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Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture

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Abstract

Background: Conventional agriculture is increasingly based on highly specialized, highly productive farms. It has been suggested that 1) this specialization leads to farms that lack resilience to changing market and environmental conditions; and 2) that by decreasing agricultural diversity, the resilience of the farming system also decreases.

Methods: We used agricultural gross margin (GM) forecasts from 1966 to 2010 and remote sensing data from agricultural landscapes in the lowland UK, in conjunction with modern portfolio theory, to test the hypothesis that decreasing land-use diversity results in landscapes that provide higher, but more volatile, economic returns. We considered the role of spatial scale on the expected levels of volatility and resilience of agricultural returns.

Results: We found that: 1) there was a strong linear trade-off between expected GMs and the expected volatility of those GMs in real lowland agricultural landscapes in the UK; 2) land-use diversification was negatively correlated with expected GMs from agriculture, and positively correlated with decreasing expected volatility in GMs; 3) the resilience of agricultural returns was positively correlated with the diversity of agricultural land use, and the resilience of agricultural returns rose quickly with increased land-holding size at small spatial extents, but this effect diminished after landholdings reached 12,000 hectares.

Conclusions: Land-use diversity may have an important role in ensuring resilient agricultural returns in the face of uncertain market and environmental conditions, and land-holding size plays a pivotal role in determining the relationships between resilience and returns at a landscape scale. Creating finer-grained land-use patterns based on pre-existing local land uses may increase the resilience of individual farms, while maintaining aggregate yield across landscapes.

Keywords: Resilience, Agro-diversity index, Agro-ecology, Specialization, Landscape heterogeneity, Land use

Background

During the past 60 years, changes in the agricultural industry have led to a global agrifood system dominated by large, capital-intensive farms [1-3]. These farms are increasingly specialized in terms of the crops they produce, and hence are dependent on inputs from other sectors of the economy [4-6]. This change in agriculture has been driven by the search for increased economic efficiency, economies of scale, and reduced marginal costs of production. However, the homogenization of agriculture may have an unintended drawback, and some evidence suggests that these more specialized farms are also less resilient [7-12] and that they experience increased income volatility [13-15]. Hence, there may be trade-offs between agricultural returns and the resilience of those returns in modern farming systems.

We present the results of an empirical study that used data on forecasted annual average agricultural gross margins (GMs) between 1966 and 2010 and data on land-use diversity (derived from census data and satellite

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imagery) to examine the relationships between landscape units with different levels of agricultural diversity and the amount and volatility of the expected GMs from agriculture that each different landscape unit provided. We examined this relationship at a range of different spatial scales to address two core research questions. We investigated first, whether more specialized landscapes (that is, those with lower land-use diversity) have higher average GMs, and second, whether more specialized landscapes have more volatile returns. In addition, we examined the role of spatial scaling of land-use patterns in real landscapes on these two relationships. Together, these analyses indicate the extent to which, and at what scales, there may be a trade-off between expected GMs and the volatility and resilience of those expected GMs.

Resilience and agricultural systems

The central theoretical concept in this paper is that of 'resilience', derived from systems dynamics thinking, which the literature broadly describes as the tendency of a system to return to its original state following a disturbance. Resilience therefore has a number of properties: the ease with which a system can be disturbed (resistance), the way in which a system returns to its pre-disturbance state (that is, its speed and trajectory), and the propensity for a system to move to an alternative stable state following disturbance [16,17]. Resilience is often interpreted as a measure of either the size of the perturbation required to flip a system into a new dynamically stable state (regime shifts or system identity shifts) [18,19] or the capacity of a system to maintain its current equilibrium state in the face of perturbations [20].

Operationalizing resilience in many empirical situations is complex, thus system behavior typically either needs a systems model or experimental perturbation to assess the way in which the system responds. Both of these factors are difficult to simulate for large-scale, complex systems. In some extreme examples, a regime shift can be identified by very significant changes. Notable examples include the Dust Bowl period of the 1930s in North America, when a prolonged drought rendered millions of hectares of farmland unproductive, and displaced hundreds of thousands of people from their homes [21]; the Ethiopian Famine in the 1980s, when a relatively minor drought triggered a catastrophic famine [22-24]; or the Irish Potato Famine, when the failure of a single crop caused a permanent depopulation of western Ireland [25,26]. Although extremely important, studying such tragedies lends itself to a qualitative case study-based research approach, and are difficult to analyze quantitatively, for a sample of other case studies see [27,28].

Attempts to quantify resilience in the absence of clear regime shifts are hampered by the multi-dimensional nature of the concept, particularly given that the different properties of resilience may be quantified in incommensurable units. As most systems are continually disturbed and fluctuate around a quasi-equilibrium state [20], examining resilience as the relationship between the size of disturbance and the effect of that disturbance [29-31] is perhaps more generally useful. For most applications to agricultural systems not subject to catastrophic change, this element of resilience can be articulated as the stability of agricultural returns in the presence of different exogenous shocks [32]. Agricultural returns are inherently volatile, and change in response to a range of exogenous (for example, disease outbreaks, climate, currency exchange rates, market forces, rapidly changing subsidy systems) and endogenous (for example, crop choice) factors [33,34], with the returns from different agricultural sectors being sensitive to different exogenous drivers of change [35].

One of the key themes deriving from the resilience literature is the hypothesis that agricultural landscapes that are more heterogeneous may also be more resilient in terms of the stability of agricultural returns, as such diverse landscapes should reduce risk (defined in terms of the expected variance in returns [28,36-41]). However, there is potentially an inherent trade-off, in that a diversified strategy reduces volatility at the cost of reduced expected mean returns. The concept of 'bet-hedging' captures this dichotomy; in highly variable systems, strategies that trade off the variance against mean returns can often be superior [42-44]. Hence, in this study, we were interested in determining whether land-use diversity influences the volatility and resilience of the expected GMs in agricultural landscapes.

Land-use diversification has the potential to reduce resilience (expected volatility of GM per unit of expected GM) because the returns generated from an individual land use are dependent on a relatively narrow range of weather conditions and the vagaries of commodity price. Both weather conditions and commodity markets have become increasingly erratic [45,46], causing concerns that farm returns have become less resilient [47]. For example, between 1990 and 2007, the average annual net income of a UK farming enterprise (excluding horticulture) was approximately £23,000; however, this averaged figure hides the significant volatility in these returns over this time period, with the average return ranging from approximately £45,000 in 2002 to just £8,700 in 2000 [48].

In this research, we quantified the volatility of agricultural returns in terms of the expected standard deviation (SD) of GMs and economic resilience (or rather one important aspect of economic resilience) as the coefficient of variation (CV) in expected GM. CV is a normalized measure of dispersion of a probability distribution, which is defined as the ratio of the SD to the mean. In this case, we used the ratio of the expected (mean) GMs to the expected SD of the expected GMs as our measure of resilience. We based this on the assumption that agricultural land-use portfolios (the choice of agricultural land-use investments within a landscape) that provide a lower expected variance to returns ratio would be more resilient. It should be noted that we did not address the resilience of individual farmers, which would require detailed knowledge of the assets, capacities and access to formal and informal institutional support of individual farmers; rather, we sought to investigate the potential role of land-use diversification on the volatility and resilience of returns from agriculture.

