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PHD THESIS CHAPTER NINE

DISCUSSION AND CONCLUSIONS

9.1 INTRODUCTION

This socio-ecological modelling project has taken an interdisciplinary approach (i.e. used theory and methods from ecology and sociology) to represent the interaction of LUCC and wildfire. Brewer (1999) discussed several opportunities an interdisciplinary approach offers, including the emphases of the approach on the orientation of problem formulation and the context of research practice. Funtowicz and Ravetz (1993) have suggested the task of scientific quality assurance should not stop at product (the model and its results) but must also consider the process (the modelling), particularly with regards to the social aspects of the process. In this concluding chapter therefore, a reflexive approach which considers some of the more contextual aspects of the research is taken in order to summarise what has been learned from the modelling process of this thesis. This reflexivity has been more common in the social sciences than the natural sciences but, as Brown (2004) has suggested, modellers of physical environmental processes might also learn from examining the process by which they gain knowledge. Socio-ecological modelling lies at the interface between the social and natural sciences and remains a relatively immature research area. As such, it seems pertinent to reflect on what has happened in this modelling project so far. This chapter presents the research in chronological order, taking what is termed a 'narrative approach'.

9.2 NARRATIVE APPROACHES TO REFLECT ON THE MODELLING PROCESS

A narrative approach is used here in an attempt to 'open up' the process of model construction for better scrutiny, and to allow better evaluation and understanding of the modelling process and its results. In recent years a recognition of the historical nature of many forms of earth and environmental science (e.g. Frodeman 1995) have led to suggestions that 'narratives' would be useful tools to foster better understanding in subjects like geology (Gould 1987), environmental history (Cronon 1992) and science in general (Allen *et al.* 2001, Zellmer *et al.* 2006). In concluding a review on complexity science, human geography and modelling, O'Sullivan (2004 p.291) suggested the possible use of narratives to examine the modelling process to reveal the 'story' behind the decisions that were made during model construction. The presence of equifinality highlights the importance of observer dependencies in simulation modelling and the decisions modellers must make regarding the location of model boundaries (model closure – section 7.2.2). Simulation modelling is undertaken in situations in which data on the system being examined are sparse and logical transformations (approximations) are required to represent the system *in silico*. The justification of these transformations is made on a variety of fronts including theoretical knowledge, empirical generalisations, and experience from modelling similar phenomena (Winsberg 2001). Making explicit the implicit decisions and understanding made in the development of a simulation model is important if it is to be adequately evaluated.

The modelling process is not linear from conceptualisation through model execution and testing to analysis and interpretation of results. Rather, it is an iterative process that demands movement back and forth through these various stages, with modification and refinement, as a continual process (e.g. Figure 8.1). Iteration is required as the modeller(s) learn more about both the system they aim to represent and the adequacy of the model structures that have been put in place to do so. 'Dead-ends' are often encountered in the research process, but current academic and publishing conventions regularly inhibit the full story to be told of what was learnt from the (iterative) modelling processes (O'Sullivan 2004). Furthermore, if science, and in particular socio-ecological simulation modelling, is to move 'upstream' (sections 7.3.2 and 8.2), a more creative mix of formal and informal methods will be required to 'democratise science' (Wilsdon and Willis 2004) and reveal its inner workings. A narrative approach to presentation of the modelling process might help improve communication about both what was learnt and how it was learnt.

A narrative in the sense used here is a formal, but non-technical, representation of the history of events that "organises all representations of time into a configured sequence of completed actions" (Cronon 1992, footnote 5). Narratives provide meaning and understanding about events by representing these events as causal sequences, thereby ordering and simplifying. Thus, this chapter attempts to discuss not only what SPASIMv1, its results and the process of constructing it tell us, but also how this knowledge was gained. The success of a storytelling can only be evaluated by the audience – hopefully this narrative will be useful to provide insight into the messiness of the research process that this thesis presented as a formal and orderly progression.

9.3 SPASIMv1 Modelling Narrative

9.3.1 Research Proposal

The research presented in this thesis was funded by a joint UK Economic and Social Research Council/Natural Environment Research Council (ESRC/NERC) Interdisciplinary Research Studentship and undertaken within the Department of Geography at King's College, London (KCL). The interdisciplinary ESRC/NERC studentships are designed to encourage "postgraduate research on environmental issues which are of interest to both Councils and which require the combined approaches of both the environmental and social sciences" (ESRC 2007). The application for the studentship arose from my interest in studying wildfire/vegetation-dynamics modelling with Dr George Perry (then at KCL – currently at University of Auckland, New Zealand). I had been supervised by Dr Perry during my undergraduate degree dissertation, and we strengthened our relationship during my Master's studies of environmental monitoring and management. At the time Dr Perry was completing a manuscript on the role of land abandonment in the landscape dynamics of SPA 56 with Dr Raul Romero Calcerrada (then at Universidad de Alcalá, Spain – currently at Universidad Rey Juan Carlos, Spain) that was later published as Romero-Calcerrada and Perry (2004). With data available, a willing collaborator, and an academically established research question in the early stages of study (i.e. the question of the importance of agricultural land abandonment on wildfire dynamics), the application was made in May 2003. The original research objectives stated in this research proposal were to:

(i) develop a spatially explicit model of vegetation dynamics that considers both wildfire and human activity in the Mediterranean;

(ii) produce scenarios of future land-use change based on expert input from local collaborators, surveys of and discussion with local stakeholders, and informed judgement based on the literature;

(iii) use the model to explore the implications of these independently generated scenarios for future fire regimes;

(iv) use model outputs to assess, in collaboration with local stakeholders, the management implications of potential landscape changes to maintain future biodiversity and sustainability.

