What drives long-run biodiversity change? New insights from combining economics, paleoecology and environmental history.

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Abstract

This paper presents a new approach to understanding the effects of economic factors on biodiversity change over the long run. We illustrate this approach by studying the determinants of biodiversity change in upland Scotland from 1600-2000. The measure of biodiversity used is a proxy for plant species diversity, constructed using statistical analysis of paleoecological (pollen) data. We assemble a new data set of historical land use and prices over 11 sites during this 400 year period; this data set also includes information on changes in agricultural technology, climate and land ownership. A panel model is then estimated, which controls for both supply and demand shifts over time. A main result is that prices, which act in our model as a proxy for livestock numbers, do indeed impact on biodiversity, with higher prices leading to lower biodiversity.

Keywords: agricultural development, biodiversity, paleoecology, panel models, instrumental variables.

JEL codes: C33, N53, O13, Q57

1. Introduction

The state of a nation's "biodiversity" has emerged as an increasingly important indicator of environmental health [49]. Biodiversity incorporates the range and abundance of plant and animal species, the interactions between them, and the natural systems that support them [7]. Whilst many measures of biodiversity exist, the number of different species existing in a given area is an important component of most indicators, and this is the concept used in this paper. Biodiversity can be expected to change over time as ecosystems evolve, partly in response to exogenous shocks. What interests us in this paper is quantifying the long-term relationship between biodiversity (derived from pollen data) and the functioning of the economic system: in particular, we focus on agricultural change as a potential driver of biodiversity change.

Threats to biodiversity from human activity are usually thought of by biologists in terms of habitat loss, degradation, and fragmentation; harvesting; and human-induced climate change [33]. Addressing these threats at both the theoretical and empirical level has been an important theme in environmental economics work in the recent past, as evidenced for instance in work on drivers of rainforest loss [9]. But at the empirical level, this work has been limited to looking either at rather recent cross-sectional data (eg species loss by country) or at rather short-duration time series data, typically looking no further back than the 1970s.

The main contribution of this paper is two-fold. First, we set out a new, empirical method for investigating the drivers of biodiversity loss over time, in manner which allows for the relative weights of economic, social and environmental factors to be judged. Second, we assemble and analyze an illustrative data set which allows econometric modeling of one estimate of biodiversity change (using pollen richness as a proxy for plant diversity) as a function of economic development in an agricultural economy over a 400 year period for Scotland. This data set is assembled using inputs from economic history and paleoecology for a sample of upland sites. We estimate a structural model which is based on the dominant ecological theory about what drives plant species change in the uplands of North-West Europe, namely changes in grazing pressure from livestock [5], [34], [44]. Given the lack of historical data on livestock numbers, we illustrate how livestock prices may be used instead of grazing pressure as a determinant of long-term biodiversity impacts. We then test the findings of this main model using a shorter panel with actual livestock densities, albeit at a less precise spatial level.

2. A new approach to modeling biodiversity change over the long run.

Contemporary economic analysis of the determinants of biodiversity change take it as a necessary condition for analysis that a dataset on biodiversity indicators exists, which can be combined with economic (e.g. prices), social (e.g. civil liberty measures) and environmental (e.g. climate) data in an econometric analysis. This, for example, is the basis for the many studies on determinants of rainforest loss summarized in Barbier and Burgess [9]. However, this kind of data on biodiversity is typically rather modern – few time series or cross sections amenable to economic analysis exist pre-20th century. Yet our understanding of the long-term process of biodiversity change would be much enhanced if economists could look back further into the past, rather than relying on short-run time series or cross sectional variation. Moreover, much of the debate on the restoration of habitats and indeed water quality in North America and Europe is based on an ideal of returning systems to “natural conditions” – by which is often meant “pre-anthropogenic” or “pre-industrial” conditions [51]. Understanding the environmental past, and how economic forces have helped shape these processes of change, can enrich our ability to inform contemporary policy debates.

The disciplines of paleoecology and environmental history offer a route to understanding past environmental change. Paleoecology is the science of reconstructing past environments using sources such as pollen records found in lake sediments and peat bogs [29]. By identifying plants from their pollen remains, and dating the sediments in which the pollen occurs, changes in the distribution of vegetation and patterns of land-use around a given site can be reconstructed through time. In our data, these pollen records stretch back to 5500 BP (years before present). Paleoecological analysis has been combined with both archaeological techniques [17], [39] and historical sources [21], [46], [47] to understand the environmental impacts of human land use.

The discipline of environmental history [30], [38] uses a range of sources, primarily written sources, but also ecological and paleoecological data, to understand historic environmental change, and has been increasingly applied in North America and Europe [52], [41]. However, no attempt that the authors are aware of has been previously made to combine paleoecological methods with a quantitative economic analysis of the determinants of land use and land management intensity. This is the approach taken here: we use paleoecological methods to estimate plant diversity over time for a range of sites, and then use historical analysis of documentary sources to construct a database of candidate determinants of changes in the biodiversity measure which are informed by an economic model of land use. Finally, panel data econometric methods are used to examine this combined data-base.