We examined this question at a range of different spatial scales (from 25 to 3600 hectares) to investigate the degree to which spatial extent would influence the results.

Modern portfolio theory (MPT) provides analytical tools for investigating the relationships between land-use choices, expected GMs, and the expected variance in those GMs on a landscape scale. MPT was developed in the field of finance in the 1950s, to quantify the optimum level of diversification that would balance risks (the expected variance in returns) and the expected mean return of a given investment portfolio [49]. The key concept in portfolio management is that income streams are additive, whereas risks may partially cancel each other out [49,50]. The logic is that diversification in a portfolio can reduce the risk (or the expected variance) of the portfolio's returns to perturbations, as long as not all possible investments respond in the same way to the same shocks; that is, provided there is not perfect covariance over time in the returns from different agricultural activities. This concept can be applied to agricultural systems by considering the different land-use choices as the individual elements of a portfolio. Therefore, the key to reducing expected variance in returns is for a farmer to select a diversity of land uses that will respond differently to market, institutional, or environmental perturbations. For example, when this concept is applied to an agricultural system of wheat and oats, it is clear that the inputs needed to produce both of these crops are roughly the same (because the crops are of a similar type, namely cereals), and thus the costs of these inputs are likely to increase or decrease by the same amount (this is called a systematic risk). However, the market price of these crops is inversely correlated; wheat prices often increase at the same time as the price of oats decreases (this is called a unique risk) [50]. Thus, by investing in both wheat and oats, the farmer can diversify away the unique risks associated with market-price volatility.

The application of MPT to natural rather than financial assets has, to date, been limited. It has been suggested that the principles of MPT could be transferable to the field of biodiversity conservation [51], and MPT has previously been used to quantify the risk and return profiles of individual farmers in Northern Ireland [52] and to the genetic diversity within cereal crops [53,54]. It has also been suggested that MPT is an appropriate tool for assessing vulnerability of food systems through the diversification of crop production and the basket of food entitlements [38]. However, the application of MPT to agricultural landscape patterns represents a novel approach to operationalizing agricultural ecosystem resilience.

In this study, we used published data for land use and expected average agricultural GM data in conjunction with MPT to analyze the relationships between land-use diversity, expected mean returns for agriculture, and the expected variance and resilience of those returns in three UK lowland agricultural regions. This analysis differs from previous applications of MPT to agricultural land-use investments [52] in that it used real land-use patterns to assess the relationships between expected returns and expected variance of returns for actual land-use portfolios.

Methods

For the study, we first identified three representative lowland agricultural regions in southern England for which we could obtain detailed data on agricultural land cover. We then utilized 353 study sites each 1 km^2 in size, and three, regional sub-extents, each 576 km^2 in size, to explore different aspects of the relationships between land-use diversity and expected agricultural GMs at a various landscape scales within these three different agricultural regions (Figure 1).

We used published satellite-derived land-cover data and livestock estimates to quantify spatially explicit agricultural land-use patterns in each region. To assess diversity, this land-use data was used to calculate a diversity index score for each landscape unit. For assessment of expected agricultural GMs, we used published annual forecasts of expected agricultural GMs to calculate the average GMs (including income from agricultural subsidies) of the farming activities found in each region over the period 1966 to 2010. To assess the relationship between agricultural returns, resilience, and diversity, we used a number of metrics that allowed us to assess the expected mean, SD, and CV of agricultural GMs in these landscapes, using the analytic tools of MPT, and then we related these to land-use diversity.

Study sites

Three lowland regions broadly representative of lowland English agriculture were selected for investigation. Each region represents a different spatial arrangement of agricultural activities. Region 1 (south-west region) is primarily (but far from exclusively) a livestock and dairy farming region. Region 2 (south central region) represents a more

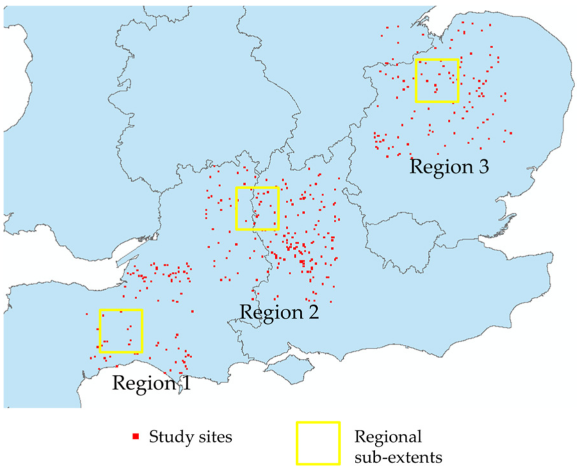

Figure 1 The regions used in the study. The 3 regional sub-extents (576 km^2 each) and 353 individual study sites (1 km^2 each) are indicated.

mixed agricultural landscape, including horticulture, arable, and dairy farming. Region 3 (in eastern England) is dominated by larger expanses of arable farming compared with the other two regions, with increasing concentrations of horticultural production in the northeast corner. Within these three regions, 353 individual sites each 1 km^2 in size (the small red squares in Figure 1) and three regional sub-extents of 576 km^2 each (the yellow squares in Figure 1) were selected for analysis. Using individual study sites allowed us to explore the relationship between landscape diversity, resilience, and agricultural returns between the study regions. Within the regional sub-extents, we analyzed nine portfolio sizes ranging from 25 to 3600 hectares, to reflect the range of farm land holdings typically found in UK lowland agricultural landscapes.

Data used to assess agricultural returns

We found only a single source of data that could provide consistent quantification of returns from UK agricultural activities over a suitable time frame, namely the *John Nix Farm Management Pocketbook*. The John Nix pocketbooks provide forecasts of annual farm GMs per hectare for different agricultural activities for the years 1966–2010 (no pocketbooks were produced for 1970, 1973, 1975, or 1982). The John Nix GM forecasts relate to the average expected margins of individual agricultural activities and not to the expected margins for individual farms. GM is defined as the difference between farm revenue (including subsides) and the associated variable costs for a given activity. Although GM does not include fixed costs and, therefore, is not a perfect measure of agricultural returns [55], it is a widely applied measure within the field of agricultural economics. However, it is important to note that the John Nix GM forecasts represent estimated average returns for England, and thus are likely to underestimate the actual variance in returns for individual landscapes, as they cannot account for variability in yields for a given field. Nevertheless, these data do provide an indicator of the covariance in GM for different land uses over a relatively long period (44 years), and therefore provide an insight into the role of land-use diversification as a means of reducing expected variance in returns.