Whilst these objectives bear some resemblance to the stated research aims in chapter one (section 1.4), the emphasis on model evaluation made in chapters seven and eight is clearly absent. Furthermore, there is a much stronger emphasis on scenarios of land-use change and their generation with the aid of local stakeholders than was realised here. Much of this shift was a result of the encouragement of my 'social science supervisor' Dr David Demeritt, whose research interests lie in cross-cutting areas of nature-society expertise and the articulation of environmental knowledges (particularly scientific and technical). ESRC/NERC studentships require a supervisor from each of the environmental and social sciences – initially, Dr Geoff Wilson was proposed as the social science supervisor. However, soon after the success of the ESRC/NERC application, Dr Wilson moved from KCL to the University of Plymouth and Dr Demeritt replaced him. Other changing ideas and influences are discussed below.

9.3.2 Initial Exploratory Research

In early October 2003, soon after completion of my MSc thesis (Millington 2003), I set about a more detailed literature review of Spanish landscape change and wildfire (chapter two) and some initial statistical modelling and data exploration (chapter three). These two areas of research took me up to, and composed, my interim 'upgrade' report in November 2004. The report takes this moniker as its completion and acceptance following an oral defence 'upgrades' the student from MPhil status to PhD status – thus it is seen as a formal stage of the PhD research process in the Department of Geography at KCL. During this time I also made a trip to SPA 56 with Dr Perry and Dr Romero Calcerrada to get a better 'picture' (i.e. intuitive understanding) of the study area.

The initial literature review of the issues facing Mediterranean landscapes, with particular regard to the potential effects of contemporary socio-economic change on ecological systems, provided the context for the study and made the case for the need to study the questions required to achieve the first research aim (section 1.4 – though these question were refined and finalised during the work described in section 9.3.3). The literature review suggested that in traditional Spanish pine-oak woodland landscapes (of which SPA 56 is a prime example) vegetation dynamics are strongly influenced by disturbance, predominantly human activity and wildfire (section 2.2). High spatial heterogeneity in Mediterranean environmental resources (e.g. water) and the spatial nature of wildfire ignition and spread mean the consideration of spatial dynamics is vital to the study of ecosystems in Mediterranean regions (section 2.4.4). Furthermore, lengthy human occupation and the high proportion of wildfire ignition by humans make humans a direct and important driver of land-cover and wildfire dynamics (section 2.3). Changes in human activity recently have led to decreasing land use for agriculture and increasing scrub-like covers (as found by Romero-Calcerrada and Perry 2004), with potential implications for wildfire occurrence and spread.

The literature review and the case made for the research questions regarding the interaction of LUCC and wildfire are justified in their own academic and scientific right. However, two points can be made regarding the context of the framing of this particular literature review and the research questions. First, the literature review and research questions highlight the importance of human activity as a component of ecological processes in the landscape, in keeping with the interdisciplinary remit of the research funding. Second, the research questions focus on the importance of wildfire rather than any of the other outlined environmental consequences of land abandonment. There are currently many similar ecological questions being addressed in Mediterranean environments that focus on problems that are not directly influenced by humans (e.g. Keeley *et al.* 2006, Pausas *et al.* 2006, Pons and Pausas 2006), and the alternative environmental questions posed by agricultural land abandonment could be claimed to be equally important. The particular issues examined in this thesis were chosen because the context of the research project made them most relevant in terms of the project funding and my interest and expertise. There is no scientific or academic problem with this selection process and stressing that the context of the selection of research focus was based on academic rather than political or commercial grounds lends credibility to the process.

My initial literature review also examined the methods used to model LUCC and highlighted the reasons to model rather than examine landscape change using other techniques. Specifically, the large time and space extents involved in landscape study make empirical experimentation virtually impossible because of logistical, political and financial constraints. The use of empirical regression-based models is one approach which has been used frequently to examine LUCC (section 3.2). However, when assessed on a pixel-by-pixel basis the performance of these models has regularly been found to be poorer than that of using no model at all (i.e. a map at time t1 is often a better predictor of change at a later time t2 than a model based on empirical data from time t1 Pontius *et al.* 2004). To examine both this issue and the data available for SPA 56, we (I with the aid of Dr Perry) developed logistic regression models using both socio-economic and biophysical data (section 3.3.3). The predictive inadequacies detailed by Pontius *et al.* (2004) were also observed in our models for SPA 56. Furthermore, issues regarding differing levels of data resolution between these data types were found to hinder model performance (section 3.3.4). Problems of stationarity mean that these models are likely to perform poorly in regions where processes of change are dynamic, for example in human-dominated areas where socio-economic (i.e. institutional) structures are being modified (like in SPA 56 – section 3.3.4). In light of this empirical modelling exercise, it was suggested that a simulation model approach would prove more useful for representing spatially dynamic processes of change (such as land abandonment and wildfire) and improving understanding about these dynamics (section 3.4).