The example we use to illustrate this approach is the use of upland grazing in Scotland, over the period 1600-2000. The measure of biodiversity extracted from the paleoecological record is the standardized number of pollen types observed at each site i in each time period t. Based on current ecological understanding of how grazing pressure from livestock relates to plant diversity at upland sites , we expect that sheep and cattle stocking decisions will impact on this estimate of plant diversity over time. In what follows, we first explain how the database for the case study was created, before detailing the econometric analysis undertaken. In the Conclusions section, we comment on other contexts in which this “new approach” can be applied.

3. Data collection

Virtually all of the data used in this application had to be obtained from primary documentary sources and new paleoecological investigations by the research team. The first requirement was to select the sites to be used for data collection. Sites were intended to represent a range of biogeographical zones in the Scottish uplands, from the hills of the Scottish borders to the northernmost areas on the mainland (note that sites were *not* sampled on the basis of expected biodiversity levels[i]). This was an iterative process, involving identifying sites with historical potential (i.e. sites where there was a reasonable chance of obtaining enough, intact primary documentary sources), alongside fieldwork to seek suitable peat deposits (to obtain intact, undisturbed historic pollen sequences), and then final joint site selection.

The eleven sites eventually selected are shown in Figure One. They include two sites in the Southern Uplands (Greenshiels and Bush of Ewes), four sites in the Central Highlands (Leadour farm and sheiling (the latter known as Ardtalnaig) in Loch Tayside), Corries farm and shieling, in Glen Orchy), four sites in the Northern Highlands (Glenleraig, Ruigh Dorch, Rogart farm and shieling) and one in the Eastern Highlands (Rynuie). The original intention had been to sample pairs of farm and shieling sites: farms being where livestock were kept in winter, shielings being summer grazing sites at higher levels, to which all stock and many farm workers and their families moved for the summer. However, due to lack of suitable peat deposits yielding intact sequences, this did not turn out to be possible. Instead, the sites consist of a mix of shieling and farm areas, sampled across four main parts of the Scottish uplands All sites were predominantly upland livestock farms, with very limited arable cropping potential. Areas which had been, or which are currently, principally woodlands were excluded. Sites vary in altitude: hillside sites such as Ardtalnaig are around 400 metres above sea level; southern upland sites such as Greenshiels and Bush of Ewes are 160 metres and 260 metres high; lower lying sites include Glenleraig, which is 80 metres above sea level. Soils are mostly poor, limiting agricultural potential.

The second need was to construct a time series for a biodiversity index for each of our sites. This was accomplished by focusing on a proxy for plant diversity using a paleoecological technique known as rarefaction [11]. We refer to this measure of "palynological richness" below as B_{it}, the estimated pollen count at site *i* in time period *t.* This involved taking pollen samples from peat cores, dating these using a combination of radiocarbon (^{14}C) and lead-210 techniques (the former for samples pre- mid nineteenth century, the latter for samples post this date), and identifying and quantifying the pollen types present in each peat sequence, thus effectively reconstructing vegetation change through time[ii]. Note that this is an estimate of the number of plant taxa since not all plant species can be distinguished from their pollen remains, whilst the dating of each sample is also an estimate. The pollen analyses also allow us to see how the vegetation composition changed through time at individual sites.

Figures 2 and 3 show example pollen data[iii]. As can be seen, the pollen richness values do not change linearly or monotonically over the time period. Whilst a simple estimate of identifiable plant taxa is a rather limiting measure of biodiversity, note that it is not possible to construct alternative diversity measures such as the Shannon-Weaver, Shannon or Simpson indices from pollen data, as pollen assemblages are influenced by differences in representation (not all plants produce equal amounts of pollen). The pollen signal records vegetation cover within a radius of up to 1 kilometer at our sites, reflecting nearby communities most strongly, and is thus representative of changing vegetation patterns on a scale of fields or hillsides, rather than the broader region represented by many of the historical model variables. This was deliberate as regional-scale pollen sequences (e.g. from large lakes) amalgamate evidence for many plant communities and land-uses, thus introducing many uncertainties to the ecological interpretation of both vegetation patterning and the drivers of change. Furthermore, our case studies include numerous pairs of sites, which reflect spatial and temporal patterns within single farm management units.

The third need was to construct a historical and cross-sectional database of agricultural land management. Cattle and sheep grazing was the dominant agricultural land use at the sites we investigated over the period in question, and we expect impacts on biodiversity to depend on how intensively land was managed - particularly in terms of stocking rates - and what technology was available and utilized (e.g. new breeds of sheep which exert different grazing pressure than older breeds). Few alternative land uses than cattle or sheep production are recorded for our sites: management decisions thus appear to be mainly concerned with how many cattle or sheep to stock at any point in time. A contemporary study of agricultural impacts on upland plant diversity would focus on grazing density, measured in livestock units per hectare (ha). Unfortunately, the records of livestock numbers and the area grazed on individual farms are very patchy, and official data was only collected on this from the 1860s onwards, and then only at a higher level of spatial aggregation, known as the parish. Individual farm estate records typically do not record either the area being grazed or the total number of livestock at individual sites. We thus cannot use a modern grazing intensity measure. Instead, we reconstruct a time series of prices for livestock and crops by region, since we can expect that higher prices of livestock (for meat) and other products (e.g. wool), ceteris paribus, would motivate farmers to increase their herds as a normal supply response. However, we are able to represent technological change directly, by creating count variables for tallying recorded instances of new breeds or new agricultural techniques such as liming, or the introduction of fodder crops at each of our sites (for a perspective on the overall effects of technological change in agriculture during this period – albeit for English data – see

[14])[iv]. Distinct changes in farm management, such as enclosure, are also recorded, whilst we are also able to record the degree of utilization of each site through a typical farming year, from abandonment to summer-only use to year-round cultivation.

