributing to the Sustainable
14 Development Goals of the UN's 2030 Agenda (Biermann et al., 2017).

15 In a third step, representative farmers from different agro-ecological zones should then be involved
16 in construction of the strategy, to anticipate possible constraints and oppositions. This will lead to a
17 better understanding of the potential trade-offs between agro-ecological zones (who would be
18 winners/who would be losers?) that might cause social, economic and environmental inequalities.

19 From a methodological perspective, we anticipate three ways of validation and further development
20 of our approach. First, due to the scarcity of data in the basin, we focused our in-depth analyses (plot
21 scale, farm survey) on eight representative areas distributed along transects of the main agro-
22 ecological zones of the basin, creating an as precise as possible picture approaching the work carried
23 out in other well-studied areas, such as in Houet and Hubert-Moy (2006) or Vacquie et al. (2015).
24 This methodological choice, although having a strong potential for implementation in data-scarce
25 basins, should further gain from comparing our results with LU maps incorporating a larger number
26 of representative zones.

27 Second, our methodology for constructing LU maps can be refined, as our maps are constrained by
28 different drivers, some being similar to the “suitability maps” of Houet and Hubert-Moy (2006).
29 However, our “suitability maps” suffered from a lower discretization level than those in Houet and
30 Hubert-Moy (2006) due to a lack of data. It will be interesting to test the added value of using the
31 Fuzzy set theory developed by Kok et al (2014) to render the suitability maps more realistic, by letting
32 the stakeholders express how different drivers constrained each land use, using terms such as “low”,
33 “medium” or “high” for example.

1 Third, assessing the impact of LU scenarios on services, which remains limited in this paper, will be
2 extended. It has since been reinforced by SWAT modelling (Choukri et al., 2020). They used LU
3 scenarios as a basis for the biophysical modelling of changes in soil movement and water flow at the
4 catchment scale, in combination with climate scenarios, to anticipate future water availability and
5 sediment load in the reservoir. A more complete analysis of the diverse impacts of contrasting land-
6 use scenarios on the levels of services should highlight possible trade-offs between services (Nelson
7 et al., 2009). These different levels of services can be assessed from a perspective of value pluralism,
8 using biophysical, economic and socio-cultural indicators (Jacobs et al., 2017).

9 Overall, two main lessons can be drawn from our work. First, the use of a Land System approach
10 helps integrating the soil-erosion problem into a more global perspective on land-use planning and
11 economic and rural development. Through its systemic approach, Land System research considers a
12 whole range of drivers influencing changes in land use and, ultimately, erosion processes. The strong
13 involvement of farmers and institutional stakeholders in the identification of drivers and the analysis
14 of scenarios, provides a broader perspective on soil erosion by exploring and analysing different
15 possible futures. Although we developed LU scenarios for use as input to biophysical models for
16 simulating future soil losses, our results show that such scenarios can also be used for initiating
17 participatory processes with various stakeholder groups, and for encouraging reflection on
18 alternative futures (Griewald et al., 2017). We show that the coupling of narratives and LUCC
19 modelling produces future LU maps that make sense to stakeholders. Indeed, the map, a technical
20 object whose creation is beyond them, is clearly perceived as the representation of a narrative
21 scenario that they have helped building and that they have appropriated. The combination of
22 narrative scenarios and LU maps constitutes a concrete support for discussion, deemed truly relevant
23 by the scientific experts and institutional stakeholders to explore possible future agricultural and
24 landscape changes in the basin. We recommend their combined (and not separate) use in Land
25 System research when debating scenarios with the actors.

26 Second, the coupling of Land System research and the Ecosystem Services framework places the
27 issue of erosion in the more general perspective of Nature's Contribution to People (NCP) (Ellis et al.,
28 2019) and the United Nations Sustainable Development Goals (Biermann et al., 2017). Services
29 provided by agro-ecosystems are not limited to erosion control. Mediterranean rain-fed agro-
30 ecosystems provide various other services such as agricultural production, biodiversity conservation,
31 soil carbon sequestration, water conservation, preservation of employment and local knowhow,
32 downstream water delivery, or mitigation of rural exodus (MA, 2005; Almagro et al., 2016).
33 Contrasting land-use scenarios can have quite different impact on the levels of services provided to
34 society. Institutional actors also have expressed a strong need for better understanding of this

1 diversity of impacts on the agricultural economy, the social component and the state of the
2 environment, in order to be able to judge the desirability of the scenarios. By assessing agricultural
3 production and the erosion control service associated with each LU scenario, our approach illustrates
4 how a diversity of impacts can be assessed and represented spatially, and how Land System science
5 and the NCP framework can be combined, as recommended by Ellis et al. (2019). Our research thus
6 contributes to a better integration of the erosion issue from a global sustainability perspective.

7 Finally, our approach has a strong potential for implementation in the Mediterranean context, where
8 ongoing demographic, agricultural and economic changes are very rapid and can strongly affect
9 erosion processes at the catchment scale, with a resulting loss of soil fertility and silting-up of
10 reservoirs. Engaging stakeholders in the exploration of possible futures and their potential impact is
11 an essential step for building sustainable trajectories in these watersheds.

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