Dynamics of a salinity-prone agricultural catchment driven by markets, farmers' attitudes and climate change

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EXTENDED ABSTRACT

An agent-based simulation model has been developed with CORMAS combining simplified bio-physical processes of land cover, dry-land salinity changes, rainfall, farm profitability and farmer decisions on land uses in a dry-land agricultural catchment (no irrigation). Simulated farmers formulate individual decisions dealing with land use changes based on the combined performance of their past land cover productivity and market returns. The willingness to adapt to market drivers and the ability to maximize returns varies across farmers. In addition, farmers in the model can demonstrate various attitudes towards salinity mitigation as a consequence of experiencing and perceiving salinity on their farm, in the neighborhood or in the entire region. Consequently, farmers can adopt land cover strategies aiming at reducing salinity impact. The simulation results using historical rainfall records reproduces similar trends of crop-pasture ratios, salinity change and farm decline as observed in the last 20 years in the Katanning catchment (Western Australia). Using the model as an explorative tool for future scenarios, the simulation results highlighted the importance of rainfall changes and wide-spread willingness of farmers to combat dry-land salinity. Rainfall changes as a consequence of climate change can lead to prolonged sequences of dry and wet seasons. Adaptation to these sequences by farmers seems to be critical for farm survival in this catchment.

1. INTRODUCTION

Rainfall is usually considered as the main factor limiting agricultural production in the rain-fed Mediterranean-type region of Western Australia (Turner and Asseng, 2005). However, rainfall is also one of the main drivers of secondary salinity in dry-land agriculture in Western Australia. With the replacement of 19M ha of native perennial vegetation by annual crops and pastures over the last century in the wheat-belt of Western Australia, deep drainage below the maximum root zone has often increased by a magnitude compared to native vegetation (Turner and Ward, 2002). These high rates of deep drainage are causing groundwater tables to rise, bringing salt to the surface with widespread salinisation and degradation of agricultural land and adjacent native vegetation (George *et al.* 1997). McFarlane and Williamson (2002) estimated that about 10% of cropping land in south-west Australia is affected by dryland salinity which could increase to up to 30% in the coming decades.

Since the mid 1970's, the wheat-belt of Western Australia has experienced a significant decline in winter rainfall (Smith, 2000; IOCI, 2002). This decline in rainfall was associated with, and probably caused by, a large scale change in global atmospheric circulation during the mid 1970's (IOCI, 2002). Noticeably, the spread of dryland salinity over the last decade has already been less than initially predicted (McFarlane et al., 2004).

Further future climate change may have a considerable impact on agricultural production (Ludwig and Asseng, 2006) and soil degradation like salinity, and hence on the dynamics of an entire agricultural region, especially if the amount and distribution of rainfall change. However, the impact of climate change on an entire agricultural region is often not clear (IPCC Report 2007) due to the complex interactions between individual farmers' behaviors and the bio-physical landscape, the large range of multiple external and internal factors and the further complication from continuous changes of variables in time and space. To explore likely scenarios of climate change impact and adaptation and its consequences on socio-economic and environmental indicators of a salinity-prone agricultural region, an agent-based simulation model is developed with CORMAS (Bousquet et al., 1998). The model aims to simulate the complex interactions between bio-physical processes of paddock cover, dry-land salinity changes, rainfall changes, market signals, farm profitability and individual farmer decisions on land uses in an agricultural catchment. The model and simulation results are described hereafter.

2. METHODS

An agent-based model has been developed and parameterized for the agricultural catchment located in the Katanning region (a sub-catchment of the Blackwood River) in the South-West of Western Australia. The Katanning region consists of 300 000 ha with about 280 crop/sheep or mixed farms, 84% arable land, 10% native vegetation and 6% salinity (Department of Agriculture and Food WA). Note, the catchment consists of dry-land agriculture only with no irrigation. In the model, individual farmers (agents) take their own decisions to modify their farm's land cover based on the performance of their past land cover productivity and market returns. The level of willingness to adapt to market drivers and the ability to maximize returns vary across farmers. In addition, simulated farmers can display various attitudes (not profit driven) towards salinity mitigation as a consequence of salinity being located on their farm, in the neighborhood or the region. Thus, farmers can adopt land use changes with less salinity impact.

2.1 Time scale

One time step in the model is equivalent to a 1-year period in reality to represent the main decision making process.