The historical data was collected, firstly, from the estate papers (archives of material relating to the landholdings of particular noble families and encompassing a wide range of material generated by, most usually, the owners, their estate officials and lawyers, and, less frequently, their tenant farmers) relating to each site, i.e. Scott of Buccleuch (Bush of Ewes and Greenshiels study sites), Campbells of Glenorchy/Breadalbane (Leadour, Corries), Sutherland (Glenleraig, Rogart), Grant of Freuchy (Rynuie). These are mostly to be found in the National Archives of Scotland in Edinburgh, although some of the Sutherland papers are still held *in situ*. As well as searching for evidence specifically for each site and of the kind of quantitative and qualitative detail necessary for the model (e.g. animal breeds, prices, ownership patterns, changes in land management), we also collected more general material, both spatially (i.e. covering neighboring farms to act as a comparison, corroboration, or fill data gaps) and socially (i.e. material of a more general nature to illuminate the wider estate/regional context within which our sites fitted). Finally, because of the lack of price data at a site-specific level, neighbouring estate papers were also consulted to provide a credible dataset at the regional market level. A timeline of significant external events (e.g. national or significant regional famine, major periods of warfare) was also constructed from secondary sources to act as a wider context for site specific activity.

Prices for livestock (sheep and cattle) were taken from estate papers, as noted above, for the early period, and from secondary sources for later periods. In the early period, these prices often relate to local livestock auctions, and price series were assembled for each region in our analysis. Despite these regional price series being rather patchy and incomplete, they show that regional prices closely tracked each other over the period 1580-1880, although regional price differentials remain. The importance of local market factors in the Highlands relative to national market factors has long been argued for by historians: some evidence can be found, for example, in clearly local supply and demand effects in the period immediately after the Jacobite rising was crushed in 1745, whilst rents were often paid in cattle in the early period [20]. Local supply and demand factors were key to determining regional market prices, and these factors varied across livestock producing regions of the Highlands and Southern Uplands. Transportation of cattle was still by “droving”: that is, walking the cattle from the producing area to a regional market, a distance of over 200 miles in some cases (eg from the Isle of Skye to the cattle “tryst” in Crieff). In the period 1640-1659, average cattle sale prices in Argyll were, across the records we have, 302 Sterling pennies per beast (1 penny = £/240), whilst in Buccleuch the mean price was 192 pennies. More than 100 years later in the period 1780-1799, these kind of price differentials can be seen to persist, with a mean price of 869 pennies in Argyll and 1248 pennies for Loch Tay.

Where a regional price was found in the documentary records for a given site, we use this regional price in the regressions. Where a regional price is missing for a site at a given time period, we used data from the most consistent and well supported source of an alternative region available to us. After 1880, we assume a single national price exists for sheep and for cattle, since regional price variations effectively disappear around this date. Prices for arable crops (which although a minor part of the farms being studied nonetheless provide additional income and direct subsistence) were taken from the “fiars” prices available from 1626-1780 in Gibson and Smout [25]. Later figures for these prices were found in the General Records Office. The arable crop focussed on was that of most relevance to our case study sites, namely bere (an early type of barley). Fiars prices were “declared” by regional sheriff courts each year as “...a just assessment of the prevailing winter price for each type of grain grown and traded”. Their use was as officially-sanctioned prices in settling a range of contracts and bargains. According to Gibson and Smout [26], “comparisons with known transactions prices tend to confirm their reliability”. Whilst regional series exist for these prices, Gibson and Smout [26] argue that regional grain markets were well-integrated by the late seventeenth century.

Finally, information was needed on environmental factors likely to influence biodiversity change. Since no long-term time series on climate is available at even the national level for Scotland, we use English data for precipitation and temperature, which is available for temperature from the period 1641-1660, and for rainfall from 1761-1780. However, an “extreme weather events” dummy variable was also constructed for each site, to represent weather events such as floods or droughts that were unusual enough to be recorded in our historical documents (although in the early period this record is rather fragmentary).

Table 1 summarises the data series available for use in the model.

4. Modeling strategy

Adequate data are not available to conduct either a time-series analysis of drivers of biodiversity change at one site, or a cross-sectional analysis across all sites in a given time period. Instead, we use panel data techniques to allow variability across time to be considered jointly with variability across space. The model we are interested in estimating can be written as:

$$B_{it} = \alpha B_{i,t-1} + bQ_{it} + S_{it}\delta + c_i + u_{it} \tag{4}$$

where B_{it} is our estimate of biodiversity, Q_{it} is a measure of the numbers of livestock which farmers keep and thus the preferred indicator of grazing pressure, S_{it} includes other observed variables that are also thought to affect biodiversity, c_i are site-specific (fixed) effects relating to biodiversity levels (such as soil type and elevation), u_{it} is the idiosyncratic error term and α, b, δ are parameters to be estimated.[v] Our null hypothesis, based on the ecological work cited above, is that increases in *Q* will be associated with declines in *B*. We will also test whether a quadratic relationship exists between *Q* and *B*, namely whether the data shows that increased grazing pressure increases plant diversity up to some turning point (threshold), and then reduces it.

