An Agent-Based Policy Impact Assessment Tool for the Great Barrier Reef Region

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EXTENDED ABSTRACT

Resource issues for the Great Barrier Reef (GBR) are characterised by heterogenous multiple users incurring diverse non-point source environmental impacts. Of particular concern is sediment and nutrient runoff caused by cattle grazing and sugar cane growing, among other practices in the lowland agricultural and upland grazing areas. In this paper we present a decision support tool for resource managers charged with improving GBR resource conditions, within the context of the 2003 Reef Water Quality Protection Plan.

The SEPIA (Single Entity Policy Impact Assessment) model simulates land-use decision making (LUDM) enacted by agents involved in agricultural production. The current application includes sugar cane, tree fruit, and beef cattle (grazing) producers, and is applied in the Douglas Shire, north Queensland.

LUDM lies at the interface between the human drivers and environmental impacts, and is based on endogenous and exogenous conditions, as well as top-down policy controls. To accommodate characteristics of the biophysical and human systems involved, the approach of agent-based modelling (ABM) is employed.

The structure of the ABM applied here involves individual decision makers (producers) and a landscape upon which they operate (farms). Agent behaviour is composite of both market-based economic drivers and a preference-based utility function for non-market environmental conditions. Economic and financial conditions are calculated to yield a payoff to agents resulting from costs and revenues associated with their land-use decisions.

Agent decision making results in the enactment of one of a number of possible land-use strategies. The effect of these land-use decisions in turn has an effect on environmental conditions on the ground (sediment and nutrient contributions), a resulting outcome for agent financial payoffs associated with agricultural production, and a realised level of utility derived from the state of water services. Based on their satisfaction with outcomes for water services, the community of agents may apply pressure across the population to adopt minimum standards of on-farm best management practices. Agents employ adaptive behaviour based on their satisfaction with individual payoffs, and may change their land-use decisions based on innovation or imitation.

The purpose of this paper is to show a proof of concept stage application of how the SEPIA model can address a variety of policy levers and report on indicators across disciplines. Exemplar model simulations are used to examine outcomes of various scenarios of sugar price changes provision of subsidies, and the imposition of controls on fertiliser use.

Development of the SEPIA model is continuing, with integration activities involved with other modelling work (see Smajgl, Heckbert and Morris 2005).

Our results demonstrate the operations and reporting capacity of the model. Outcomes for changing production decisions, areas under different types of production, environmental conditions and human benefits are outlined. Results suggest that policy options can be successful for both environmental and human well-being considerations where adaptive capacity of producers is encouraged, even where individual constraints are imposed.

1. INTRODUCTION

Resource issues for the Great Barrier Reef (GBR) are characterised by heterogenous multiple users incurring diverse non-point source environmental impacts. Of particular concern is sediment and nutrient runoff caused by cattle grazing and sugar cane growing, among other practices in the lowland agricultural and upland grazing areas. In this paper we present a decision support tool for resource managers charged with improving GBR resource conditions, within the context of the 2003 Reef Water Quality Protection Plan.

The SEPIA (Single Entity Policy Impact Assessment) model simulates land-use decision making (LUDM) enacted by agents involved in agricultural production. The current application includes sugar cane producers, tree fruit producers, and beef cattle (grazing) producers, and is applied in the Douglas Shire, north Queensland.

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A number of ‘levers’ exist by which LUDM can be influenced. Hatfield Dodds (2005) describes a hierarchy (of force) of such levers including:

1. Persuasion within a community to ‘do the right thing’
2. Provision of information and education on an issue
3. Adoption of self regulation or standards for individuals within a group
4. Economic / financial incentives such as subsidies and grants
5. Use of market-based instruments to deal with allocation of scarce resources
6. Outright regulation through legislation to constrain individual behaviour.

In this application, results for levers 3, 4, and 6 are addressed. Model simulations are used to examine outcomes of various scenarios of sugar price changes, provision of subsidies, and the imposition of controls of fertiliser use. Results are presented for a variety of indicators, including:

- Utility derived from water services
- Financial conditions of agents
- Total sediment and nutrient contributions
- Total area of the catchment under production for each commodity

Results are generated for a preliminary case study to demonstrate the operations and reporting capacity of the model.

2. METHODS

The SEPIA model is applied here to the Douglas Shire in north Queensland. The Douglas Shire was used as a preliminary case study due to data availability.

