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New measures and tests of temporal and spatial pattern of crops in agricultural landscapes

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Abstract

Crops are allocated to their fields by growers according to rotational principles and such rotations may be defined and classified. Rotations evolve through the aggregate choices of crops by growers over time which create the characteristic agricultural landscapes for a given region. As agriculture becomes ever more competitive, growers increasingly should use such rotational principles to maximise efficiency. Their choices of crop allocations alter the observed temporal heterogeneity and spatial pattern of cropped landscapes. Within the European Union the forms of heterogeneity studied here are increasingly evident at the landscape scale. We present techniques to study these patterns of crops in time and space. This is essential in order to build realistic simulators of large-scale cropped landscapes within which farming practices may be studied across national boundaries. Simulation is required to provide realistic arenas to extend current models of gene flow from the field to the landscape scale, in furtherance of studies of coexistence between genetically modified and conventional and organic crops. We provide simple, empirical descriptors of cropped landscapes in terms of the degree of the non-randomness of the allocation. Non-randomness of fields is assessed in terms of (i) spatial pattern, (ii) temporal heterogeneity, and (iii) spatio-temporal heterogeneity. Four formal statistical tests of significance are presented: one of spatial pattern, two of temporal heterogeneity and one of spatio-temporal heterogeneity that may also be used to test for spatial pattern. The tests were exemplified using data taken from a study landscape of 72 arable fields farmed by 10 different growers in Burgundy, France, from 1994 to 1997. Two of the tests were based on simple χ^2-statistics; two were randomisation tests. The χ^2-test of spatial pattern demonstrated clustering in the distribution of set aside fields. The χ^2-test of temporal heterogeneity demonstrated non-randomness for eight growers who employed 15 rotations. The randomisation test of temporal heterogeneity found significant non-randomness for one grower in three of the five crops examined. The common 3-year rotation of oilseed rape, wheat, winter barley was employed by one grower on 10 of their fields, for which significant spatio-temporal heterogeneity was shown by the proposed randomisation test. It is possible to extend the analysis of these test-statistics between – and within – units in a hierarchy, so that the methods could be used to study pattern at larger scales than landscapes, say at regional or national scales.
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1. Introduction

In ecology, there are long-established techniques for the quantification of spatial pattern, both in plant (Diggle, 1983) and animal ecology (Perry et al., 2002). However, there is no such corpus of methodology to detect and measure non-randomness in the allocation of crop types to fields by growers. This paper provides some techniques to measure and test patterns arising from these crop allocations in time and space.

Crops are allocated to their fields by farmers according to rotational principles, within environmental, socio-economic

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and agronomic constraints (Rounsevell et al., 2003). Crop rotations evolve through the aggregate choices of crops by growers over time which create characteristic agricultural landscapes for a given region. We explain below how these choices maximise efficiency and at the same time alter the observed temporal heterogeneity and spatial pattern of cropped landscapes. We present techniques to facilitate the study of these patterns of crops in time and space. For the first time, crop allocation may be quantified through the measurement of the degree of non-randomness and assessed with statistical tests. This is essential in order to build realistic simulators of large-scale cropped landscapes within which farming practices may be studied across national boundaries. The context for this paper is the need to provide realistic arenas to develop current models of gene flow (Colbach et al., 2001a,b, 2005a) from the field to the landscape scale, in furtherance of studies of coexistence between genetically modified and conventional and organic crops.

Coexistence (see SIGMEA, 2006) may involve care in the location of genetically modified crops and the possible need for temporal or spatial separation from other varieties of the same crop type. This separation will affect further the observed temporal heterogeneity and spatial pattern of cropped landscapes.