Data used to assess land use

To identify the land uses in the study regions, we made use of the 2000 *Land Cover Map* (LCM2000) [56], which provides a satellite-based assessment of land cover for all of the UK in the year 2000. For agricultural crops (including hay/silage) the relationships between land cover and land use are clear, and 12 agricultural crops were identified within the LCM2000 land-cover data for which GM data was available (Table 1).

Associating LCM2000 grassland types with the GM data was more difficult, as the LCM2000 data provides only information on land cover and not land use. For example, the LCM2000 reports managed grassland as a land cover; however, this may be used for raising different types of livestock, each of which will have different GMs. There are three primary land uses for lowland grassland: dairy, beef, and sheep production. Therefore, a number of assumptions had to be made in order to attribute GMs from these three land uses to grassland land covers. The LCM2000 data was reclassified as either managed grassland (intensive, managed calcareous, and grazing marsh) and unmanaged grass (rough grass, rough acid grass, unimproved/neutral grass, and calcareous unmanaged grass). Livestock estimates were drawn from the June Agricultural Census (JAC) for the year 2000 to estimate the livestock-based land uses for the LCM2000 grassland data. The JAC provided total livestock numbers for 4 km^2 grid squares. The JAC grid square, within which each of the centroids of the 353 study sites fell, was spatially joined to the study sites using the geographic mapping system ArgGIS [58]. This provided average per head estimates for the three livestock types in each study site. To allow for direct land-use comparisons between the three livestock types, livestock numbers were converted into livestock units (LUs). LUs represent the average land requirements for different livestock types, and we based these on LU conversion factors of 1 for dairy, 0.7 for beef and 0.12 for sheep [59]. The LU ratios for each livestock type (based on LU values and per head estimates) was then used to estimate the proportion of grassland (identified from the LCM2000 data) used by each livestock type for each study site.

Table 1 The assumptions used to select GM estimates[a]

Land use	Assumptions for GM from the pocketbooks
Dairy	Average GM for average stocking rate (two cows per hectare) of Holstein Friesians
Managed grass (beef)	Lowland average GM for average spring and winter calving (single suckling)
Unmanaged grass (beef)	Upland average GM for average spring and winter calving (single suckling)
Sheep	Lowland average GM for average spring and winter calving
Hay, silage	Silage sales minus silage costs
Barley	Average GM for winter barley
Maize	Average GM for fodder maize
Wheat	Average GM for winter-sown wheat
Cereal (spring)	Average GM for spring-sown cereals (wheat, barley, and oats)
Cereal (winter)	Average GM for winter-sown cereals (wheat, barley, and oats)
Field beans, peas	Average GM for winter-sown beans and dried peas
Horticulture	Average GM for carrots, onions, and broad beans
Linseed	Average GM for linseed
Potatoes	Average GM for maincrop potatoes
Oilseed rape	Average GM for winter-sown oilseed rape
Sugar beet	Average GM for sugar beet

Abbreviations: GM, gross margin.
[a]Sources: *John Nix Farm Management Pocketbooks* and the UK Department for the Environment, Food and Rural Affairs [57].

We assumed that managed grassland (70% of the total grassland extent) was used only for dairy and beef production, and that the unmanaged grass was used only for sheep and beef production. In practice, a small proportion of the lowland managed grassland is used for sheep production. However, the JAC data suggested that less than 2% of the grassland in the study regions are given over to sheep production and it is likely that only 10% [60] of this would be on managed grass. Therefore, we assumed that sheep would be confined only to unmanaged grasses. Through this process, four new land-use classes were created: dairy, beef (improved grass), beef (rough grazing), and sheep, for which the GM estimates from John Nix could be applied. Because of the difference in productivity between managed and unmanaged grasslands, the GM estimates for upland beef production were used to value beef on rough grazing, whereas the lowland GM estimates were applied to beef on improved grass. The lowland GM estimates were used for sheep. Table 1 details the final 16 land-use classes valued in the MPT analysis, and the assumptions used to estimate GM for each land use.

The LCM2000 land-cover map and JAC data were used in ArcGIS [58] to identify the agricultural land uses (including estimates of the livestock uses for grasslands) within each study site, and for each landscape in the regional and sub-regional analyses. Fragstats [61] was used to calculate the area covered and the percentage of the total landscape of each agricultural land use for each spatial extent. All land-use estimates were converted to per -hectare measurements when calculating annual expected returns. This allowed direct comparison between landscapes with different agricultural extents.

Evaluating diversity

Shannon's diversity index (H′) [62] was used as the indicator of agricultural landscape diversity. This widely used index was selected because it takes into account both the abundance and the evenness of agricultural land uses present in a given landscape. Moreover, given the discriminatory power of this index, it is a particularly useful measure for comparing diversity between similar landscapes [63]. Shannon's index was calculated as:

$$H^{'} = -\sum_{1=0}^{n} (P_i * lnP_i) \quad (1)$$

where P_i = proportion of the landscape occupied by the land-use patch type *i*.

Analysis: applying modern portfolio theory to explore the relationships between productivity, resilience, and diversity

We used MPT to calculate the expected GMs, expected SD in GMs, and the CV of GMs for different land-use portfolios, where these metrics were assessed based on the inter-annual covariance of the forecast GMs of each land-use type over the analysis period (1966 to 2010). The calculations, all of which are based on the work of Sharpe [50], are detailed below.

The expected rate of return (E) was averaged over all possible outcomes with weights equal to respective probabilities. E_i is the expected rate of return for the ith land cover given by

$$E_i = \sum_{t=1}^{M} P_t R_t \tag{2}$$

where P_t is the probability of the R_t where R is the return on investment for the year t and M is the total number of years over which returns from the land cover are known. As all outcomes are equally likely (one outcome per year) then

$$E_i = \sum_{t=1}^{M} \frac{R_t}{M} \tag{3}$$

under the condition that

$$\sum_{i=1}^{N} X_i = 1 \tag{4}$$

When this condition is met, any given spatial arrangement of land covers within a landscape represents an investment landscape portfolio p. If R_{pj} is the jth return on the portfolio, X_i is the fraction of the landscape invested in land cover i, and N is the number of land-cover investments, then the portfolio return for a given year is

$$P_{pj} = \sum_{i=1}^{N} X_i R_i \tag{5}$$

and the expected return of the land-cover portfolio p is the weighted average (the proportion of the landscape under each land cover) of the sum of the expected returns

$$E_p = \sum_{i=1}^{N} X_i E_i \tag{6}$$

The variance of returns for the ith land cover is, therefore,

$$\sigma_i^2 = \frac{\sum_{t=1}^{m} (R_i - E_i)^2}{m-1} \tag{7}$$

and the variance of the land cover portfolio, p, is the expected value of the squared deviations of the return on the land-cover portfolio from the expected return on the land-cover portfolio. For a portfolio with two investments (*1* and *2*), and given that the expected value of the sum of a series of returns is equal to the sum of the expected value of each return, and the expected value of a constant (percentage of landscape under a land cover) multiplied by a return is equal to the constant times the expected return, we have

$$\sigma_p^2 = X_1^2\sigma_1^2 + 2X_1X_2E_p[(R_1 - E_1)(R_2 - E_2)] + X_2^2\sigma_2^2 \tag{8}$$