The model is implemented in the C# programming language, using GIS .dbf files prepared for the Douglas Shire as landscape input files. Data are organised into two interacting linked-list data structures, one representing the landscape data, and one representing agricultural agents. The Douglas Shire data represents a set of 110 farms, each associated with one agent representing the owner / manager household, and contains relevant attributes of the farms according to model data needs.

Agents attributes are calibrated from a number of secondary literature sources, as discussed below, and use data from landscape GIS files to inform on-farm physical conditions. Calculations proceed from initialisation in the order discussed below.

2.1. GIS landscape data

Spatial data for farms in the Douglas Shire were generated for use by integrating a number of existing GIS layers for the region, including:

- Land use
- Soils
- Digital Cadastre Database (DCDB)
- Digital Elevation Model (DEM)

The farm GIS layer was created using DCDB data and contains a set of 'pseudo' farms based on Roebeling et al. (2005). A number of additional farms were also added. At present, three land uses are considered: sugar cane production, grazing and tree fruit production. The farm layer is intersected with a reclassified soils layer defining areas of farms according to soil type. Finally, areas with slopes greater than 20%, as defined in the DEM were intersected with the farms.

2.2. Adoption of Best Management Practices (BMPs)

Depending on the type of production engaged, agents are able to adopt BMPs in their on-farm operations, including reduced cattle stocking rate, stock exclusion, minimum tillage, optimal fertiliser management, contour planting, fallow cover, drain management, cover management, riparian revegetation and wetland restoration. Agents have the option to adopt increased use of BMPs. Adoption of a BMP at the farm level potentially has an effect on productivity of the land and resulting change in revenues, costs incurred to adopt the practice, and nutrient and sediment contributions. Hence, a set of BMP multipliers are enacted for use in later calculations involving production, costs, sediment and nutrient contributions. Multipliers are initialised at a default value of 1, increasing or decreasing based on the effect the BMP has.

2.3. Costs, Revenues and Returns from Production

Drawing from Beare et al. (2003), Gleeson et al. (2003) and Smith et al. (2005), a list of costs and revenues associated with production of beef, sugar cane, and tree fruits was drawn. Financial calculations return a payoff for the production decision enacted. The production decision is taken to be the strategy, which specifically represents the proportion of the total area under production devoted to each production type.

Financial payoff is defined as,

$$\pi = TR - TC \quad (1)$$

where π refers to the payoff of each farmer agent, which amounts to total revenues, TR, minus total costs, TC. Total revenues for each producer are calculated as,

$$TR = \sum_{q=1}^{Q} (P^q S^{By})(A^q r B^{qr}) + FP^q \quad (2)$$

where P^q is the constant base year $/ha value for commodity q (a vector of products specific to each type of production, Q being the total number of commodities), S^{By} is the percent change in the price of the commodity from the base year, A^q is the area under production type q, r is the productivity of the farm (in terms of quantity per ha), B^{qr} are multipliers associated with the use of BMPs as per their effect on incidences of the vector of revenue factors, and FP^q are fixed revenues, such as off-farm income.

Total costs for each producer are calculated as,

$$TC = \sum_{q=1}^{Q} (C^q F^q)(A^q B^{qc}) + FC^q \quad (3)$$

where C^q is the constant base year $/ha cost of production type q, F^q is the percentage change in the purchasing price of an input, B^{qr} are multipliers associated with the use of BMPs as per their effect on incidences of the vector of cost factors, and FC^q are fixed costs. Total costs are further multiplied by a random variable, e which is uniformly distributed with a variance of 5% of calculated costs. This accounts for unforseen costs or cost savings that may arise throughout the year. Once the payoff is calculated, agents then compare realised profits to internal payoff thresholds. The threshold set at $30,000 per year with a uniformly distributed variance of 17%, which represents a minimum desired level of disposable income above the break-even point (see ABS 2005).

2.4. Changes in LUDM

The land-use strategy employed by an agent is defined here to be the proportion of the total area under production devoted to one of the three production types. If the individual payoff threshold discussed above is not met under the current strategy, agents may examine opportunities to change their land-use strategy in order to receive a better payoff. Satisfied agents continue production decisions in the same fashion as they previously did. In exploring changes to their current strategy, agents are uniformly divided between those who are 'innovators' and those who are 'imitators' (see Polhill 2002).