Our estimate of biodiversity is also, however, state dependent. Past vegetation composition and land-use influence current ecology, but the rates at which plants respond to change may differ between species. The ecological argument is thus in favor of including the past pollen diversity estimate as a determinant of the current diversity at a site. We therefore include a lagged term for diversity, $B_{i,t-1}$ as a predictor of B_{it}. We expect higher values for $B_{i,t-1}$ to result in higher values of B_{it}. However, our main interest here lies on the effect of economic variables on biodiversity and primarily on the effect of the variable Q_{it} on biodiversity. As we noted, we cannot directly observe Q_{it}. We would expect, as per Section 1, that higher livestock densities are in general associated with lower levels of plant diversity, although we also allow for other influences which might have caused changes on or in the ground. For instance, we include in S_{it} management variables, such as *sizechange*, *mgtchange* and *mgtinten.* The first of these represents whether farm amalgamations occurred in a time period. We know historically that such amalgamations are sometimes linked to changes in management, particularly in the Improvement period when many landowners deliberately encouraged, or acquiesced in, the transformation of the agricultural landscape from multiple-tenanted “fermetouns” to single-tenant farms as part of a wider revolution in agricultural practices and organisation [19]. *Mgtchange* is a count variable which represents changes such as enclosure and large-scale draining, again associated with the multiple major changes that formed part of the Improvement revolution, but also allowing us to trace the potential effects of small-scale change in other periods. Enclosure is only noted at three of our sites: Abernethy in 1763, Rogart between 1781-1800 and Corries in 1841. Enclosure has been argued to have been responsible for a major increase in Scottish agricultural productivity (eg [18]) but this has been questioned by others, who pinpoint the late 17th and early 19th centuries as being more associated with major increases in output, with output stagnating or even falling during the main period of enclosure (eg see [22], [48]; and, for a similar viewpoint in an English context, [2]). *Mgtinten* represents how much of the year the site was actively managed for agriculture, from abandonment, to summer-only use as a sheiling, to year-round use for grazing. This is an important aspect of the overall history of a site to be taken into account, since almost all experienced such a change at least once during the time period studied (for example, Leadour was abandoned as a farm unit in the 1880s, after being grazed continually since 1580 by the tenant: Rogart changed from summer only use up to 1780 to year-round use, and then was abandoned but still occasionally grazed from 1820). A small literature exists on the effects of site abandonment which led us to wish to examine this factor in the present study [41], [21], whilst the variable also allowed for control over the changing seasonal management of a site noted above.

Finally we included in S_{it} some historical, technological and climatological variables that the interdisciplinary team deemed likely to affect biodiversity. These are *andisease*, *annewbread*, *extrweather* and *extrcivil*. These represent major outbreaks of animal disease (associated with falling stocking densities), the introduction of new breeds (the new type of Cheviot sheep introduced at various times to our sites were much bigger than the native breeds and might be expected, therefore, per head, to have higher grazing demands), extreme weather events that were sufficiently unusual to be recorded as a site-specific supplement to the general climate data, and extreme civil events such as civil war, which might disrupt supply chains, take labour away from farms and cause a complete loss of crops and stock as happened at Corries in the mid-seventeenth century [20]. This variable also picks up national famines, such as occurred in the late 1840s, and outbreaks of bubonic plague, as occurred up to the 1640s, again due to their possible impact on labour supply and thus on the intensity of agricultural activity in what was still a labour-intensive production system. Finally, site fixed effects are included to represent the importance of factors such as soil type and altitude on biodiversity change.

To allow for the likely non-alignment in time of diversity and historical information, dating uncertainties associated with the pollen data, and to handle the relative paucity of historical information on land use change, we decided to construct 20-year “time slices” over the 400-year study period. This time interval was decided on as a compromise between (i) the degree of error in the carbon-14 and lead-210 dating estimates (ii) the desire to have as small a time slice as possible to maximise the number of observations generated for the panel data analysis, and (iii) the gaps in the historical record, especially in the early period, which would have meant the dropping of time observations due to missing data on a finer temporal scale. The model thus analyses change from one twenty-year period to the next. Where multiple responses are available on a variable within a twenty-year period, we simply construct a mean score (for quantitative independent variables) or a count (for discrete independent variables). However, the paucity of historical sources available means we often encounter gaps in even this 20-year averaged data for some variables. Although the aim of pollen analysis was to provide a sample every 20 years, more “observations” are available in recent, near-surface sediments due to the relative lack of compaction and decay in upper peat compared with older, deeper sediments. As this varies between sites, our final dataset is not balanced and we can finally use (taking into account lagged-variables requirements) a total of 119 observations.

Our modeling strategy is as follows. First, we control for the site-specific effects directly by including a dummy for each site. We then turn to the variable Q_{it}. As noted above, we cannot observe the number of animals on each of the sites in each time period; this historical information simply does not exist. We do, however, have census data on the number of livestock for some time periods at the parish level. These data will be used in a validity check on the main model results below. The main disadvantage with using these data is that they are available since 1860 only, so we cannot exploit information on biodiversity for earlier periods; and that they refer to a wider geographic area than a single farm: parishes are collections of farms aggregated together for government farm survey purposes. In our case, they represent the average animal stocking numbers for farms in the neighborhood of our sample sites, and are thus less spatially exact than Q_{it}. To be able to examine the effect of increased grazing on biodiversity for the whole time period, we therefore make use of data on prices of livestock, which represent the local prices faced by land managers at our sample sites.