Several studies have modelled crop allocation by simulating the process of decision making by growers regarding choices of crops (Audsley et al., 1999; Dogliotti et al., 2003; Oxley et al., 2004). Environmental constraints affecting crop choice include water supply (Oxley et al., 2004), climate (Rounsevell et al., 2003), soil properties (Stöckle et al., 2003) and the field mosaic (Thenail and Baudry, 2004). Oxley et al. (2002) considered socio-economic constraints, examples of which are market forces, crop quotas (Wünsch, 2004) and sustainability criteria (DEFRA, 2005). Logistical constraints, which may be more specific to individual growers, can modulate crop choice through field size and access (Thenail and Baudry, 2004), or through location of food processing factories, machinery and labour resources (Rounsevell et al., 2003). For our purposes the simulation of landscapes does not require such mechanistic approaches. Instead, we seek to provide simple, empirical descriptors of cropped landscapes (Colbach et al., 2005b, and see also SIGMEA, 2006).

Crop rotation is one of the oldest agronomic techniques (Chambers and Mingay, 1966; Lawes and Gilbert, 1895). In England, Viscount Charles Townshend popularised the four-field crop rotation of turnips (*Brassica rapa var. rapa*), wheat (*Triticum* spp.), barley (*Hordeum vulgare*) and clover (*Trifolium* spp.), designed to produce fodder for livestock and cereal grain, aid weed control, and maintain soil fertility. Rotations can also prevent the spread of pests and diseases (Kirkegaard et al., 2004), help schedule management tasks evenly through the year (Cook and Weller, 2004), and spread economic risks through crop diversification.

The degree to which growers exercise flexibility within the constraints imposed by rotations varies, both across nations and between growers (Joannon, 2004). A crop rotation may be a fixed, invariable, repeating cycle of crops allocated to a particular field, having a definite period. For example, Townshend's rotation above has a period of 4 years defined by the sequence turnips, wheat, barley, clover in that order, although the starting crop could be any of the four. More usually, while the main rotation is decided in advance, one crop may be interchanged with another that has a similar function (Maxime et al., 1996). For example, the crop 'peas' (*Pisum sativum*) could be substituted for 'clover' after barley in the above rotation, say with equal probability of 0.5. In that case the rotation may be termed a fixed-length stochastic rotation, since the period remains 4 years. If, however, the substitution of the single year of clover was instead 2 successive years of peas, then the rotation would be defined by: turnips, wheat, barley, clover (4-year period) with probability 0.5 and turnips, wheat, barley, peas, peas (5-year period) with probability 0.5. This may be termed a stochastic crop sequence which is cyclical but has no fixed return period. Finally, if any of the above four crops could be followed by any other, with probability 0.25, that could be termed a stochastic crop sequence which is not cyclical and has no return period. Examples of this are seen in extreme situations, such as those pertaining currently in the south-east of England, where economic constraints currently dominate to the extent that rotations can no longer be recognised (Orson, 2005, personal communication) because short-term crop choices dominate decisions, but basic agronomic rules are still followed.

Agronomic constraints usually limit the number of different crop types in a landscape to a relatively small number. However, even within the limited number of rotations available to a given grower, there is still considerable flexibility in the allocation of crops to fields. Firstly, the grower must select what fields should be allocated to what rotation. Secondly, given the rotation and field, the grower must select what phase that rotation is in, i.e. what was referred to above as the starting crop of the sequence. With these two choices a grower may thereby impose non-randomness, in space and time respectively, of the crop types in fields. The resulting spatial pattern, temporal heterogeneity and spatio-temporal heterogeneity (*sensu* Perry et al., 2002) are driven by the decisions made by the grower to improve efficiency.

Landscape ecology typically analyses area-referenced geographic data to study habitats (Gustafson, 1998). However, the usual raster format used in landscape ecology which regards areas as a collection of contiguous grid cells is not helpful for our approach. In this paper we consider a single field to be the base unit and therefore must represent each of these in vector format, as polygons. As Perry et al. (2002) noted, whilst there are many landscape ecological metrics for measuring features such as patch shape, fragmentation and connectivity (Gustafson, 1998; McGarigal, 2002), few studies

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