Imitation involves comparing their own payoff and thresholds with the observed payoffs of others. Imitation compares current payoffs against possible payoffs calculated from an internal search given a hypothetical change in the agent's strategy (of incremental land-use changes) using sets of fictitious plays (see Young 1998). Both strategies employ a revenue-cost calculation (performed in the same fashion as outlined in section 2.3) and accounts for both opportunity costs of foregone production while the new strategy comes into full production, and once-off start-up costs associated with making the transition.

2.5. Environmental Indicators

Sediment and nutrient contributions are calculated for each farm and summed to represent the total contributions within the catchment. There is at present no consideration of temporal and spatial movements of nutrients and sediments.

The sediment contribution Y^q, is rudimentally calculated based on a simplified RUSLE equation from Lu et al. (2001), such that,

$$Y^q = RKLC^q\beta^{qs} \qquad (4)$$

where R is rainfall erosivity, K is soil erodibility, L is hillslope length factor, C is ground cover factor, and P is the supporting practice factor associated with use of BMPs. The values for variables are at present either taken from GIS data, or from secondary literature. Hence, K is linked to proportion of different soil classification types. S represents the proportion of area with slope greater than 20%, C^q is calibrated from Cook and Henderson (2005), which associates different c factors according to land-use practice, and β^{qs} represents a sediment-related multiplier effect of BMPs used on the property.

The nutrient contribution of each farm N^q, is represented simply by the amount of nutrient released through agricultural production Nit^q, connected to a multiplier β^{qn}, accounting for BMPs, which serves to capture nutrients which would otherwise make their way into the surface and ground water systems:

$$N^q = Nit^q * \beta^{qn} \qquad (5)$$

The level of Nit^q is in turn dependant on the area and intensity of production, such that

$$Nit^q = SR^q * AG + FA^q * AS + FA^q * AT \qquad (6)$$

Where SR^q is the nitrogen contribution from cattle (dependant on the stocking rate), FA^q is the amount of applied fertiliser, and AG, AS and AT is the area under grazing, sugar and tree fruit production, respectively.

2.6. Calculating Impacts on Water Services

A rudimentary water service response function is calculated based on outcomes for sediment and nutrient contributions. Hajkowicz (2005) describes the strength of relationship for sediment and nutrient contributions in terms of their effect on 14 water services k.

The state of each water services, ES^k within the range of the identified relationship strength, S^k is calculated such that,

$$ES^k = 1 - (MinO - O)/(MinO - MaxO) * S^k \qquad (7)$$

where O is the current outcome for total sediment and nutrient contributions across all simulated farms. $MinO$ and $MaxO$ represent the minimum and maximum outcomes across a multitude of control model runs. Maximum values are found when the model restricts agents from using any BMPs, and does not allow adaptive behaviour, and minimum values are found by requiring agents to adopt all BMPs, and employ adaptive behaviour in each time step during the simulation.

2.7. Non-Market Decision Making

On the non-market side of decision making, agents employ a preference-based utility function to measure their satisfaction with the current state of water services. The utility calculation is based on parameter weights for each water service. Each producer is provided with β^k preference values, according to a given variance, with the parameters for each attribute uniformly distributed, where the variance is a function of the weighting value.

The 14 water services as identified by Hajkowicz (2005) are ranked according to importance. Hence, the β^k value for each correlates with their rank. Utility U calculations (expressed in 'utils') are performed on outcomes for k such that,

$$U = \sum_{k=1}^{K} \beta^k ES^k \qquad (8)$$

Agents also maintain a low-end threshold for acceptable utility levels derived from each water service, which is set and varied for each agent in the same fashion that the preference parameters are set. Hence, some agents will accept a low level of utility, and some will have a higher expectation.

2.8. Community Level Constraints

Using utility calculations from water services discussed above, the agent population determines what level of BMP use is acceptable, and sets minimum standards for their use. This represents lever 3, discussed in the introduction. If threshold conditions are not met, agents 'flag' their dissatisfaction. If 50% (+1) of the population flags their dissatisfaction (see Smajgl 2004), a community level expectation for the state of the given water service is identified to have not been met. BMPs which contribute to the maintenance or improvement of the specific water services are imposed on all agents. Agents may defect based on the probability of BMPs improving water services. Imposition of BMPs feeds back into individual costs, revenues, and production decisions.

3. RESULTS

For demonstrative purposes, results for three scenarios are compared to a baseline case which assumes (1) no change in sugar prices, (2) the adoption of BMPs are endogenous to the community, and (3) there are no financial subsidies for agents interested in making a land-use strategy change. Each scenario alters one assumption.