A typical supply response equation would imply that grazing pressure will increase with the market price of livestock (e.g. for meat), $dQ_{it}/dp_{it} > 0$, since higher prices would encourage farmers to increase production. This suggests that we can use instead of Q_{it} in equation (4) either the price of cattle (denoted as *pcattle* in Table 1) or the price of sheep (denoted as *psheep*). We created a historical regional series for these livestock prices over the period from 1580 to 1880, noting the regional prices closely track each other over this period. After 1880 there is essentially a single national price for sheep and cattle. We expect each individual farmer to treat the market price as exogenous, and to act accordingly, as noted in section 3. In response to a rise in the price of livestock the farmer will want to sell more livestock, and thus will increase the existing herd size on the farm. The result of this supply response, according to (4), should ceteris paribus be a fall in B_{it}**.** However, since the observed prices are endogenous, as equilibrium prices are jointly determined with quantity, this effect is uncertain in our analysis. The main concern with substituting our observed livestock prices *pcattle* and *psheep* for Q_{it} in (4) is therefore that prices are endogenous in this regression, as their effect is not immediately identified as a demand or a supply effect.

If we could assume the existence of a supply equation,

$$Q_{it} = \eta P_t + S_{it}\theta + e_{it} \tag{5}$$

then an increase in prices would result in an increase in the number of animals per ha and hence a decrease in the number of species (a fall in B_{it}). This requires that equation (5) is identified as a supply equation; in this case, we would expect η to be positive in (5). However, the equilibrium prices that we observe historically are most likely an endogenous outcome, determined jointly with quantity. In this case, the effect of prices in (5), and hence in (4) may be affected by reverse causality, and therefore is not identified. In other words, we do not know if, when estimating equation (5), we estimate a supply or a demand function. A demand function would imply a negative η. Hence, endogeneity of prices in (5) implies that we cannot ex ante sign η. If we do not indentify (5) as a supply equation, we should expect a downward bias in our estimate in η. This then implies that the effect of prices in (4) is not indentified.

To make this clear, substitute (5) in (4) to get (note that the supply shifters in (5) are essentially the variables already included as S_{it} in (4)):

$$\begin{aligned} &B_{it} = \alpha B_{i,t-1} + \left(b\eta\right) P_t + S_{it}(\delta + b\theta) + c_i + u_{it} + be_{it}, or \\ &B_{it} = \alpha B_{i,t-1} + \beta P_t + S_{it}\gamma + c_i + v_{it} \\ &where \\ &\beta = b\eta, \gamma = \delta + b\theta, v_{it} = u_{it} + be_{it} \end{aligned} \tag{6}$$

Therefore, α, β, γ are the parameters we can estimate in (6). If P_{it} is correlated with e_{it} in (5), then P_{it} will also be correlated with v_{it} in (6). This implies that if the estimation of (6) does not take into account this type of endogeneity of prices, the downward (simultaneity) bias of η in (5) will result in underestimating β in (6), as it will be biased towards zero.

Our approach to identify the effect of P_{it} in (6) is essentially the method used to identify P_{it} in a supply equation like (5). That is, we use demand shifters that are correlated with prices, but uncorrelated with e_{it} (and hence with v_{it}), as instruments in IV methods to estimate (6). In this way, since P_{it} is identified in (5), we expect η to be positive and thus a negative β will imply a negative b. As demand shifters we use the variables: *pbere*, *garrison*, *union*, *popenglish* and *refrigeration*. All these variables are expected to have affected demand for meat in Scotland. The price of bere (barley) *pbere* is used as the price of a substitute good in consumption (none of our sites engaged in significant grain production, due to their locations). When the price of bere increases, consumers would increase their demand for substitutes, including meat, and hence the demand for cattle and sheep would increase. Regarding *garrison*, it was a feature of the Highlands from the mid-seventeenth century onwards that particular areas had a military garrison installed for considerable periods of time, even beyond periods of civil unrest and actual warfare. This acted as a new and potentially lucrative market for both meat and grain, as well as bringing highland cattle owners into contact with those familiar with the wider English market during the Cromwellian occupation (1650-60) [37]. Our sites were not likely to be equally affected by this aspect.

The *union* variable refers to the impact of the act of incorporating union between the parliaments of England and Scotland, creating the single parliament of Great Britain. The practical aspects of this involved the relaxing of trade barriers between England and Scotland which, prior to then, had operated as two separate countries (as, indeed, they were) with their own restrictive tariffs, mostly on the English side. This removal of trade barriers with England gave additional impetus to the growing market in black cattle particularly, which had begun in the previous century [40]. The variable *popenglish* is included given that we would expect that increased population in England represents increased demand from consumers in England for Scottish livestock exports. Finally, *refrigeration* is expected to have had a negative effect on the demand for Scottish-produced meat, as the advent of refrigerated transport in the 1890s meant that consumers could substitute imported meat from the New World for Scottish meat. Overall, this set of variables were derived from an overview of the historical literature to enable us to ascertain the key issues most likely to have had an effect on demand for livestock production in Scotland. These variables can be thought of as unrelated with either e_{it} or u_{it}, conditioning on the right hand side variables in equations (5) and (6) and can thus be used together with the variables in S_{it} as instruments for the prices. In any case, the validity of the instruments will be tested by over-identification tests. We will also examine the effects of treating prices as exogenous in (6).