2.2 Spatial grid

The Katanning region is portrayed as a regular 40 x 75 square mesh, each cell – elementary spatial unit – accounts for a 100-ha unit in reality. The size of the grid has been chosen to fit the real number of farms to be modeled and located in the environment. We create two grids, one for 1986 with 350 farms and one for 2005 with 280 farms (Department of Agriculture and Food WA). Farms are defined as an aggregation of neighboring cells and created with different sizes and shapes. The average farm size is 1000 ha in the model (1040 ha in reality, in 2005 (Department of Agriculture and Food WA)), ranging from 200 to 3700 ha (50-9000 ha in reality, in 2005 (Department of Agriculture and Food WA)). Real GIS-based representation exists but was not used in this model. The main focus of the model development lies on biophysical and social processes interacting with the environment in an abstract way.

Ten cells, randomly located, are initially tagged as "natural salinity" and used as seeds to generate small pockets of saline areas. The total saline area accounts for 5.1% of the grid in 1985 and 5.9% in 2005, following observed data. Similarly, 10 cells were labeled as "native vegetation" and were used to generate 10% of the grid with native vegetation for both years. The remaining cells are either converted into crop or pasture according to the observed ratio between crop and pasture.

Each cell calculates its own contribution to salinity as a function of its cover and the rainfall data. We assume that each paddock (i.e. a 100-ha unit or cell in the model) contributes to the extent of salinity within its catchment. Possible local impact of a paddock on local salinity (i.e. within a paddock) is ignored here.

The relationship between land use, rainfall, and salinity impact is obtained by combining two equations: (i) one correlating rainfall with change in the salinity area in the Katanning catchment and (ii) the other establishing deep drainage as a function of vegetation cover and rainfall developed by Ward (2006) for Western Australia.

McFarlane et al. (2004) reported the extent of salinity in this region (using data from the Katanning and the Kent shires) as 5.1% (which translate to 15210 ha in the Katanning catchment) in 1989 and 5.9% (17400 ha) in 1996. According to McFarlane (2005), between 1996 and 2005, the salinity in Western Australia has not changed. Rainfall between 1989 and 1996 was in average 442 mm for the catchment, rainfall between 1997 and 2005 was 393 mm. Using the average rainfall of the catchment for each period and relating the rainfall to salinity change gives a simple relationship (Equation 1) based on three data pairs between salinity change and rainfall.

salinity change (%/year) = 0.0023 * rainfall – 0.8859 **(1)**

Since this is based on a limited number of data points, the actual relationship might not be linear, thus extending the relationship beyond these data requires some caution. However, when using this relationship for the individual years, the sum of the relative salinity changes per year equals the two reported salinity numbers (data not shown). Note that this relationship is also equal to the contribution of a 100-ha unit to the entire catchment.

The recently published drainage calculator by Ward (2006) estimates the drainage below the maximum root zone based on the ability of plants to create storage for water (buffer or drying of soil) before water is drained below the reach of the plants. It allowed us to calculate drainage as a function of rainfall and land use:

drainageCropAndPasture = 0.5023 * rainfall **- 156.02** **(2)**

drainageLucerne = 0.2419 * rainfall **- 87.44** **(3)**

drainageTrees= 0.0948 * rainfall **- 35.674** **(4)**

Note that the DrainageTrees equation is also used to calculate drainage (in this case excess water) for saline areas.

Using the same rainfall data as used to build Equation 1, drainage is calculated based on equations 2 to 4 according to the proportion of the land cover of the region (about 10% perennial natural vegetation and 5% salinity in average over the last 20 years) and then relates back to a salinity contribution of a 100-ha unit.

This results in a linear relationship between salinity contribution of a 100-ha unit and drainage (in mm/m^2) within the 300 000 ha catchment:

salinityContributionOf100Ha (ha/year) = 0.0051 * drainage - 0.1803 **(5)**

While equations 2 to 4 supply drainage estimates for each land use, equation 5 translates this drainage into a global impact on salinity area change within the catchment. Drainage calculated in equations 2-4 can result in negative drainage with certain rainfall - land cover combinations, which allows the consideration of a negative contribution of land cover to salinity (i.e. reduction in salinity area) in equation 5. This is a simple approach to consider land cover and rainfall impact on salinity in a catchment without considering the dynamics of hydrology in the system.

We acknowledge the large soil variability in this catchment but ignore its impact in this version of the model for simplicity purposes. One has to be aware that the parameterization of this salinity-drainage relationship is very regional specific and would probably need to be recalibrated for other regions. However, the data required to calibrate this relationship (annual rainfall data, salinity area for at least three periods of time over a 15-20 year period) are frequently available for other catchments of Western Australia (McFarlane et al. 2004) and likely to be available in some other catchments affected by salinity.

2.3 Farm

Each farm calculates its balance per year as a sum of the growth margins from all covers minus a fix cost imposed by the Market. It then assesses and remembers from which cover (crop or pasture) it gets the maximum growth margin.