Real-world sugar prices have (on average) decreased throughout time, putting increased financial pressure on growers. Prices paid to Queensland growers are subject to a number of exogenous conditions including world price trends driven by major production centres such as Brazil, the world market price of oil, and the exchange rate between Australia and the USA. At present the price paid to growers is $260/t, with short term projections ranging from $220/t to $280/t (Attard, pers. comm.), averaging a decrease in price of 4%. Scenario 1 therefore assumes that the sugar price in the initial year decreases by 4%, and then remains constant. All other prices are held constant throughout. Scenario 2 assumes that a policy of fertiliser management that is optimal for (soils based) conditions on individual's land is imposed on each producer, representing lever 6 discussed in the introduction. Hence the presence of this BMP and associated multipliers are constant for all agents. Scenario 3 assumes a subsidy to cover 30% of once-off costs associated with transitioning areas from one land-use to another, representing lever 4. This applies to agents who are considering a land use strategy change.

Each simulation was run for 25 time steps, each representing a one-year period. Results are generated such that only the scenarios under question are altered for the simulation. Indicators used to communicate outcomes for the agents and the resource base include:

- Total utility derived from water services
- Total financial payoffs across the agent population
- Total sediment and nutrient contributions
- Total area of the catchment under production for each commodity

The following figures depict the mean outcome for 10 simulation runs, per scenario, and compared to the baseline scenario for purposes of demonstrating indicator trajectories.

3.1. Changes in areas of production

The sugar price change scenario shows a large transition from sugar toward grazing in the initial year, and sustained transition through time (Figure 1). The transition subsidy scenario also shows large changes to areas of all three production types, showing no difference in the initial year, but having a marked effect over time as agents are more likely to adapt their land-use strategy with a subsidy helping to cover initial start up costs. The fertiliser management restriction scenario has a slight effect on changing areas of production from sugar to tree fruits, explained by the necessary higher fertiliser applications rates for sugar cane, making tree fruits more attractive during searches for adaptive strategy decisions.

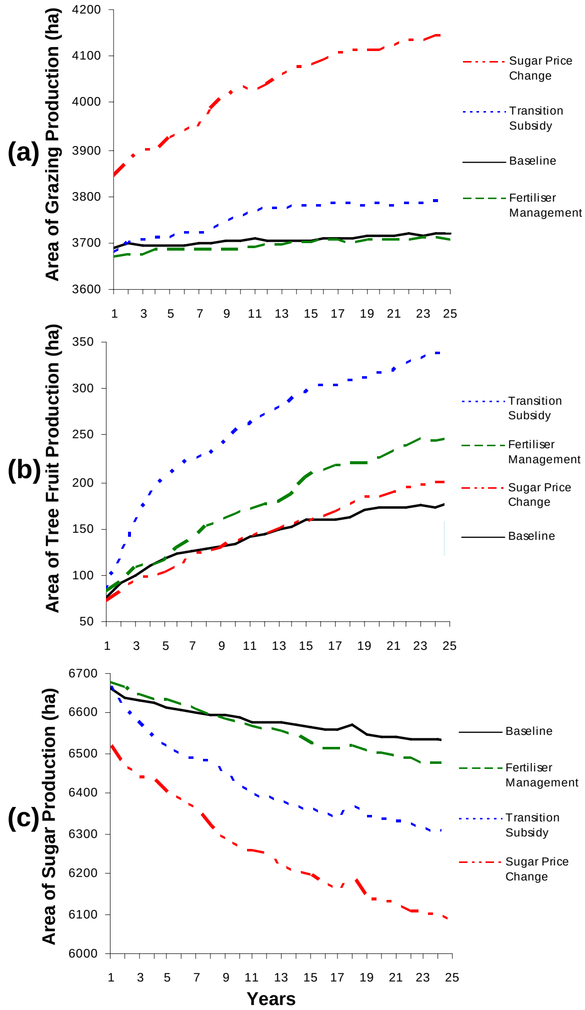

Figure 1: Total area of production for (a) grazing, (b) sugar cane and (c) tree fruits for three scenarios and the baseline scenario.

3.2. Nitrogen and Sediment Outcomes

Outcomes for sediment and nutrient contributions are depicted in figure 2. The downward trend observed in both is in part due to the fact that all farms are initialised without using on-farm BMPs, and the use of these emerges endogenously from this point. Comparison of trajectories and the outcome at the end of simulation runs is therefore indicative of the effect the scenario has. As would be expected, the fertiliser management restriction scenario yields the lowest overall nitrogen contributions. The sugar price change scenario also results in lower nitrogen contributions.