At the time of the work presented in chapter three, several other aspects of empirical modelling were explored that are not presented in the thesis. These omissions are because the later shift in emphasis toward stakeholder validation and assessment of models restricted what could be included. For example, an empirical GIS-model approach attempted to incorporate aspects of the temporal and spatial dynamics of wildfire regimes into static wildfire risk framework using the results of the logistic regression models presented in chapter three (Millington 2005). I felt that this modelling approach had limited success and that a dynamic simulation approach remained the most pertinent, and as an attitude is representative of the operator dependencies described by Beven (2004). Thus this GIS-model research was somewhat of a ‘dead end’ (despite being published!), of the type that shapes the researcher’s thinking but is never reported as such (O'Sullivan 2004). Other research on explanatory forms of empirical modelling (Millington *et al.* 2007) was not presented in the thesis because of the later shifting emphasis toward work on SESM evaluation. This explanatory empirical modelling was not so much a ‘dead end’, as research that did not fit with the resulting emphasis of the thesis. Again, this process helped to shape my resolve that a more explicitly process-based model was the best way to proceed with the modelling project. Whilst the regression models produced (section 3.3) performed as well as similar previously applied regression models (e.g. Carmel *et al.* 2001), it was felt that such a static and deterministic approach did not reveal much more than was already known from direct empirical observation. It was hoped that a more process-based modelling exercise would provide greater insights into potential future landscapes.

The intended structure of the integrated Socio-Ecological Simulation Model (SESM) at this time was a Landscape Fire Succession Model (LFSM) much the same as the current version, but with human activity imposed in a top-down fashion by broad scenarios of socio-economic change. This attitude, emphasising representation of the ecological processes, was based upon my expertise and interests arising from my physical geography background. During the 'upgrade report' defence however, questions regarding whether the representation of human activity via large-scale scenarios was appropriate and whether an agent-based approach might be pursued. Initially, I was not keen on this idea of incorporating an agent-based approach – I saw problems relating to data availability (i.e. lack of land-tenure data at that point in time), computational requirements, and, indeed, my own technical (computer programming) skills.

9.3.3 Model Conceptualisation and Initial Construction

Following the upgrade report, I started development of the LFSM (chapter four). Work proceeded quickly (relative to development of the ABM/LUCC) as I had a good understanding of the literature on this type of model, of how I thought the model should be constructed, and the raster/cellular-automata approach suited my programming skills well. The literature on LFSM-type modelling (section 4.2) highlighted that the large spatial and temporal extent of the proposed research (1×10^3 km^2 over decades) and the limits of data available for model parameterisation in Mediterranean-type environments demand trade-offs between processing power and model complexity (section 4.2.4). These tradeoffs have been satisfied most frequently in the past, and were satisfied in the LFSM here, by using a spatially-explicit landscape model-type approach utilising conceptual Plant Functional Types (PFTs). The two PFTs that best describe the life-history strategies adopted by Mediterranean-type vegetation to survive in the face of frequent disturbance are 'resprouters' and 'seeders' (representing oak and pine species respectively – section 4.3.2). The Rule-Based Community-Level Modelling (RBCLM) was used to represent changes in 11 land-use categories through time via conditional rules regarding environmental conditions (mainly moisture and light) and vegetation succession-pathways (secondary or regeneration – section 4.4). Land-cover state transitions were modelled using a time-based approach based on a look-up table specifying expected directions and times to transition for pixels under given environmental conditions (section 4.4.1 and Appendix I). Wildfire was represented in the model using a cellular automata approach that explicitly considered ignition frequency and location, particularly with regard to human activity as a cause (section 4.5). The model considers land-cover flammability, slope, wind and human activity as factors influencing wildfire spread.

At this point it should be noted that my supervisory panel had changed once again – Dr Perry had moved to the University of Auckland and was replaced by Prof John Wainwright (then at KCL – currently at the University of Sheffield) whose research focuses mainly on geomorphic modelling but who also has experience in modelling human-environment interactions in Mediterranean environments. During this time I successfully applied for an ESRC travel award to visit the School of Geography and Environmental Science at the University of Auckland for three months to work with Dr Perry and Dr David O'Sullivan. In Auckland (May – August 2005) I reviewed the literature on agricultural location theory and agricultural decision-making (section 5.2) which highlighted recent advances in ABM approaches (section 5.3). The highly spatially heterogeneous and a temporally-dynamic nature of environmental resources and land-tenure in SPA 56 suggested that land-use decision-making would be highly dependent upon individual farmers' circumstances. The literature review also suggested very few previous ABMs had explicitly represented interactions between human decision-making and the biophysical environment, and none seem to consider spatial land-tenure structure explicitly as a factor influencing LUCC (section 5.3). An ABM approach therefore appeared useful both to ensure adequate representation of agricultural decision-making and because it was a novel approach that was at the cutting edge of LUCC modelling. However, the literature also highlighted the drawbacks of an ABM approach (and supported my own concerns), including data demands, difficulties in agent representation and model validation issues.