Growth margins are calculated as followed:

- *for crop (and similar for pasture and trees):*

cropGrowthMargin = number_of_crops * farmerAbility * rainfall_index *** MaxCropYield * cropReturn – cropCost** **(6)**

with MaxCropYield = 5 t/ha for the Katanning and rainfall_index developed from a linear relationship between observed shire yields, some farm yields and 100 years of APSIM simulations (Asseng et al., 1998; Keating et al., 2003) and annual rainfall data.

Grain yields are commonly correlated to seasonal rainfall (April-October) (French and Schulz, 1986). However, a close correlation exists between seasonal and annual rainfall in this region (seasonalRainfall = 0.77 ***** annualRainfall + 5.6, r2=0.69), which allows to use annual rainfall data for production calculations.

The farm entity is also able to convert former saline areas into crop or pasture land use according to a 50% probability.

2.4 Salinity process in the model

The salinity is modified at the regional level. An overall index is obtained by summing the contributions to salinity from the individual cells. The index divided by 100 (1 cell = 100 ha in reality), translates into a positive or negative number of saline cells to be added or removed. Saline cells to be removed or new saline cells to appear are randomly picked on the grid, provided they fulfill the following rules:

- to be turned into non-saline, a saline cell must be located on the edge of the saline areas and have at least three non-saline cells around,

- to be turned into saline, a non saline cell must be located next to a native saline cell or surrounded by at least three saline cells.

Again, this approach assumes that local groundwater tables are fully connected in this catchment.

2.5 Passive Objects

Weather

It is possible to use an existing rainfall data set or initialize a new weather data series as followed:

- **rainfall_index**: random between 0 and 1 (as real rainfall data for this catchment appear near evenly distributed over last 20 years) or can be imported from a table with real measured rainfall data or generated through other means (e.g. through Global Circulation Models) .

- random **rainfall** is calculated by:

rainfall = **rainfall_index** * (maxRain – minRain) + minRain **(7)**

with minRain = 312 mm and maxRain = 518 mm, as measured over the last 20 years in the Katanning region.

A trend to explore climate change scenarios can be added to generate patterns of dryer or wetter periods.

Market

Market prices and production costs can be input as constants (with and without trends) or as time series.

2.6 Social agents: Farmer

We created, respectively for 1986 and 2005, 350 and 280 located agents “farmers”, one on each farm.

“Adopter” farmers (as economic adapters to maximize their profits) can re-adjust their cover according to the market and their financial results. If they get better income through crops over the last three years, they increase their crop cover by a ratio, randomly selected between 0 and a fixed maximum cover change ratio. New crops are created from pastures and lucerne plots. The same applies if pasture is the main source of income.

“Salinity conscious” farmers can partially introduce lucerne or trees on their land according to given thresholds. Once established, lucerne remains on a paddock for four years, trees for 20 years. After these periods, the continuation is evaluated based on the environmental factors which caused the introduction of lucerne and trees.

2.7 Simulation experiments

Model outputs have been compared with historical observed data from the Katanning region and indicated a reasonable agreement (data not shown). A number of scenarios were simulated over 100 years using a random rainfall data series based on the last 20 years for: 1) no salinity consciousness, 2) salinity consciousness at the farm level, 3) salinity consciousness at the farm and neighborhood levels, 4) salinity consciousness at the region level and 5) scenario ‘4’ combined with a rainfall decline trend (-0.5% and minimum of

238 mm) as observed in the last 100 years in this region. Note 'salinity consciousness' translates in the model into lucerne planting (if a reasonable pasture component on the farm allows for that) and tree planting, both for salinity mitigation (Turner and Ward, 2002).

Note, while future rainfall trends can be simulated with the model, other climate change variables (like atmospheric CO_2 or temperature) which can have a significant impact on crop production (Ludwig and Asseng, 2006) are current not directly considered.

3. RESULTS

The simulation with this agent-based model focusing on human-landscape interactions using historical rainfall records indicates similar trends of crop-pasture ratios, salinity area changes and farm number declines observed in the last 20 years in the Katanning catchment of Western Australia (data not shown). Using the model for future scenarios highlighted the importance of rainfall changes and wide-spread willingness of farmers to combat dry-land secondary salinity. Dry-land salinity is caused by excess water in annual cropping and pasture systems, draining this excess water below the potential root zone with consequently increasing water table rises, which is highly saline or mobilizes large amounts of salt stored in the soil which is than brought up to the surface. Figure 1 shows the results for the simulation experiment '1' described above, without salinity consciousness. Current input costs and market returns are assumed constant for this experiment, which of cause are likely to change in the future.

