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A fuzzy set approach to assess the predictive accuracy of land use simulations

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ABSTRACT

The predictive accuracy of land use models is frequently assessed by comparing two data sets: the simulated land use map and the observed land use map at the end of the simulation period. A common statistic for this is Kappa, which expresses the agreement between two categorical maps, corrected for the agreement as can be expected by chance. This chance agreement is based on a stochastic model of random allocation given the distribution of class sizes. Two existing statistics extend Kappa to make it more appropriate for the assessment of land use models: Fuzzy Kappa uses fuzzy set theory to include degrees of similarity, which adds geographical nuance because it distinguishes between small and large disagreement in position and in land use classes. Kappa Simulation, on the other hand, addresses the stochastic model that underlies the expected agreement: when a model starts from an initial land use map and subsequently makes changes to it, a stochastic model of random allocation given the distribution of class sizes has little relevance. The expected accuracy in Kappa Simulation is therefore based on transition probabilities relative to the initial map. This paper presents Fuzzy Kappa Simulation, a statistic that combines the geographical nuance of Fuzzy Kappa with the stochastic model of Kappa Simulation. This new statistic is demonstrated on a case study example and results are compared with other variations of Kappa. The comparison confirms that Fuzzy Kappa Simulation is the only statistic to evaluate models in terms of land use transitions, while also being sensitive to geographical nuance.

1. Introduction

In the last decade, many land use models have evolved into tools that can be used to study land use change processes, conduct scenario studies or perform policy analyses for real world cases (Aljoufie et al., 2013; Hellmann and Verburg, 2011; Stanilov and Batty, 2011). Applying land use models for these purposes requires an understanding of their performance. This performance can at least partly be characterized by their predictive accuracy, which is often assessed from its capacity to reproduce historical land use changes. This is typically assessed by comparing the simulated land use map and the observed land use map at the pixel level. Several map-comparison methods exist for this, including the Kappa statistic (Monserud and Leemans, 1992), the Tau coefficient (Ma and Redmond, 1994), and the Average Mutual Information (Foody, 2006).

Map comparison methods indicate for each pixel whether the land use is similar in both maps or not. Consequently, when a model simulates a particular land use change in the wrong location, it is registered as two errors: one change where it should not be and one non-change where it should be. However, from a modeller's point of view, simulating the right change in nearly the right location may be considered as partially correct, while simulating this change at the other side of the study area would be a complete miss. Similarly, when a model simulates a land use change of a different nature than occurs in reality, it is traditionally registered as one error. However, some transitions may be considered a more severe error than others. For instance, a change from cropland to dense residential land simulated as a change from cropland into sparse residential land may be considered as partially correct, because both are transitions towards residential land. A crisp assessment of land use classes would therefore be unnecessarily harsh for the comparison of two maps (Foody, 2008), hence it can be meaningful to allow for spatial as well as thematic tolerance in the assessment of results of land use models. The use of fuzziness to interpret land use maps is further justified by uncertainties in land use data, including mixed pixels (Fisher et al., 2006; Foody, 2008) and uncertainty inherent to data acquisition techniques (Foody, 2002; Fritz and See, 2005).

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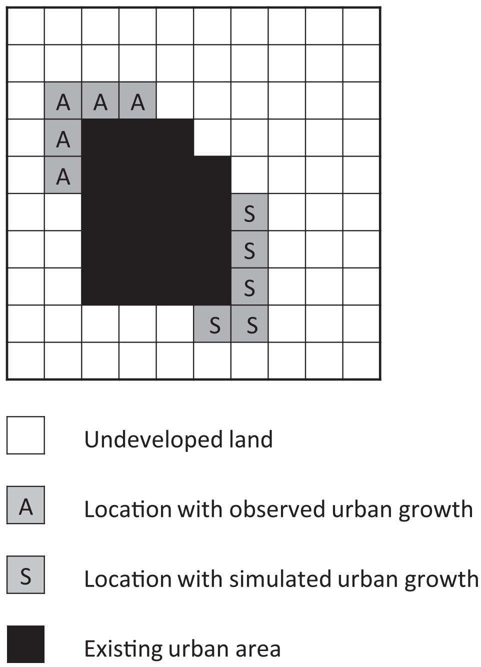

Fig. 1. A synthetic example to illustrate the difference between change and persistence. Both the simulated and the actual land use changes are close to the existing urban land, while they are quite far from one another.