The final issue we deal with is the presence of the lagged endogenous variable as a regressor. This implies that (6) will not satisfy the strict exogeneity assumption needed for the fixed effects estimator to be consistent, as v_{it} will be correlated with future realizations of $B_{i,t-1}$.

In such dynamic models, the usual approach is to exploit *sequential* moment restrictions, i.e. the fact that the error term is correlated with leads but not with lags of $B_{i,t-1}$, and use the latter as instruments in IV methods. As the main interest here lies in consistently estimating (primarily) β and (also) γ, we deal with potential biases introduced by $B_{i,t-1}$, by using $B_{i,t-2}$, along with the demand shifters and the variables in S_{it} to instrument $B_{i,t-1}$ (see e.g. [43], for panel data models without the strict exogeneity assumption).

5. Results

We start by presenting the basic results obtained for the whole period, using prices for livestock to estimate equation (6) as described above, within a fixed effects IV panel model. We then discuss the robustness of these basic results by using relative prices, testing for breaks in price endogeneity, and also present results obtained by using parish census livestock data for the period starting from 1860.

5.1 Livestock prices – the main model.

Results from the panel model are presented in Table 2. All regressions include a dummy for each site. The first two columns present results using *pcattle* for P_{it} in (6), and the following two columns we use *psheep* for P_{it}. As the two prices are highly correlated (the correlation coefficient is 0.99) it makes little sense to include them together in the regression. The variables $B_{i,t-1}$, *pcattle* and *psheep* are treated as endogenous and the excluded instruments in these regressions are $B_{i,t-2}$, *popenglish*, *war*, *union*, *refrigeration* and *pbere*.[vi] Columns (1) and (3) presents 2SLS results while columns (2) and (4) report results obtained by Fuller's [24] modified LIML, with a = 1, as it has been found in simulation studies to be more robust to potentially weak instruments (the potential biases due to weak instruments are much smaller with LIML, see [6] and [43].

Before discussing the results, we note that the model does well with respect to the diagnostics for the validity and relevance of the instruments. In particular, we first see that the Sargan over-identifying tests clearly support the null that the instruments are uncorrelated with the structural error term. In addition, the Anderson [4] canonical correlations and the Cragg and Donald [16] tests reject the null of under-identification. To further examine instrument relevance, we report the first stage F-statistics (of the test that the joint effect of the excluded instruments on the endogenous variable is zero in the first stage regression) and Shea's [36] first stage *"partial R-squared"*. Both present strong evidence of high correlation of the instruments with the endogenous variables (especially with prices). The Stock and Yogo [43] tests for weak instruments suggest that the first stage correlations may introduce biases in the 2SLS regressions but not in LIML regressions and thus favour Fuller's LIML estimator. In any case, we do not find important differences between the 2SLS and LIML estimates. Finally, Shapiro and Wilk [35] tests for normality suggest that the residuals from the structural equations are in all regressions normally distributed.

The results show that higher prices for both sheep and cattle imply lower levels of biodiversity over time and across sites. The implication is that the rise in the price in livestock markets for "meat on the hoof" means that the farmer will want to sell more livestock, and thus will want to increase the existing herd size, which in turn results in a loss in plant species diversity. This response seems to "confirm" modern ecological thinking about the likely effects of overgrazing on fragile upland ecosystems. It is interesting to note the implication that increased sheep grazing (as captured by increases in the price of sheep) has been much worse for biodiversity than increased cattle grazing (as captured by increases in the price of cattle) –

although recall that these parameters refer to increases in prices, not increases in animal numbers which are only inferred – we do not know how elastic the supply response was at individual sites, or on average. The only other variable that emerges as significant is the degree to which sites are managed year-round; results show that abandonment of sites reduces biodiversity. Neither technological innovations nor extreme weather events seem to matter to our estimate of biodiversity. Finally, in accord with expectations, it can be seen that higher plant species numbers in preceding periods are associated with higher species numbers in subsequent periods – there is a biological inheritance effect present in the data.

Since most of the variables in S_{it} are not significant, we repeat the regressions in columns (2) and (4) by keeping only *annewbreed* and *mgtinten* to check whether the estimates for the main variables of interest are affected by the inclusion of irrelevant variables (the former variable was retained since there has been considerable interest in the effects of new breeds on biodiversity). The new results are reported in columns (5) and (6). As may be seen, this produced no major changes to the results noted above.