The covariance of returns on investments 1 and 2 is given by

$$cov_{12} = E_p[(R_1 - E_1)(R_2 - E_2)] \tag{9}$$

therefore

$$\sigma_p^2 = X_1^2\sigma_1^2 + 2X_1X_2cov_{12} + X_2^2\sigma_2^2 \tag{10}$$

For a land-cover portfolio with N land covers, the variance of the portfolio is, therefore, given by:

$$\sigma_p^2 = \sum\nolimits_{i=1}^{N} \left(X_i^2\sigma_i^2\right) + \sum\nolimits_{i=1}^{N} \sum\nolimits_{j \neq i}^{j=1^N} \left(X_iX_jCov_{ij}\right) \tag{11}$$

The value of E_p and σ_p^2 were calculated for the different landscapes to allow the investigation of the relationships between agricultural land-use diversity, average expected economic GMs, and the relative resilience (that is, the CV) of those margins over time. Here it should be noted that such measures of variance include both the 'upside' and 'downside' variances. Upside variance refers to variations above the mean, whereas where downside variance (or semi-variance) considers only deviation below the mean (in this case, the expected return *Ep*). There is an argument that that only downside variance should be considered, because deviations above the mean are desirable; however, semi-variance is difficult to apply to portfolios and may not be relevant. For instance, in cases where the distribution of returns is symmetric, the evaluation of portfolios based on upside and downside variance will be the same. Therefore, semi-variance was not used here. All GM values were converted to 2010 prices using the UK Treasury's gross domestic product deflator [64].

Results

Historic returns and resilience of individual land uses

The average expected GMs per hectare for each of the agricultural land uses have changed considerably since 1966 (Figure 2). There was a clear pattern of declining average GMs across all land uses, with a particular steep decline in GMs within the period 1972 to 1986. After 1986, the GMs continued to decline, but at a less rapid rate.

Across all land uses, horticulture (including sugar beet and potatoes), and dairy showed the highest expected returns over the analysis period of 1966 to 2010 (Table 2). However, these GMs may be misleading in comparison to the other GMs presented here, owing to the lack of information about the fixed cost of

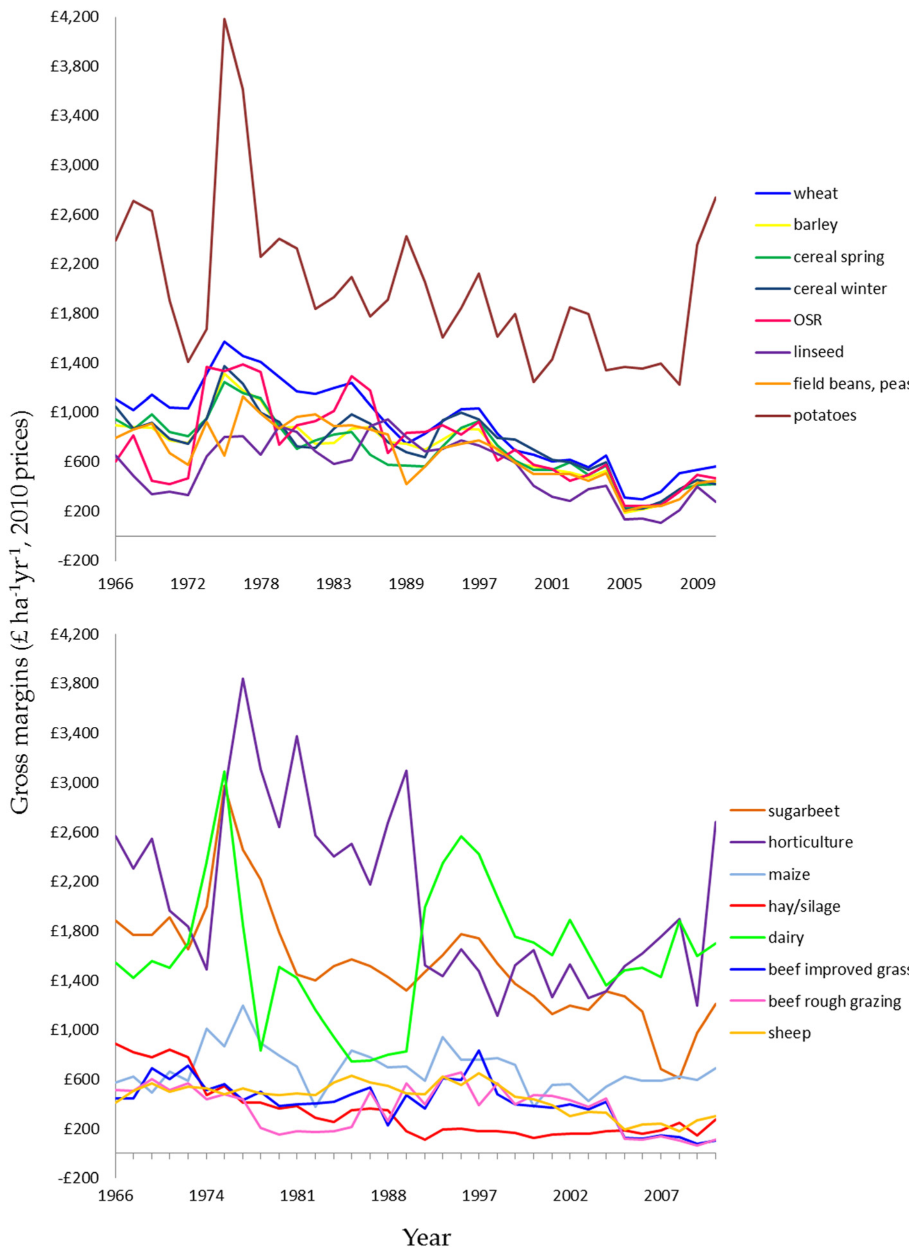

Figure 2 Mean gross margin (GM) values for selected land uses from 1966 to 2010 (in 2010 prices). Data taken from the *John Nix Farm Management Pocketbooks*.

machinery in the estimates, which are likely to be high for these particular land uses. Cereal, oilseed rape, and maize fell into the middle range of expected returns, while livestock farming and hay/silage production had lower than average expected GMs (Table 2). Linseed in particular showed poor economic resilience as measured by the expected variance:return ratios, with the expected SD in GM being 87% of the expected GMs over the 1966 to 2010 period. The data (Table 2, Figure 2) highlight the volatility in individual land-use investments in lowland agricultural landscapes in the UK.