Thus, it had become apparent that an agent-based approach would be required to ensure a properly integrated and novel SESM. The opportunity to work with Dr O'Sullivan at this time was particularly influential (and enlightening) given his expertise in simulation – particularly agent-based – modelling of geographic phenomena. During my time at the University of Auckland I began playing with the NetLogo agent-based modelling environment (Wilensky 1999) and started working on prototype models of agent-based decision making for SPA 56 based on an understanding I had developed via the literature and my previous visit to the study area. Furthermore, it was during this time that we (Drs Perry, O'Sullivan and I) discussed issues regarding modelling the 'real world', which provided the foundation for much of discussion presented in chapter seven.

On return from Auckland I felt that I needed a more secure empirical base on which to further develop the ABM/LUCC. Thus, interviews with local stakeholders (November 2005) were undertaken to supplement the understanding gleaned from the literature (section 5.4). As a result, two different 'farmer types' were conceptualised to represent the attitudes toward land-use decision-making in SPA 56 (section 5.4.2). 'Commercial' agents were based on the frequently used, but fictional, perfectly economically rational decision-making agent *Homo economicus* (section 4.5.3.1). 'Traditional' agents represented the part-time or 'hobby' farmers that continued tending their land regardless of economic profitability, because it was a part of their culture (section 5.5.3.2). Depending upon their type, agents made decisions based upon market conditions, their own personal attributes (e.g. age) and spatial rules regarding their land tenure (section 5.4.3). The conceptualisation of these farmer 'types' was not straight-forward as it was evident that numerous attitudes toward agriculture were present in SPA 56. However, upon reflection of the interviews and discussions these farmer types offered the most divergent worldviews whilst also representing the differing attitudes of older and younger generations of farmers.

9.3.4 Model Construction, Testing and Sensitivity Analyses

The majority of 2006 (January – September) was spent coding the agent-based model structure (developed in NetLogo) in the object-oriented programming language C++, and testing, running sensitivity analyses on, and integrating the two models (LFSM and ABM/LUCC) into the current SESM (SPASIMv1). By this time, land tenure data (i.e. maps of land ownership boundaries) of a quality high enough to represent individual agricultural decision-making agents had become available. The opening sentence of this section does little to describe the many hours of de-bugging, wrestling with understanding what (if anything) the ABM/LUCC model was doing, how best to undertake model analysis and 'validation', and despairing about whether the model would actually work or be of use for anything or anyone. From my experiences modelling LUCC in SPA 56, this confusion, uncertainty and insecurity seems likely to be an inherent part of the process of modelling an open, middle-numbered system for which knowledge about the important (and importance of) processes of change is poor.

The testing and sensitivity analysis of the LFSM was more straight-forward than the ABM/LUCC, largely because the parameter space was smaller and there were less, and more homogenous, interactions between elements of the model (i.e. it was less 'complex' than the ABM/LUCC). The sensitivity analysis showed the fire parameters to be most sensitive and influential on land-cover composition and wildfire regime behaviour (section 4.6). These wildfire-spread probabilities have been found previously to be highly sensitive, exhibiting critical threshold behaviour (e.g. Ratz 1995 – and see section 6.5.2, McCarthy and Gill 1997, Perry and Enright 2002). However, ensuring accurate values were used for these parameters was troublesome because of the difficulty of translating data collected for the parameterisation of models such as the Rothermel (1972) semi-empirical model for use in cellular automata (although Berjak and Hearne 2002 did recently attempt this). Thus, a sweep of the parameter space to find parameter values that produced system behaviour similar to that empirically observed (i.e. similar burned areas and frequency-area relationships) was used to derive the baseline parameters. This approach relied little on process knowledge other than that described in sections 4.4 and 4.5. Furthermore, specification of the soil moisture class definitions (section 4.4.2.2), 'random seed dispersal' (section 4.4.3.2), and 'oak mortality burn frequency' (section 4.4.3.1) parameters are examples of observer dependencies in model construction. Whilst based on the best available empirical evidence, insufficient data (for example, unknown locations of viable seeds in SPA 56 at model initialisation – section 4.4.3.2) and understanding at the scale at which these processes are modelled demands decisions be made using the modeller's experience and understanding of the system. These processes of parameterisation also applied to the state-and-transition look-up table, the values of which are based on previous literature (Barbero *et al.* 1990) and expert understanding about the system being studied (i.e. discussion with Dr. Romero Calcerrada and his colleagues). All aspects of these parameterisations are open to improvement dependent upon increased understanding and data availability at the landscape scales considered.

