Supplementary Material

Assessing the quality of land system models: moving from *valibration* to *evaludation*

Summary of application of the LUC-TRACE framework to the CRAFTY modelling framework

This supporting information document summarises the extent of application of the LUC-TRACE protocol to the CRAFTY agent-based modelling framework. A complete TRACE document for one application of this framework, CRAFTY-GB, can be found in Brown et al. (2022).

1. Problem formulation

A general problem formulation was included in the first description of the CRAFTY framework. Key to this was the requirement for a land use model "to be run over large spatial extents and to be capable of accounting for relevant forms of human behaviour, variations in land use intensities, multifunctional ecosystem service production and the actions of institutions that affect land use change" (Dave Murray-Rust et al. 2011). Decision-making contexts, target audiences and outputs were also addressed at this general level. More specific problems have been formulated in subsequent applications of the framework (for instance CRAFTY-Sweden addressed a need "to explore a) future Ecosystem Service provision and how Ecosystem Service demands may be met, b) land-use change, and c) changes in land owner objectives, in the Swedish forestry sector" (Blanco et al. 2017)). However, no applications of the CRAFTY framework have given precise delimitations of model clients, stakeholders, domains or questions that should be addressed, as opposed to those actually being addressed in individual research outputs. Implicitly, this is left open for model users to make informed decisions about, and to that end there have instead been consistent warnings and caveats in descriptions of model applications, especially to emphasise that model outputs are not predictive in nature.

2. Model description

The CRAFTY framework has been described in a number of ODD protocols for different model versions and applications (Murray-Rust et al. 2014; Blanco et al. 2017; Holzhauer, Brown, and Rounsevell 2019), as well as in online documentation (which, perhaps typically, has been sometimes incomplete and hard to follow).

3. Data evaluation

In applications of CRAFTY, data evaluation has been carried out intermittently. The recently developed CRAFTY-GB model uses a large number of input datasets, all of which have been evaluated (Brown et al., 2022). Prior to this, agent typologies have been validated against independent data (Blanco et al., 2017), and comparisons have been made of different uses of input data (Brown, Holman, and Rounsevell 2021). Many applications have used only limited data, and in these cases evaluation of assumptions and parameterisations based on empirical knowledge has generally been provided, although not always rigorously.

4. Conceptual model evaluation

This evaluation step has been applied to CRAFTY through presentation of its conceptual design supported by both theoretical (Arneth, Brown, and Rounsevell 2014; M. D. A. Rounsevell et al. 2014; Rounsevell, Robinson, and Murray-Rust 2012) and practical (Murray-Rust et al., 2014) publications. This information provision is not equivalent to a 'trial by publication' and clearly cannot be interpreted as a test of model quality, but allows users to make their own informed decisions about model applications. In some cases, key conceptual components of the model have been grouped together, with underlying justifications, for this purpose.

5. Implementation verification

Unit tests were used in the development of the CRAFTY framework, with thorough checks also made on model implementation and performance (Murray-Rust et al., 2014). This ensured that the shared code base is sound for all applications of the framework. Substantial effort has also been put into model usability. By default, CRAFTY provides facilities to graphically control and monitor model parameters, processes and outputs, as well as a range of file types and contents to capture model results. The CRAFTY framework code is open-access and documented through formal and informal written descriptions, including installation and usage instructions. Nevertheless, as with most land system models, there is a tension between model development and use for research projects, and good practice in implementation verification that is typically not required or directly supported by funders or publishers. In the absence of stronger short-term incentives for implementation verification, it is likely to remain relatively difficult for modellers to resolve this tension.

6. Model output verification

In CRAFTY, output verification has been used to check agent typologies (Blanco et al., 2017) and emergent land use patterns (Brown, Seo, and Rounsevell 2019; Millington et al. 2021), while full descriptions of calibration procedures have been provided in all applications. The most important aspect of this step is clarification of the extent to which model calibration and validation are separated in the development process; a separation that is not always achieved or described (Brown et al. 2017). For example, Millington et al. (2021) used empirical data to valibrate agent functional type production functions to reproduce observed crop production through time. Subsequently, model outputs were evaluated by examining spatial outputs, but the separation of calibration and validation could not be completely ensured.

7. Model analysis and application

Sensitivity and uncertainty analyses have been carried out on the CRAFTY framework (Holzhauer et al., 2019; Murray-Rust et al., 2014), although comprehensive analyses have not been carried out for many individual applications. Model stability, stochasticity and expected responses to particular drivers have been checked for almost all applications.

8. Model output corroboration

Many of the above challenges to corroboration apply to the CRAFTY framework, a model of the land system that includes some behavioural detail but excludes various crucial parts of the real-world land system: international trade, tenure arrangements or policy controls, for instance. It should in principle be incapable of accurately predicting complete real-world outcomes as a result, except under the most tightly constrained circumstances. Nevertheless, a limited machine learning application showed substantially increased fit-to-data through variation of just three key parameters (Seo, Brown, and Rounsevell 2018), and specific model outputs have been compared to independent data both qualitatively and qualitatively (Blanco et al. 2017; Brown, Seo, and Rounsevell 2019). Perhaps more informatively, CRAFTY has been compared to other models in benchmarking and convergence experiments (Alexander et al., 2017; Brown et al., 2021).

9. Participatory/companion modelling

Participatory applications with CRAFTY have been limited and unpublished, although online interfaces have been developed to allow the model to be used in this way. Existing applications have been mainly in teaching, where interfaces are used to aid student understanding of the modelling approach.

10. Model replication

In the case of CRAFTY, barriers to replication are relatively low because the model is open access and well-described. Nevertheless, no formal analysis of replicability has been carried out, and informal checks have only been made of runnability and reproducibility. To date, adequate descriptions of computational environments have not been provided.

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