Historic correlations and covariance of land use, gross margins, and resilience

The correlation coefficients (a normalized measure of covariance) are presented (Table 3) as they are easier to interpret than covariance. The covariance structure of these data was the basis for the MPT analysis of expected GMs and expected variance of GMs for the different agricultural land-use portfolios presented below. The forecast GMs from cereal, oilseed crops (linseed and rape), and field beans and peas were found to be closely correlated over the 44 years analyzed in this

Table 2 Descriptive statistics of UK annual average GM per hectare (in 2010 prices)[a,b]

Land use	Proportion of land base across the three study regions, %	Predicted GM, GBP/hectare/year	StDev of predicted annual GMs across analysis period), GBP/hectare/year	CV of GM, %
Wheat	19.2	£909	£338	0.37
Barley	10.3	£716	£260	0.36
Cereal spring	2.3	£703	£258	0.37
Cereal winter	4.8	£755	£268	0.36
Oilseed rape	6.7	£744	£339	0.46
Linseed	5.2	£280	£243	0.87
Field beans, peas	5.6	£668	£244	0.37
Potatoes	3.3	£2,020	£644	0.32
Sugar beet	2.7	£1,209	£462	0.38
Horticulture	1.7	£2,067	£707	0.34
Maize	1.1	£678	£173	0.26
Hay/silage	7.6	£336	£231	0.69
Dairy	10.7	£1,613	£542	0.34
Beef (improved)	9.3	£413	£182	0.44
Beef (rough)	9.2	£361	£180	0.50
Sheep	0.2	£448	£129	0.29
Mean weighted by investment proportion		£815	316	0.44

Abbreviations: CV, coefficient of variation; GM, gross margin; GBP, Great British pounds.
[a]Based on historic forecast GMs for agricultural activities from 1966–2010
[b]Source: *John Nix Farm-Management Pocketbooks.*

study with an average Pearson's correlation coefficient of 0.83 (Table 3). GMs from beef and sheep production were also closely correlated. The weakest correlations were between fodder crops (maize, hay/silage), dairy, and beef, horticulture, and cereal production. Although Table 3 does not provide complete information about the covariance structure through time, it does suggest that landscapes containing a mixture of cereal, livestock, and horticultural land uses were those most likely to have the highest resilience.

Relation between land-use diversity, expected gross margins, and expected variance in gross margins

The relationships between the expected GMs, the expected SD of those GMs, and the landscape diversity for the bundles of land uses found within each of the 1 km^2 study sites (n = 353) were significant (Figure 3). There was a strong linear relationship (r^2 =0.82, P<0.0005) between expected GMs and the expected variance in those GMs (Figure 3a); higher landscape diversity imply lower expected GMs (r^2 = 0.30, P<0.0005) (Figure 3b). Similarly, the expected variance (SD) in GM declined with increased land-use diversity (r^2 = 0.45, P<0.0005) (Figure 3c). The relationship between the CV (coefficient of variation of GMs and variance of GMs) and land-use diversity (Figure 3d) was very weak (r^2 = 0.05, P = 0.02), with high variances in expected GMs in homogenous landscapes balanced by high expected GMs, and low variance in GMs in heterogeneous landscapes counteracted by generally low levels of expected GMs. It should be noted that no attempt to imply direct causation between landscape diversity and resilience is intended, as the resilience of GMs is entirely explained by the historic covariance structure of GM data for the land-use portfolio at each study site rather than by the land-use diversity of the sites *per se.*

Portfolio size, diversity, and the resilience of lowland agricultural landscapes in the UK

To further explore the relationships between land-use diversity, portfolio size, and GMs, we calculated land-use diversity, expected GM, expected SD of GM, and CV of GM using nine different landscape portfolio sizes (the spatial extent over which the land-use portfolio returns were calculated) within the three regional sub-extents. The portfolio sizes ranged from 25 to 3600 hectares, and were designed to capture the range of land-holding size in lowland UK agricultural regions. As with the study site analysis, it can be seen that areas with lower expected GMs (Figure 4a) tended to have lower expected variance in GMs (Figure 4b). The relationship between expected GM, expected SD of GM, and CV (Figure 4c) was less clear. In the region 1 and 2 sub-extents, the lower GMs and variances in GMs tended to

Table 3 Correlation matrix of gross margins from different lowland agricultural land uses (1966 to 2010)

	Wheat	Barley	Cereal (spring)	Cereal (winter)	Oilseed rape	Linseed	Field beans	Potatoes	Sugar beet	Horticulture	Maize	Hay/ silage	Dairy	Beef (improved grass)	Beef (rough grass)
Barley	0.936														
Cereal (spring)	0.9505	0.932													
Cereal (winter)	0.9185	0.9425	0.9506												
Oilseed rape	0.8242	0.8066	0.7424	0.7951											
Linseed	0.7428	0.7732	0.6379	0.7508	0.7526										
Field beans	0.8999	0.8246	0.8326	0.8088	0.7635	0.747									
Potatoes	0.6426	0.606	0.6527	0.6372	0.53	0.492	0.4904								
Sugar beet	0.8655	0.8606	0.9082	0.8792	0.7031	0.596	0.6771	0.7173							
Horticulture	0.6557	0.5542	0.5362	0.4973	0.5218	0.5333	0.6155	0.7038	0.5189						
Maize	0.5836	0.5633	0.5426	0.5924	0.688	0.5578	0.4979	0.4676	0.6092	0.4165					
Hay/silage	0.5348	0.492	0.5732	0.4644	0.1288	0.1015	0.4386	0.3919	0.5394	0.4117	0.1069				
Dairy	0.0976	0.1426	0.2317	0.2339	0.0353	0.0248	−0.089	0.205	0.3094	−0.287	0.2202	−0.05			
Beef (improved grass)	0.6509	0.7132	0.7444	0.727	0.4715	0.4544	0.5685	0.2081	0.6135	0.1202	0.2643	0.421	0.2474		
Beef (rough grass)	0.2294	0.4179	0.3959	0.4754	0.1372	0.2179	0.1739	0.0444	0.3632	−0.166	0.0633	0.3017	0.3172	0.7103	
Sheep	0.7713	0.7692	0.7384	0.798	0.6818	0.7416	0.7971	0.314	0.6103	0.3431	0.4485	0.3141	0.0147	0.8028	0.475