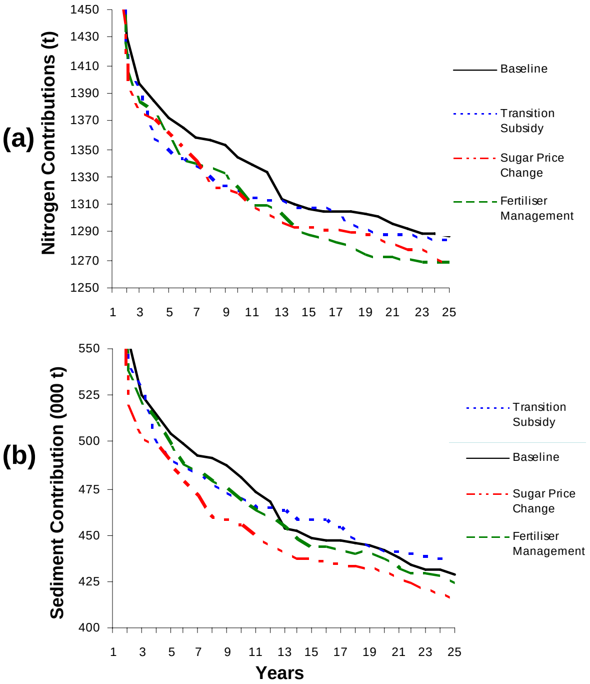

Figure 2: Total (a) nitrogen and (b) sediment contributions for three scenarios and the baseline scenario.

In terms of sediment contributions, the transition subsidy scenario is seen to show a small increase in sediment contributions in the latter half of the simulation. The sugar price change scenario yields the lowest sediment contributions.

3.3. Payoffs and Utility Derived

Figure 3 shows outcomes for total financial payoff and total utility derived from water services across the agent population. As would be expected, the sugar price change scenario reduces total payoff. The transition subsidy scenario realises the highest total payoffs. The fertiliser management restriction scenario is seen to yield higher payoffs compared to the baseline scenario.

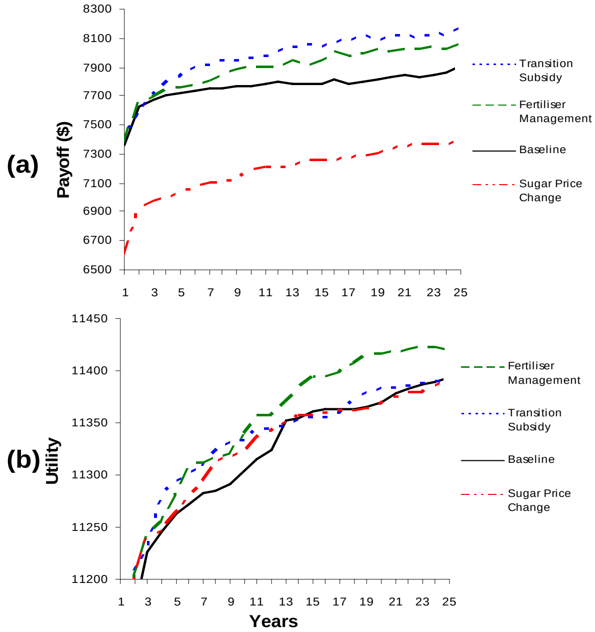

Figure 3: Total (a) financial payoffs and (b) total utility derived from water services for three scenarios and the baseline scenario.

In terms of utility derived from water services, the fertiliser management restriction scenario yields the greatest outcome. Results for the other two scenarios do not show notable differences to the baseline case, except during the first half of simulation.

4. DISCUSSION

The purpose of this paper is to show a proof of concept application of how the SEPIA model can address a variety of policy levers and report on indicators across disciplines. The results we present are for demonstrating model reporting capacity.

The sugar price change scenario yields the largest effect in terms of changing land-use areas, with agents moving into tree fruits and (predominantly) grazing. As a result, sediment contributions and total payoff decreased. The transition subsidy scenario showed increased adaptive behaviour, with a dramatic increase in tree fruit production. The fertiliser management restriction scenario shows land converting from sugar cane to tree fruits, given the relative cheaper fertiliser inputs needed. Agent adaptation away from sugar cane (which is fertiliser intensive) also lead to lower nitrogen contributions.