The 'complex' nature of the ABM/LUCC (i.e. many non-homogenous interacting agents) made testing and sensitivity analyses of this model very difficult. Testing for debugging often involved tracking the behaviour of individual agents through their spatial decision-making activities during a model replicate. At this point I realised that any analysis would need to be taken at the macro, system (i.e. landscape) level as analysis at the micro (i.e. decision-making actor) level would be too demanding in terms of time, data and computation. Later, I came to understand this approach as being 'generative' (Brown *et al.* 2006). I did consider analysis examining individual agents' life-histories and decisions, but decided this approach would be uneconomical (trading off the resources available with the likely knowledge gained). The system-level sensitivity analysis indicated that market conditions were the predominant factor driving decisions and LUCC (section 5.5). Neighbourhood effects between agents were observed (influencing agent attitudes) and land-tenure was also found to influence decision-making as the model specified. I didn't deem any more detailed, rigorous analysis worthwhile at this point in the modelling process given my uncertainty about how accurately the model represented the real-world system. Many of the parameters values used in the ABM/LUCC had been enumerated out of necessity and common sense – more colloquially, they felt like 'fudge factors' (i.e. values were used that ensured 'realistic' model behaviour but were not based on proven empirical fact). Furthermore, representation of the market forces driving LUCC, though found to be the most important, wasn't explicit or dynamic enough – but 'it would have to do for now'. This uncertainty was an important factor leading to the idea of engaging with local stakeholders to assess the model.

My experiences during this model development phase have led me to appreciate fully the suggestions of Matthews and Selman (2006 p.208) that "at their current level of development, ABMs are probably more useful as tools to *explore* options for effecting change in landscapes and rural communities, rather than *predicting* them, and as such, it is important that the structure of the models and the assumptions incorporated into them are transparent, and therefore well-documented, and also that the mechanistic behaviours assumed for the agents are well grounded in actual behaviour patterns". This passage serves to summarise my experiences and understanding developed through the model development, the result of which, in turn, is the final section of this thesis (i.e. chapters seven, eight and nine). What I felt I needed to do was to go to talk with people that might be able to indicate where and why my model was inadequate, but also to assess whether in this state it could be of any use.

Alongside the idea that I might be able to use local knowledge to evaluate and improve my model, I had come to think that if models are to explore rather than predict, many of the established, laboratory-type scientific methods for establishing the veracity of the knowledge produced by models and theories (e.g. the hypothetic-deductive method) become unavailable. In this case, I concluded, alternatives needed to be sought. The thinking (as presented in chapter seven) proceeds as follows. Socio-ecological systems, like the one I was trying to study (i.e. LUCC in SPA 56) are ‘open’, middle-numbered systems. Open systems are those in which mass and energy (and when humans are considered, information, meaning and value) flows both into and out of them, placing them in a state of disequilibrium (section 7.2.1). Middle-numbered systems have many components whose interactions are heterogeneous, and therefore cannot be studied easily using the methods of Cartesian science (e.g. calculus) or thermodynamics (e.g. statistical mechanics). This nature raises the epistemological problems of equifinality (i.e. there are multiple logical model structures that are able to reproduce empirically observed system behaviour – Beven 2002) and the potential of committing the logical fallacy of ‘affirming the consequent’ (i.e. rejecting a model if it does not reproduce the observed data, or accepting it if it does – Oreskes *et al.* 1994 – section 7.2.2). Alongside these epistemological problems, through attendance of seminars, wider reading and talking with other geographers in the department at KCL, I had become aware of the recent attitudes toward the issues facing contemporary society and the environment (e.g. Beck 1992, Funtowicz and Ravetz 1993 – section 7.3).

Thus, I have suggested a shift in emphasis in model ‘validation’ (i.e. evaluation) away from establishing the truth of the model’s structure via mimetic accuracy and toward ensuring trust in the model’s results via practical adequacy (section 7.3.1). These two criteria (trust and practical adequacy) would be useful alongside the necessity to ensure a model structure is based on sound logical and factual basis and possesses a realistic degree of mimetic accuracy. In this way validation becomes centred on the model user(s) and uses rather than the model, and suggests a shift away from falsification and deduction toward more reflexive approaches. For models of socio-ecological systems these criteria will likely be more useful than establishing the factual accuracy of a model structure or its results, but should be considered as additions to, rather than substitutions for, the criteria more suited to laboratory-based experiments. In turn, these additional criteria mean recent issues regarding expertise (e.g. Collins and Evans 2002), public engagement (Jackson *et al.* 2005) and the democratisation of science (Wilsdon and Willis 2004) become relevant (section 7.3.2).

The argument presented in chapter seven arose partly out of my problems of formally justifying the simulation model I was developing, due largely to insufficient data. But further, the sheer complexity (i.e. open, middle-numbered nature) of the socio-ecological system under study left me realising there was no way the model, given the timeframe and resources available, would ever be able to precisely match observed patterns and trends. Upon exploring the underlying problems it was realised that this was not simply an issue of data and other resources, but rather was an epistemological problem that had been previously explored and debated, particularly within the UK geography literature (e.g. Lane 2001, Brown 2004, Lane *et al.* 2006). As such, I felt that with regard to my experiences constructing this landscape-level SESM I might be able to contribute to the discussion. By this point I had already been confronted by much literature from outside my previous undergraduate and graduate training (e.g. section 5.2) and felt willing to challenge myself to ensure a truly interdisciplinary study. Alongside the epistemological issues, the more socially-oriented issues of ‘expertise’ and ‘public engagement’ were also evidently related. The context of an interdisciplinary socio-ecological modelling study provided a good opportunity to test the possibility and utility of ‘participatory approaches’ in modelling (e.g. Matthews and Selman 2006). With this in mind preparations for a stakeholder model assessment exercise were made (as presented in chapter eight).