Most areas are characterized by land use persistence rather than land use change during a typical land use change simulation (Pontius et al., 2008). The predominance of persistence has a large implication for the assessment of land use models, as the amount of change influences the similarity between the actual land use map and the simulated land use map at least as much as the accuracy of the simulated land use changes. In other words: a model may appear to perform well only because it reproduces a static landscape and not because changes are simulated accurately (van Vliet et al., 2011; Walker, 2003). Therefore, an end-state comparison is meaningless as a measure of the predictive accuracy without an appropriate reference level (Hagen-Zanker and Lajoie, 2008). Moreover, the relative merits of applications cannot be compared, since the amount of change can vary considerably between applications of land use models.

The differentiation between land use changes and land use persistence has an additional implication when fuzziness in location is incorporated in the model assessment. In reality, many land uses are strongly auto-correlated (Verburg et al., 2004; Tang, 2008), and therefore new occurrences of a particular land use are likely to be next to locations where that land use already exists. A typical example of this is urban growth, as the locations for new urban areas are often adjacent to already existing urban areas (van Vliet et al., 2013). An end-state assessment of model results cannot distinguish between persisting urban land and urban growth. Consequently, an end-state comparison will interpret this as a near-hit, while it can be a complete miss from the perspective of a land use change modeller. Fig. 1 illustrates this case: the simulated land use changes are located next to the existing urban area, but they are not close the location of the actual land use changes, and vice versa. Hence when only the end state is considered, these land use changes appear as near-hits, since they are directly adjacent to existing urban land. However, for a model that aims to simulate urban growth it is the distance between equivalent changes that determines whether it can be considered a near-hit or not. In Fig. 1, the simulated land use changes and the observed land use changes are located on opposite sides of the existing urban area. Therefore these can hardly be considered near-hits.

Some map comparison methods have been proposed that either address a fuzzy interpretation of land use maps, or the amount of land use change in a simulation, but not both. Fuzziness has been used in map comparison techniques to allow for spatial tolerance (for example Constanza, 1989; Pontius et al., 2008), thematic tolerance (Fritz and See, 2005; Hagen, 2003; Townsend, 2000) or both (Hagen-Zanker, 2009). Pontius et al. (2004) use the original land use map at the start of the simulation to distinguish between persistence and changes in the assessment of land use simulations. Alternatively, Hagen-Zanker and Lajoie (2008) propose the application of a neutral reference model as a benchmark for comparison with model results. van Vliet et al. (2011) present Kappa Simulation, a method that implicitly accounts for the information available from the initial land use map.

This paper presents Fuzzy Kappa Simulation (FKS), a statistic that combines properties from Fuzzy Kappa (Hagen-Zanker, 2009) and Kappa Simulation (van Vliet et al., 2011). This new statistic has several advantages over other available map-comparison methods: it allows to differentiate between changes and persistence because it is based on land use transitions rather than land use classes, it allows to account for near-hits because it uses a fuzzy interpretation of land use transitions, and the value of FKS directly indicates whether the model under assessment has any predictive capacity, because it applies an appropriate reference model.

2. Fuzzy Kappa Simulation

2.1. Kappa and its variations

Kappa expresses the agreement that is observed between two categorical datasets, *PO*, corrected for the agreement that can be expected from a random allocation of the given class sizes, *PE* (Cohen, 1960):

$$\text{Kappa} = \frac{PO - PE}{1 - PE} \tag{1}$$

Fuzzy Kappa and Kappa Simulation also follow the same rationale albeit with different definitions for observed and expected agreement.

Fuzzy Kappa (Hagen, 2003) is an extension of the Kappa statistic that uses fuzzy set theory to account for the degree of spatial mismatch as well as similarity between categories. Spatial mismatch is accounted for by attributing a partial agreement for pixels that are not corresponding, but for which corresponding categories are found nearby. Similarity between categories is accounted for by attributing some degree of agreement to land use categories that are similar to each other. The Fuzzy Kappa statistic is parameterized by the distance decay function that specifies the level of agreement as a function of matching distance and the categorical similarity matrix that specifies the similarity relations between categories.

Kappa Simulation (van Vliet et al., 2011) was developed in recognition that the stochastic model underlying expected agreement in the Kappa statistic is not wholly appropriate for applications of land use modelling. The Kappa statistic uses a stochastic model in which each category a probability of occurring (based on its frequency) and this probability is the same for all pixels. Land use models however are strongly conditional to the distribution of land uses that are used as the starting point of the simulation. Kappa Simulation incorporates this information by considering the probability of occurrence of a category at a location conditional to the category found in the initial land use map at the same location.

Fuzzy Kappa Simulation (FKS) combines properties of Fuzzy Kappa and Kappa Simulation in one statistic: it expresses the agreement between observed land use transitions and the simulated land use transitions, corrected for the agreement that can be expected by chance given the distribution of class transitions relative to the