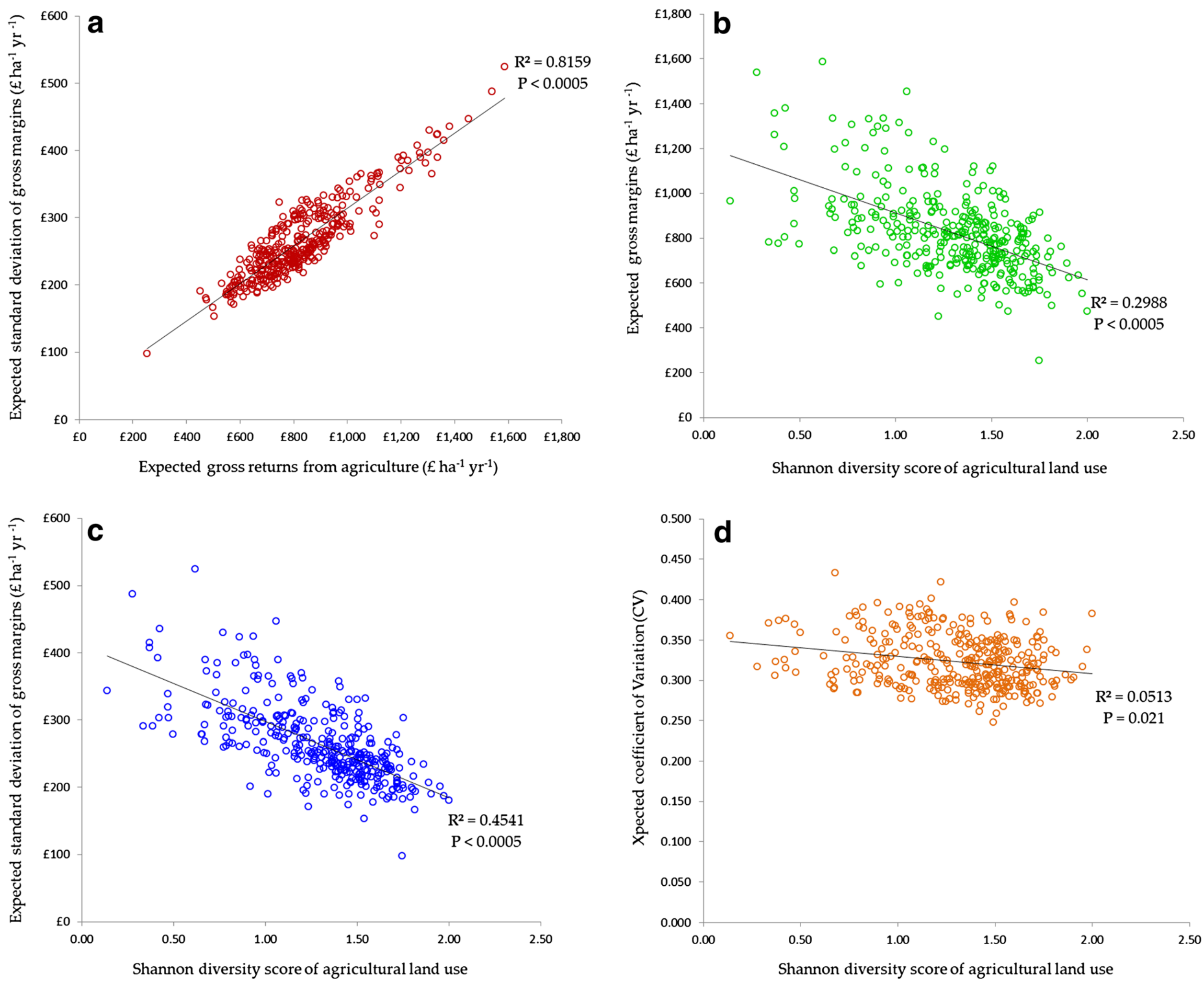

Figure 3 Scatter plots for expected GM, expected standard deviation in expected GM, coefficient of variation (CV) and Shannon diversity for the 1 km^2 study sites (n = 353) shown in Figure 1.

have a higher CV, with higher expected GMs unable to counteract the increased expected variance in GMs. A clear pattern of the relationships between GM, variance, and CV could not be seen in the region 3 sub-extent. However, it can also be seen that as the portfolio size over which the analysis was undertaken increased, there was a general increase in the economic resilience of the portfolios (that is, reduced CV) (Figure 4c), owing to decreasing expected variance in returns (Figure 4b).

The regional sub-extent analysis also showed that as the portfolio spatial extent increased, the diversity of the land uses within each portfolio also increased (Figure 5a), with diversity increasing most rapidly as portfolio size increased from 25 to 400 hectares, but continuing to increase at a slower rate up to the maximum portfolio size (3600 hectares). Agricultural economic resilience increased rapidly (decreasing CV) with increased portfolio size (Figure 5b). From this, we can infer that increased land-use diversity, and, therefore, increased diversification of the investments in each portfolio, results in increased economic resilience, but that there are few gains in resilience beyond a portfolio size of 1200 hectares. By selecting larger portfolios within the fixed sub-extents, it would also be possible to increase the economic resilience for a given portfolio of investments while maintaining the same overall GMs returned across each regional sub-extent.

The expected mean GMs per hectare for the region 1 and 2 sub-extents were similar (GPB£710 and GBP£637/hectare/year, respectively; Figure 5). However, the mean CV across the sub-extents at portfolio sizes beyond 100 hectares was considerably lower in the more mixed agricultural region (sub-extent 2) than in the more heterogeneous livestock dominated region (sub-extent 1). The arable dominated regional sub-extent (region 3) had the highest mean returns per hectare (GBP£1,113/hectare/year) and the highest mean CV at all portfolio sizes