While our results are demonstrative and preliminary, hence limiting value for policy analysis, they allow us to make comments about the model. For example, drastic shifts in production decisions as seen in year 1 of the sugar price change scenario are not generally experienced in the real world. Hence there may be issues of 'institutional stasis' which need to be explored in agent's adaptive behaviour. At this stage of model development, the demand side of the production market does not respond to changes in production levels. The changes away from sugar to tree fruits and grazing may be mitigated by this. Furthermore, prices for each of the commodities, not just sugar cane, fluctuate and are characterised by a high degree of uncertainty in the real world, hence producers may avoid risk and are less likely to use adaptive behaviour. Finally, policy controls such as fertiliser management may have net improvements for both environmental and human well-being indicators, although the adaptive capacity of the community must be present to see both.

Our simulations report outcomes for human values, including utility derived from water services and financial payoffs. Such outcomes have an explicit link to biophysical conditions such as sediment and nutrient contributions and area under production for each commodity. Few complex systems models claim to forecast accurately, but many useful models that link biophysical and social systems generate results which test and develop our own understanding and present new ideas. In our model calibration has been taken seriously, and hence even our preliminary model produces results that may be expected to eventuate over time. Furthermore, in the tradition of complex system methodologies, our model has the potential to allow policy makers to take a larger-scale view on how primary production and the GBR are interlinked.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Australian Bureau of Statistics (2005): Household Income and Income Distribution, Australia. www.abs.gov.au/Ausstats/abs@.nsf

Beare, S., Bell, R., Blias, A., Gooday, P., Heaney, A., Hooper, A., Langenkamp, D., Love, G., Levantis, C., Mues, C., Qureshi, E., and Riley, C., (2003): Natural Resource Management in the Burdekin River Catchment. ABARE eReport 03.18

Cook, F., and Henderson, A., (2005): Estimates of average hydraulic drivers for sediment and nutrient fluxes in the GBR catchment from SedNet. CSIRO Land and Water Technical Report No. 15/05

Gleeson, T., McDonald, D., Hooper, S., Martin, P. Australian Beef Industry, (2003): Report on the Australian Agricultural and Grazing Industries Surveys of Beef Producers. ABARE Research Report 03.3

Hatfield Dodds, S., (2005): Representing Human Decision Making. Presentation to CSIRO Emerging Science Area Workshop. April 2005, Townsville, QLD.

Hajkowicz, S., (2005): Multi-attributed environmental index construction. Ecological Economics, (in Press).

Lu, H., Gallant, J., Prosser, I., Moran, C., and Priestly, G., (2001): Prediction of sheet and rill erosion over the Australian continent, incorporating monthly soil loss distribution, Technical Report 13/01, CSIRO Land and Water, Canberra, Australia.

Polhill J., Gotts, N.,and Law, A., (2002): Modeling Land-Use Change Using Agents in the FEARLUS Project, in D.C. Parker, T. Berger, and S. M. Manson (eds.) Agent-Based Models of Land-Use and Land-Cover Change Report and Review of an International Workshop. Irvine, California: LUCC International Project Office, pp.35-40.

Roebeling, P.C., I. Bohnet, M. Smith, D. Westcott, F. Kroon, M. Hartcher, M. Hodgen and J. Vleeshouwer (2005): Landscapes Toolkit for triple-bottom-line assessment of land-use scenarios in Great Barrier Reef catchments. Modsim 05 Proceeding, Dec 12-15, Melbourne.

Smajgl, A., Heckbert, S., and Morris, S., (2005): Water Policy Impact Assessment: Combining Modelling Techniques in the Great Barrier Reef Region. Modsim 05 Proceeding, Dec 12-15, Melbourne.

Smajgl, A. (2004): Modelling evolving rules for the use of common-pool resources in an agent-based model. Presented at 10th Biannual Conference of the IASCP, Oaxaca, Mexico, Aug 9-13.

Smith, D.M., P.C. Roebeling, A.J. Webster, M. Kragt, I. Bohnet and A. Zull, (2005): Assessment of the socio-economic impacts of management options for improving water quality in the Douglas Shire. Report prepared for the Douglas Shire Water Quality Improvement Program, CSIRO-Sustainable Ecosystems, Townsville, Australia. 42 pp.

Young, H.P. (1998): Individual Strategy and Social Structure, an Evolutionary Theory of Institutions, Princeton, Princeton University Press.