9.3.5 Stakeholder Evaluation and Model Use

By October 2006 SPASIMv1 was in what was deemed to be a useable state, worthy of the time needed to be examined and evaluated by local stakeholders in the study area. In November 2006 seven interviews undertaken in SPA 56 with local stakeholders from within the study area, each of whom had knowledge of specific regions of the study area due to their occupation. Interviewees covered a range of institutional contexts from private, individual land owners with no governmental connections, through to the head of one of the subsections of the Autonomous Community of Madrid’s department of environment. The semi-structured interviews considered five aspects of the simulation model: drivers of change, (section 8.3.2) model results (section 8.3.3), model assumptions (section 8.3.3), model modification (section 8.3.4), and changes in understanding (section 8.3.5). Using the results of these interviews the model was assessed against the four validation criteria established in chapter seven (accuracy of logical structure, mimetic accuracy, trust and practical adequacy – section 8.4.1). Stakeholders generally accepted the model structure and output were representative decision-making processes and anticipated future change respectively. However, several shortcomings were highlighted by the stakeholders – most importantly the absence of consideration of urban change and an inadequate representation of market mechanisms and subsidies. Furthermore, it was suggested that the emphasis placed on the spatial nature of land-use decision making (arising from my reading of the literature and discussion with other ‘experts’) was not justified.

Regarding the potential uses of the model, stakeholders were somewhat divided in their opinions. Those with roles in local planning were enthusiastic about the potential use of the model and said they would be willing to work with it. In contrast, the somewhat fatalistic outlook of those directly concerned with agriculture and whose decisions are based on an individual (single farm) basis led to a more sceptical response about the possible uses of the model. Thus, in some quarters the model gained a degree of trust and was deemed practical adequacy, whilst in others this was less evident. However, as suggested in section 8.4.1, trust and practical adequacy will only really be proven once people use the model (or more specifically, knowledge gained from it) to make decisions and/or policy. According to stakeholders’ comments, and when compared against the four model validation criteria, the model was not a complete failure but had clear room for improvement in future model iterations. Much of this improvement will be based on comments made by the stakeholders, ensuring that their engagement becomes an integral component of the modelling process.

Whilst the stakeholder validation exercise proved useful, two particular shortcomings were evident. First, some stakeholders seemingly found it difficult to make the distinction between the model and the scenarios it was run for. The format of the interviews did not allow the degree to which this was a problem to be established, but any future contact between simulation models and non-modellers will need to consider this issue. Second, as noted above, several of the stakeholders were fatalistic about the change they expected to occur over the coming decades and saw little use of the model to explore alternative scenarios. This attitude was apparent despite accepting the model was generally an appropriate representation of agricultural decision-making and LUCC as it is occurring in SPA 56. However, the model did provide a useful platform from which discussion about potential LUCC was launched and the interviews indicated that the use of the model as a 'mediator' (Morrison and Morgan 1999) or 'muse' will be useful for generating discussion about future environmental policy- and decision-making if so required.

Personally, the stakeholder engagement experience, both during model development (i.e. chapter five) and later during evaluation (i.e. chapter eight), was very useful for conceptualising and understanding the processes of LUCC. Given that the agents to be represented in any simulation model of agricultural decision-making or LUCC will be actual humans able to impart knowledge about their actions, it seems necessary that all models of this type engage with local stakeholders during the model development processes, even if they are not engaged for the model evaluation phase (and as advocated will be good research practice in the future by Moss and Edmonds 2005, Matthews 2006). Whilst there are drawbacks to this approach (as highlighted above and in chapter eight) the benefits of improved system understanding and the potential for ensuring the development of a practically adequate model (if that is required) outweigh them.

Given the modelling experiences I have gained during the completion of the research presented in this thesis I would suggest that currently ABM/LUCC approaches will be useful in two distinctly contrasting situations. First, the agent-based approach will be useful for examination of essential system-level understanding of the processes of LUCC, when used in a 'metaphor model' approach (section 7.2.1 – Perry and Millington 2007). In this situation, representation of a specific real-world system or place will not be the aim – instead the multi-agent system itself will be the object of enquiry. This approach would contribute to the descriptive modelling at a low level of representation that Moss and Edmonds (2005) suggest will be necessary before more general theory can be developed. Alternatively, if explicit representation of LUCC in the context of a specific place is intended, the modeller(s) will need to ensure that iterative engagement with the actors being represented is possible from the outset and throughout the modelling process. This engagement will be vital to ensure models are based on the best available evidence and understanding. Social enquiry will be as important as systems enquiry in these modelling projects (e.g. Oxley and Lemon 2003).

Furthermore, this approach will demand detailed data for parameterisation, time for development and the services of a skilled and experienced object-oriented programmer (in contrast to the initial situation in this modelling thesis). With contemporary levels of widely available computing power as they are, a less computationally intensive modelling approach would be more suited to 'decision-support' regarding the environmental impacts of LUCC (Oxley *et al.* 2004). This less intensive approach might be achieved by taking a systems dynamics approach (instead of an agent-based approach) or by vastly simplifying agent representation, and would allow stakeholders to 'use' and interact with the model (interface at least) themselves.