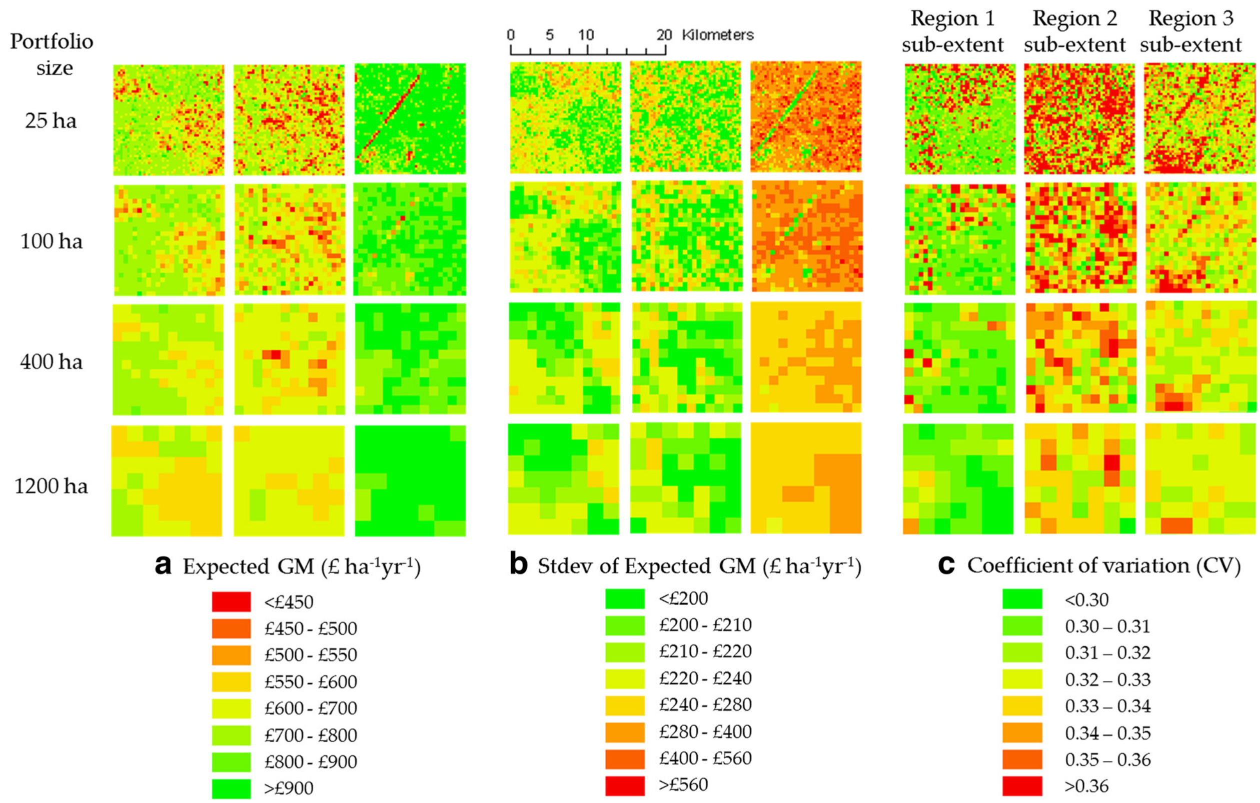

Figure 4 Expected gross margins (GM)s, expected standard deviation in GMs, and coefficient of variation (CV) for the three regional sub-extents shown in Figure 1 for four portfolio sizes.

(Figure 5b). All the regional sub-extents showed similar changes in mean CV with increased portfolio size. As the portfolios increased in size (thus taking in more land-use types), the mean economic resilience of the sub-extents increased (Figure 5b), with the CV dropping by around 5% as the landscape portfolios size increased from 25 to 400 hectares, and a reduction in CV of approximately 7% on average in the move from a portfolio size of 25 hectares to one of 1200 hectares. Beyond 1200 hectares, further increases in landscape portfolio extent made little difference to the mean resilience to returns structure, despite continued increases in portfolio diversity (Figure 5a,b).

It is notable that even small portfolios had CVs that were significantly lower than the weighted mean CV for individual land uses (Table 2), so even small amounts of land-use diversification can increase the resilience of agricultural returns, regardless of scale. A crucial finding here is that small increases in portfolio size dramatically decreased the CV of expected GMs in real lowland agricultural landscapes (suggesting increased economic resilience) and this held true in all three regions, with the majority of these gains occurring in the move from 25-hectare to 800-hectare landscape portfolios. This suggested that increases in diversity in lowland agricultural landscapes is likely to lead to increased economic resilience of those land-use, and that the most homogenous landscapes will benefit most from increased land-use diversity.

Discussion

Agricultural GMs are often used in academic research as indicators of the economic functioning of farm enterprises [65-67] and agricultural landscapes [68,69]. However, as shown in this paper, there are clear and statistically significant trade-offs between high expected GMs and the expected variance of those margins in the face of the constant environmental, economic, and policy perturbations in the real landscape, as studied here. Considering both the expected returns and the expected variance of agricultural returns may therefore provide a more complete understanding of the economic functioning of particular agricultural activities or agricultural landscapes.

This research suggests that one way to increase agricultural resilience would be to increase the diversity of land use within a landscape. This would provide a lower, but more stable, level of expected returns compared with a single land use, which gives high expected returns, but also high expected volatility of returns in the face of exogenous perturbations. The resilience of returns from

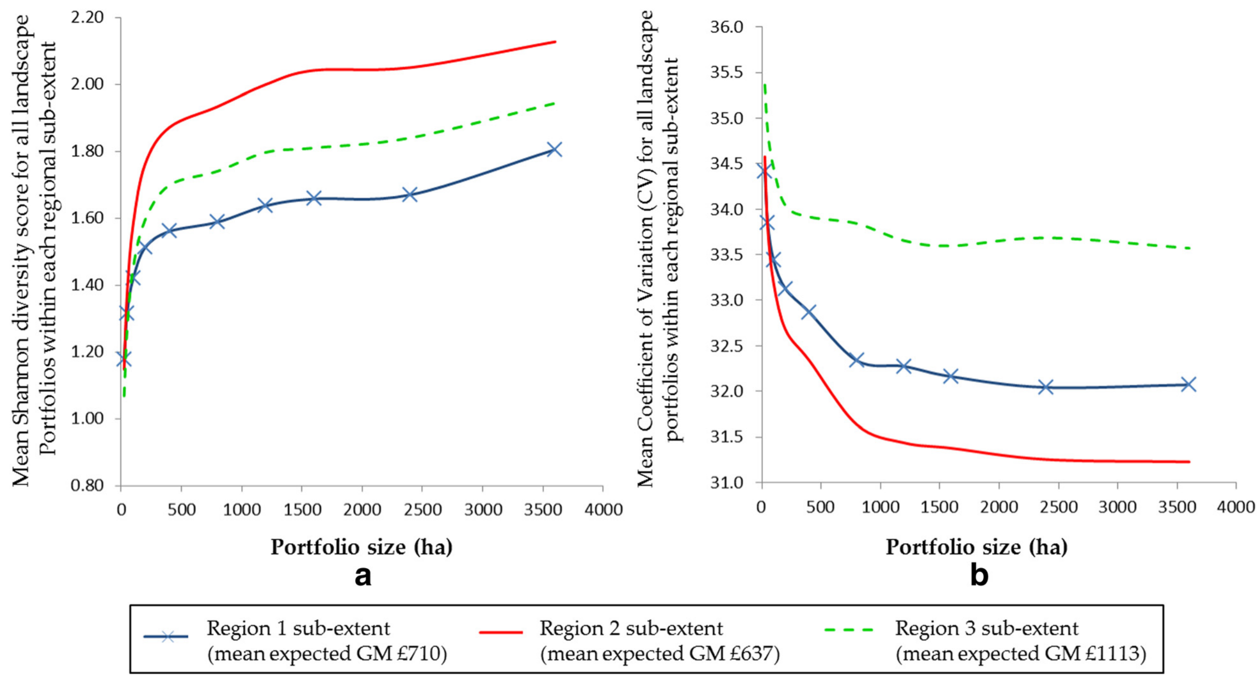

Figure 5 The relationship between landscape portfolio size and (a) land-use diversity and (b) the mean coefficient of variation across the three regional sub-extents.

agriculture is, in part, dependent not only on the agricultural economic resilience of individual land uses, but on the interactions of the expected returns between the different land uses present within any given landscape portfolio. More specifically, a mixture of cereal crops, livestock, dairy, and fodder crops creates a covariant returns structure that lowers the volatility of the aggregate returns, thereby increasing economic resilience across the landscape.