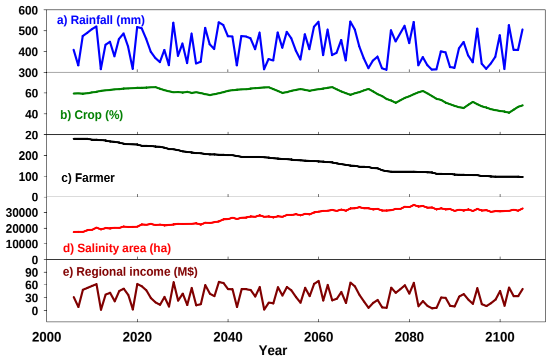

Figure 1. Simulation experiment '1' using randomly created rainfall data based on the rainfall of the last 20 years of the Katanning region assuming constant current input costs and market returns.

Of particular interest in this hypothetical experiment are the different periods of high and low rainfall years. In periods of high rainfall, e.g. 2005-2020 or 2040-2050 (Fig. 1a), cropping would be favored over pastures due to higher returns from wheat in wetter seasons (Fig.1b), farm numbers would decline less (Fig1c) most obvious during the wet period 2070-2080, but salinity would continue to increase (Fig. 1d), while regional income would be relatively high compared to other periods (Fig. 1e). In contrast, during dry periods (Fig. 1a: e.g. 2020-2025 or 2080-2090), the cropping area would decline in favor of pastures which are less profitable but better suited to dry conditions (Fig. 1b), farm number decline would be accelerated due to increased bankruptcy (Fig. 1c), salinity spread would hold (e.g. 2020-2025) or even decline (e.g. 2080-2090) (Fig. 1d) and the regional income would be relatively low (Fig. 1e).

Adaptation to these different periods of rainfall is temporally and spatially not homogeneous in the model (data not shown), depending on farming history and rate of adaptation of individual farmers. Other simulation experiments (Figure 2) indicate the low impact of adaptation strategies of framers to combat secondary salinity, unless widespread adaptation of lucerne and tree planting of the entire region is achieved. Future rainfall changes as a consequence of further climate change are likely to have a large impact on reducing dry-land salinity. Continuous reductions in future rainfall by 0.5% (a similar trend as observed during last 100 years in this region) might have more impact on salinity reductions than local or even wide-spread approaches of farmers in land-use changes (by introducing perennial pastures and trees for higher water use and less ground water recharge) trying to mediate salinity. A reduction in rainfall might also accelerate the decline in farmers in the region (Table 1). However, the impact of markets (by changing commodity prices) on land use changes and farm numbers, which also can be explored with this model, can alter these changes significantly (data not shown).

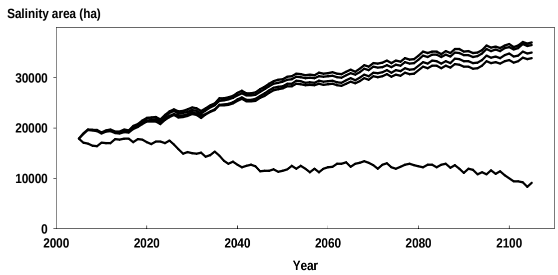

Figure 2. Simulation results of salinity area changes (from top to bottom line), using 1) no salinity consciousness, 2) salinity consciousness farm level, 3) salinity consciousness farm and

neighborhood, 4) salinity conscious region and 5) scenario ‘4’ with a rainfall decline trend (-0.5% and minimum of 238 mm). Note, simulation ‘5’ has a different set of random weather data due to the imposed trend compared to the other simulations.

Table 1. Simulation of farm numbers for the year 2105 using five simulation scenarios

Scenario	Farm numbers in 2105
1) no salinity consciousness	119
2) salinity consciousness farm level	124
3) salinity consciousness farm and neighborhood levels	122
4) salinity consciousness region level	123
5) scenario ‘4’ with a rainfall decline trend (-0.5% and minimum of 238 mm) as observed in the last 100 years in this region.	103

4. DISCUSSION AND CONCLUSIONS

A dynamic multi-agent based simulation model was developed to simulate the complex interactions of individual farmer’s behavior in a landscape with bio-physical processes of land cover, dry-land salinity changes, rainfall changes, market signals and farm profitability. The model could reproduce some of the historical dynamics of an agricultural landscape and was used to explore the sensitivity of socio-economic and environmental indicators of an agricultural region to climate change scenarios. Rainfall changes and in particularly changes in the sequence of dry and wet seasons and the adaptation to these sequences by farmers seems to be critical for crop/pasture adaptation, salinity spread and farm survival in this catchment.

5. ACKNOWLEDGMENTS

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