We also have examined what happens when prices are treated as exogenous when estimating equation (6). It turns out that the biases introduced by the correlation of prices with the error term (reverse causality) are of the order of 100%, as both coefficients have half of the values reported in Table 2 (and are not statistically significant), while the estimates for the other coefficients do not differ greatly. As a further exercise to investigate the effect of endogeneity bias in our estimates by treating prices as exogenous, we split the sample into pre- and post- 1880 (by 1880, as discussed above, our working assumption is that markets were well integrated to assume more or less a common price). We would expect endogeneity bias from OLS estimation to be larger in the pre 1880 sub-sample, as local prices would react stronger to local market forces; on the contrary, national prices should be less influenced by shocks in local markets and mainly react to national demand and supply. Indeed, when we re-estimate our model for the two sub-samples and look at the size of the estimated coefficients obtained from 2SLS and OLS estimation, we find that endogeneity bias is clearly high in the pre-1880 period – again, about 100% for the price of cattle and 80% for the price of sheep. In contrast, for the post-1880 period, the 2SLS and OLS estimated coefficients are very close for the price of cattle suggesting no endogeneity in prices, although there is still a difference for the price of sheep (all estimated coefficients, in both sub-samples, using both 2SLS and OLS, are negative). As a remark of caution, we note that we have to treat these results with caution, as they are based on small samples (the degrees of freedom drop to about 55 for the pre-1880 sample and 30 for post-1880), so that estimates are not precise and hence the estimated coefficients are not statistically significant. Nevertheless, they are supportive of the argument that regional prices are likely to be endogenous in our regressions prior to 1880, and that not accounting for this will bias our estimates.[vii]

In addition, we report that we have examined whether including some additional climatological variables affects our results. Variables describing changes in mean annual temperature and rainfall are not significant when they are entered into our regressions and they do not affect the results described above. However, since no long term climatic time series exist for Scotland, we have to use English data for these variables: this may contribute to the lack of statistical significance. Finally, a quadratic relationship between Q and B was tested for: as noted above, this would imply that up to some point, increasing grazing pressure actually increases plant diversity, but that after this turning point or threshold, increased grazing pressure reduces diversity. However, results show that no such effect is revealed in the data presented here, although more detailed site-specific paleoecological anaylsis shows some instances when over short time periods, increased grazing seems to have resulted in increased diversity at some sites.

5.2 Relative prices

As a robustness test, we also examine whether the relative prices of livestock over the price of bere are significant in explaining biodiversity change (*pbere* is used as an instrument for *pcattle* and *psheep* in the previous regressions), since our basis model uses absolute prices. Looking at relative prices implies that we are essentially looking at a proxy for "real" prices when evaluating the price effect on biodiversity.

The results of estimating equation (6) using relative prices are presented in Table 3. This follows the same structure with Table 2, so that the estimation methods used and the tests reported are the same as in Table 2 (except that now *pbere* is not used as an instrument). The main result is that relative prices are negatively related with biodiversity and this effect is in general significant at the 10% level. The tests in Table 3 again support the validity and relevance of our instruments. We also report that treating relative prices as exogenous results in a significant underestimation of the effect of relative prices on biodiversity.

5.3 Livestock numbers

We also able to examine the effect of livestock numbers, using agricultural census data, on biodiversity. There are two drawbacks when using these series, relative to the main model. First, these are available at the parish – and not the specific site – level, so that the number of animals at this larger spatial unit can only be considered as a proxy for the actual livestock number at the site where the pollen data was collected – recall that we use price changes as a proxy for the changes in the number of animals an individual farmer (ie at any of our sites) would want to hold.

For the seven parishes in this data set, the area defined as a parish extends from 10,000 hectares to 59,000 hectares (further information is given in the Appendix). The area defined as "agricultural land" within each parish also varies somewhat over time. Second, these data are available from 1860 onwards only, so that we cannot use the information on biodiversity for earlier periods. Despite these two shortcomings, however, the census data provide useful information, in the form of an additional proxy, that we want to exploit as an alternative test of the hypothesis that higher livestock numbers are related to lower biodiversity over time.

The results are presented in Table 4. Note that the numbers for cattle and sheep (denoted as *cattle* and *sheep* respectively) are naturally treated as exogenous variables in these regressions (obviously, we still have to treat B_{t-1} as an endogenous variable). Note also that some of the additional variables included in the regressions for the whole period have to be dropped here, as there is no variation after 1860. The main result is that higher cattle numbers are significantly related with a decrease in the biodiversity index, while the parameter on *sheep*, although negative, is not statistically significant. Overall, therefore, our analysis suggests that using different proxies for grazing pressure in general associates higher grazing pressure with a decrease in biodiversity; the results being more robust for cattle than for sheep. The parish data in fact shows the biggest changes as being for cattle, rather than for sheep, over the period 1860-2000. The cattle/sheep ratio at the parish level falls up to around 1940 for most parishes, but then rises again up to around 1980, regaining its former levels in most parishes. Parish ratios track each other closely. Consequently, additional grazing pressure from cattle in a system which was, by the 1860s, dominated by sheep, appear to have exacerbated existing grazing impacts, resulting in marked diversity losses.

In addition, we see that in Table 4 more variables are significant in explaining biodiversity change over this later period. An increase in the number of size changes in the farm holding, whether this was an increase in the farm size due to amalgamations, or (much more rarely in the records) a decrease due to the farm holding being split up, is associated with a fall in diversity. Discontinuities in management thus appear to be bad for biodiversity in the data. The introduction of new breeds produces an increase in diversity, whilst the extent to which sites are utilised year-round also affects diversity, in line with results from the main model, as may be seen from the parameter estimate for *mginten*. The number of management changes such as burning, liming or fencing (*mgtchange)* also has a significant effect on diversity in the sheep numbers model. Finally, extreme weather events in this later period seem to be related to plant diversity changes.