Having established a degree of confidence in SPASIMv1, it was now (i.e. December 2006 – February 2007) used with scenarios of economic and demographic change to simulate interactions between LUCC and wildfire regimes (section 6.3). Results of simulations not considering human activity, but over longer temporal extents (i.e. centuries rather than decades), were also examined (section 6.4 and 6.5). To characterise wildfire regimes for comparison between effects of different scenarios and parameters, the power-law wildfire frequency-area scaling exponent β was proposed (section 6.2). Other state variables including mean total burned area, land-cover composition and various land-cover spatial configuration metrics were used to examine the results of LUCC-wildfire interactions. Simulation results indicted that mean largest wildfire and mean total burned area will increase if agricultural activity declines and that changes in land-cover composition are driven more by human activity than wildfire. The implication of these results is that wildfire and environmental managers, both locally to SPA 56 and across other regions of the Mediterranean experiencing agricultural decline and abandonment, will need to consider social change in their wildfire and environmental management plans. Landscape configuration varied little across the scenarios of human activity (section 6.3), due to the importance of small-scale human activity on LUCC.

The investigation of the use of β (a measure of the ratio of large to medium to small events) stemmed from my previous work (Millington 2003) that was developed subsequently and concurrently with the work in this thesis (resulting in Malamud *et al.* 2005, Millington *et al.* 2006). For scenarios of human activity the power-law frequency-area scaling exponent β was not found to vary significantly in response to human activity. In contrast, simulations over longer centuries did indicate variation in β values as a function of total and maximum land-cover flammability probabilities (section 6.5). These results indicate that the power-law scaling exponent β is not the most useful measure of the wildfire frequency-area relationship over smaller, regional (i.e. 1×10^3 km^2) extents. Future investigation into the β scaling exponent and its implications should remain at larger spatial and temporal extents.

One of the most novel aspects of SPASIMv1, afforded by the integration of an ABM/LUCC with a LFSM, is the attempt to explicitly represent the impact of human activity on wildfire ignition frequency and location (section 4.5.2). Whilst it is known that the majority of fires in Spain are ignited by human activity (Moreno *et al.* 1998), there is limited data and understanding regarding the reasons people start fires or the locations in which fires occur. The model was therefore based on the scant previous research (e.g. Chuvieco and Salas 1996) and ‘expert knowledge’, which in this case meant ‘common sense’ assumptions (such as fire ignition frequency is likely to be greater nearer areas of greater outdoor human activity). The difficulties in establishing formal justifications for the modelling approach taken to represent humans as a source of wildfire ignition highlight the need for more (sociological) research in this area. However, such research is likely to be contentious and unbiased evidence may be difficult to come by (e.g. Millington 2006 and associated comments – but see discussion in section 9.3.9 below). The explicit simulation of wildfire ignition cause allows the behaviour of wildfire due to these different causes to be examined. Fires ignited by human causes were found to burn greater areas of scrub than would be expected at random, and lightning fires burned greater areas of forest than would be expected at random. As other authors have found (e.g. Mouillot *et al.* 2005) this suggests some areas will be burned more frequently than others due to human activity (this follows from the model assumptions that human ignitions will be more frequent where greater levels of outdoor human activity are present). No effect on the wildfire regime was found due to ‘types’ of people in the landscape (section 4.5.2). Further work needs to examine the human wildfire ignition representation of the model (especially a more formal justification of the assumptions) and its potential results. Furthermore, whilst not evaluated in the stakeholder model evaluation, the interaction and feedback between land burning and the human response is not well integrated currently (section 6.6). With the model assumptions in mind, and given the empirical evidence found elsewhere, these results suggest wildfire managers will need to locate their energies on areas of increased human activity.

9.3.6 Self-reflection

This chapter has attempted to do two things. First is has tried to summarise what this thesis has told us and reflect on not only what was learnt but how it was learnt. Lane *et al.* (2006 p.251) recently suggested that reflexivity often leads modellers to question "our assumptions about what the problems are that are being modelled". One of the additional model validation criteria suggested in chapter seven was that of 'practical adequacy' – ensuring that model structure allows the examination of problems the model user(s) wants to examine. As such, the work in chapter eight found that the model developed here was only partially practically adequate and that some of the key concerns for stakeholders in SPA 56 were not represented by the model, the primary omission being urban change and the pressures of a nearby growing capital city. Whilst this might be interpreted as a failure of the model, when taken as part of an iterative process of model development this is but another stage in the ongoing modelling process, at all points along which both modeller and model user can learn. Furthermore, had stakeholder engagement been even further 'upstream' and more iterative, this problem would be diminished. The thesis may end here but the modelling and learning should continue in the future.