However, caution must be used in the interpretation of these results in terms of the resilience of individual farm enterprises, because the use of generalized estimates of GM is likely to have over-simplified the volatility of agricultural returns at the farm scale. Moreover, many other factors, such as capital assets, individual capacities, adaptive management, and institutional support, all play vital roles in increased agricultural economic resilience [70-72], and these were not assessed in this analysis. Moreover, given the trade-off between expected GM and the expected variance in GM, choices of land-use investments are likely to be determined in part by the risk to returns preferences of individual farmers [15,53]. Nevertheless, these preliminary findings do suggest that, all other things being equal, land-use diversification may provide a means of increasing economic resilience in lowland agricultural landscapes.

Importantly, these findings are not based on theoretical idealized mixture of land uses, but on the pre-existing land use choices in real landscapes. Thus, our findings represent meaningful land-use strategies that are appropriate to the topographic, environmental, and economic contexts of the landscapes in which they occur. Future monitoring of the relationships between agricultural land-use diversification and economic resilience that draw on regional sample surveys of actual, rather than predicted, GMs may help further clarify the relations between land use, incomes, and economic resilience.

One key finding from this paper is the possibility of determining an optimal spatial extent over which the agricultural economic resilience is maximized for UK lowland agricultural landscapes. In real landscapes, increasing the physical size of the portfolio over which returns are estimated increases the mean expected economic resilience (that is, the CV). There were rapid increases in the mean resilience return ratio (as measured by the CV) as portfolios increased in size from 25 hectares (0.25 km^2) to around 400 hectares (4 km^2). Beyond approximately 1,200 hectares (12 km^2), increasing the size of the portfolio had little effect on the portfolio performance.

These findings suggest that if the UK lowland land-use diversity found at the sizes of 1200-hectare or even 400-hectare landscape extents were to be replicated at smaller spatial extents, this would significantly increase the resilience of UK landscapes at scales more closely associated with the average farm holdings of UK farmers (57 hectares). The resilience gains obtained from such an increase in land-use diversity are likely to be greatest in the most homogenous agricultural landscapes. Nevertheless, the benefits of increasing such relatively fine-grained land-use diversity seems to occur in grassland, arable, and mixed-agriculture landscapes. Moreover, the potential benefits of increasing agricultural land-use diversity is not limited to increasing economic resilience of farmed landscapes, but is likely to also provide co-benefits for other important functions of the agricultural landscapes. For example, it has been suggested that habitat heterogeneity is a key component in biodiversity conservation [73,74], that amenity values are positively associated with agricultural landscape diversity [75] and that the provision of cultural ecosystem services are greater in diverse agricultural landscapes [76].

It is necessary to note here that the agricultural GM data are not a perfect measure of economic returns, nor can they account for either the potential losses of economies of scale or the potential synergies that may come through increased moves towards finer-grained agricultural landscapes. Nevertheless, the relationships between land-use diversity and increased agricultural economic resilience that we found in this study are based on a sub-regional finer graining of existing land uses, rather than by the replacement of existing land uses with others that might not be suitable for local climatic or typological conditions. This, in turn, suggests that fine-scale land-use diversity managed at a sub-regional scale that takes advantage of existing local land uses can increase farming resilience without affecting the aggregate yields of agricultural goods produced by those sub-regional landscapes.

Finally, these findings suggest that there may be a role for fine-grained agricultural land-use diversification as a means of increasing the resilience of returns from agriculture. Replicating the existing the land-use diversity found within typical UK lowland agricultural extents of 400 to 1200 hectares at a farm scale would create diversified farming portfolios that might reduce the volatility of farmers' returns. Alternatively, an increase in agricultural economic resilience could potentially be achieved within existing land-use patterns through some form of portfolio sharing or other collective approaches to economic management at landscape scales. This is an area of research that warrants further investigation. In the face of increasingly volatile commodity markets and weather patterns [77], enhancing economic resilience in agricultural landscapes is no longer simply a desirable goal, but an increasingly important requirement of creating sustainable agricultural ecosystems. Article 30 of the recent Common Agricultural Policy (CAP) reform proposals are intended to increase (arable) crop diversification at the farm scale as part of the CAP 'greening' initiative [78]. However, the proposed CAP reforms provide no incentives to diversify the wider matrix of arable, horticultural, and livestock land uses at a landscape scale. The findings presented here provide empirical evidence for the long-standing theory of links between landscape-scale diversity and economic resilience. Landscape approaches to agricultural ecosystem management are increasingly being called for in relation to achieving objectives in conservation [79] and ecosystem services management [80,81]. Although they are exploratory, these results suggest that rural-development policies that include a focus on the co-ordination of land-use management at landscape level may also be beneficial in terms of increasing the economic resilience of lowland agricultural regions.

Agricultural land-use diversification at the landscape scale might be aided by policies that facilitate the sharing of resources, thereby reducing the need for the economies of scale, and the resultant homogenization of landscapes, that are required for the use of modern agricultural machinery. Such co-operation requires the building of trust between farmers [82], and could be assisted by the formation of institutions such as environmental co-operatives that have multiple objectives, such as the maintenance of landscape character and biodiversity or ecosystem service conservation, or the use of collaborative agricultural environment schemes [83].

Conclusions

Our research has produced a number of key findings. First, there is a trade-off between expected mean returns and the volatility of those expected returns, such that specialization in farmscapes is associated with maximizing mean returns, but a higher volatility of those returns. Secondly, land-use diversity is positively correlated with the expected stability of returns, and negatively correlated with expected returns. Thirdly, there is considerable scale dependency in the relationships between land-use diversity and the resilience of agricultural returns. Small spatial extents (less than 400 hectares) in UK lowlands do not currently provide sufficient portfolio diversification to minimize the CV in expected returns of agricultural production.

Perhaps, most importantly, this research suggests that the resilience of agricultural returns within lowland agricultural landscapes could potentially be increased through fine-grain land-use diversification without affecting the aggregate returns or land-use portfolio at the landscape level. Given the current volatility of agricultural returns, it seems reasonable that land-use diversity and volatility or the resilience of agricultural returns should be given greater consideration in research and policy interventions on the socio-economic functions of agricultural ecosystems.

Abbreviations
CV: Coefficient of variation; GBP: Great British pound; GM: Gross margin; JAC: June Agricultural Census; LCM2000: Land Cover Map 2000; LU: Livestock units; MPT: Modern portfolio theory; H′: Shannon's diversity index.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
DJA, EDGF, and TGB participated in the conception and design of the study and the interpretation of the results. DJA acquired the data, and carried out the GIS and MPT analysis. DJA, EDGF, and TGB were involved in the co-ordination and drafting the manuscript. All authors read and approved the final manuscript.

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