Second, this chapter has presented the research process as a narrative. The chronological orderings of events a narrative demands has highlighted areas of this research that did not occur in the order presented in the main body of the thesis (e.g. SPASIMv1 results – chapter six). Thus, the narrative presented here has illustrated the route to discovery as well as describing what has been learnt. For example, the causes of realisation that an agent-based approach was required to ensure a cutting-edge model of socio-ecological change and wildfire were discussed, and the path leading to engagement with non-modellers for model evaluation was mapped. This narrative approach to 'open up' the modelling process may not be so relevant in an academic setting where work is read and reviewed by other modellers (and who therefore understand the subtleties and vagaries of the modelling process), but it will be important for engaging models with non-modellers. One tool that may help modellers to construct and disseminate these narratives to non-modellers in the future (at least in more developed countries) is that of the weblog. Weblogs have grown in recent years as informal platforms for dissemination of material or media on the World Wide Web. Generally these user-publishing platforms are unedited and not subject to any form of peer review *before* publication, and therefore do not match the formal requirements of academic or scientific research for publication (thus comments such as those cited above – section 9.3.5 – should be treated with caution). However, given the diary-style, (reverse) chronological nature of their presentation, such a platform may provide a means to by 'open-up' the modelling process and, particularly, be a useful tool for generating model narratives. Thought processes underlying assumptions and the dead ends of research might be revealed if a rigorous log is kept. This log might just as easily be a traditional laboratory log book as a weblog, but a particular advantage of the weblog over more traditional research diaries is that it is freely available on the web and therefore will be able to aid public engagement, public understanding and the democratisation of scientific models and the process of modelling (as recent policy research has suggested is required, e.g. Wilsdon and Willis 2004). In this manner project stakeholders can keep up-to-date with the thoughts and work of the modeller(s) and the iterative nature of stakeholder engagement can become even more integrated. Whether issues will then arise then about some kind of 'over engagement' will remain to be seen. Regardless of the tool used to record the narrative of the modelling process, hopefully the attempt as it has been presented here indicates some promise for this form of model dissemination.

9.4 SUMMARY

This thesis aimed to examine the impacts of human land use/cover change (LUCC) upon wildfire regimes in a Mediterranean landscape and to explore and evaluate novel methods to 'validate' simulation models (and processes of modelling) of environmental change considering human activity. Chapter two introduced the research context and highlighted the importance of both human activity and wildfire in Mediterranean-type ecosystems. The literature review also showed how ongoing socio-economic change is driving agricultural LUCC (predominantly abandonment), with potential impacts for wildfire and vegetation dynamics. Chapter three examined the alternatives for modelling LUCC in Mediterranean-type landscapes such as SPA 56, and presented a regression-based modelling approach that demonstrated the shortcomings of empirical modelling. These shortcomings included issues such as non-stationarity in the driving forces of change, reconciliation of different 'types' of data that are aggregated at different resolutions (i.e. biophysical versus socio-economic data), and the limited process understanding an empirical approach provides. Experiences from this empirical modelling indicated that a simulation modelling approach would best serve the first aim of the thesis.

Chapters four and five presented the structure of the simulation model. A time-based, state-and–transition vegetation-dynamics model with a wildfire cellular automata component (a Landscape Fire Succession Model) was integrated with an agent-based model of agricultural decision-making (an ABM/LUCC). The integrated socio-ecological simulation model (SESM) produced directly considered the influence of human activity on wildfire ignition frequency and location, demonstrating the problems that have hindered this approach previously remain (i.e. poor data and understanding about the reasons for human ignition) but that useful representation is possible. Results from the application of the SESM (chapter six) highlighted that if agricultural change (i.e. abandonment) continues as it has recently, the risk of large fires will increase and greater total area will be burned. The explicit representation of human influence on wildfire frequency and ignition is a novel approach and highlights biases in the areas of land-covers burned according to ignition cause. These results also highlighted that scale is important for determining the appropriate measures to examine output – the wildfire frequency-area power-law exponent β was found to be sensitive only to change for model replicated considering centuries (in the absence of human activity). However, the experiences of the work presented in these chapters showed the resource intensiveness of this agent-based modelling approach at the landscape level (i.e. 1×10^3 km^2 over decades), requiring that the agent-based approach provide ‘scenarios’ of human land-use change.

Chapter seven then discussed the problems of modelling open, middle numbered systems and the associated issues of model ‘validation’ and assessment. The problems of equifinality (presence of multiple logical structures able to reproduce empirical behaviour) and the consequent logical fallacy of (incorrectly) accepting a model as valid if it reproduces observed data, mean that deduction and falsification are not useful methods for model evaluation. As a response, when simulating socio-ecological systems the model validation criteria of trust and practical adequacy were suggested as useful additions to the more traditional structural and mimetic accuracy criteria. The integrated socio-ecological simulation model developed here was then evaluated on these criteria following interviews with local stakeholders (chapter eight). Whilst the model structure was broadly accepted as adequate several shortcomings were identified, including the lack of representation of urban change and an emphasis on spatial configuration in agricultural decision-making. Subsequently, enthusiasm regarding the potential uses of the model varied according to the institutional setting of the stakeholder, being more positive in those with a planning remit. The insights provided by the stakeholder model evaluation suggest there is a need to engage with local stakeholders at all stages throughout the iterative modelling process. However, potential problems during this engagement process were observed, particularly regarding the conflation between scenarios the model was run for with the actual model itself. Finally, this chapter presented reflections on the modelling process in a chronological, narrative fashion. The narrative highlighted the vagaries of the modelling process and demonstrated a reflexive approach that this thesis has suggested would be more informative than falsification and deduction for the evaluation of models of socio-ecological systems.

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