6. Conclusions

This paper is part of a series commissioned by Resources for the Future on “Frontiers in Environmental Economics”. In what sense is it “on the frontier”? We think in two ways. First, we present a new methodology for investigating economic influences on biodiversity, which greatly extends the temporal range over which analysis can be undertaken. This method involves a combination of paleoecological methods and environmental historical research with economic reasoning and econometric analysis. Second, we present what we believe to be the first empirical application of this method to a specific context. Empirically, the paper set out to investigate the effects of economic, social and environmental factors on biodiversity over a 400-year period. We constructed a panel of estimates of plant diversity across space and time using pollen analysis, and assembled a dataset of prices, land use change, technological improvements and changes in property rights. Panel regression analysis was then used to explore relationships between the diversity estimate and these economic and social drivers. The main conclusions that emerged were that agricultural prices exerted significant influences on biodiversity over the period 1600-2000, as did the extent to which sites were farmed year-round. However, no significant effects were found for climatic variables, or for extreme civil events, or technology change in the main model estimated over the entire 400 year period. Robustness analysis which relaxed the assumption of endogenous prices, and used relative rather than absolute prices and actual livestock numbers where these are available, seems to confirm our main results for the most part.

Our results might thus be seen as confirming the ecological idea that rising grazing pressures is bad for biodiversity. These findings show that over the long run, human-induced biodiversity change was significant for these sites. While the analytical methods applied here are novel, the results support previous documentary and palaeoecological evidence for some deterioration in the quality or diversity of the UK uplands around 200-300 years ago, particularly post-1850 [17], [41], [42], [46]. That increases in grazing rates can lead to decreases in biodiversity in the uplands is well-recognised in contemporary ecological studies [28], [34], [44], [45]. For example, Fuller and Gough [23] argue that increases in sheep numbers in upland Wales from the 1970s to the 1990s “almost certainly” caused reductions in habitat quality for ground-nesting birds such as waders, partly through the effects on plant cover, leading to a decline in bird numbers. Our findings essentially confirm that this tendency has existed over a much longer time period.

The present evidence that abandonment had significant effects on diversity also supports recent historical inferences [21], [41], although we note that what is actually observed in the data here is that moving from year-round cultivation or grazing, to summer-only use, and then to abandonment for any stocking level, has a negative effect on diversity: this effect is distinct from the effect of the level of grazing pressure. No threshold grazing level effect was found using panel analysis of the data, in the sense that we do not observe implied increases in stocking actually raising plant diversity levels over some range. If one has in mind a concave relationship between diversity and stocking density (the intermediate disturbance hypothesis), then our observations would appear to lie mainly beyond such a turning point – although as we note above, some local instances of short-term increases in diversity due to increases in stocking are noticeable in the detailed paleoecological analysis..

However, perhaps the approach and process behind this research are more interesting than the results. We know of no other similar combination of historical, paleoecological and economic analysis to look at this or similar issues. This approach also has wider ecological implications since the impacts of past grazing and its role as a tool for present biodiversity management remain topics of considerable debate [31], [32]. Despite considerable gaps in the data (due in part to the paucity of historical records in Scotland for the early period), we were able to test whether change in biodiversity has been unidirectional over time, and what effects economic, social and environmental factors had on this. Problems of course exist. The first is simply that of missing information, most importantly perhaps on the number of animals grazed on our sites over time: data on animal numbers was only available at a wider spatial scale and from 1860 onwards. We also note the problems in transforming historical information into a form suitable for quantitative analysis; for example, in terms of changes in farm management. Much detail is lost from the historian in transferring this information into a quantitative form useable in a regression model. The same applies in reducing complex pollen data to a single variable. To the ecologist, our measure of "biodiversity" would cause problems, in that it treats all observable taxa as equal (rather than placing a higher weight on, for instance, native or representative species relative to introduced species), whilst the pollen record cannot always distinguish between plant species.

However, biodiversity, as a measure of ecosystem health also has limitations, so our application is little different in that respect.

Requiring a matching of historical and paleoecological information has also caused difficulties. Where the historical data is relatively rich (e.g. the 17th century) the interval between pollen samples is slightly larger (often >20 years) or the records only begin post-1600, militating against a time series analysis for each site. In other periods, it is primarily the lack of historical data that frustrates the analyst: historians are well-used to dealing with such gaps, but economists typically look for "full and complete" datasets before embarking on econometric research. This requirement would have stymied inter-disciplinary work of this kind if rigorously enforced.

A frontier also has to be capable of being extended. To what extent is the method set out here unique to the circumstance in which it was applied? In fact, the combination of paleoecological, historical, archaeological and economic analysis could be applied in many contexts globally. Pollen sequences are in a sense first-best for this work, since they provide a source of long-term vegetation and land-use histories matched by few other sources. The technique is dependent on the accumulation of sediments under conditions of low biological activity (usually waterlogged and anaerobic, e.g. peat, lake sediments). However, these have been found across the globe at a wide variety of locations, ranging from heathlands, boreal woodlands and tundra to volcanic crater lakes. Alternative sources of information on past biodiversity levels are, however, available to the analyst, where pollen sequences cannot be found. These alternatives include molluscs, phytoliths (plant silica bodies), charred botanical assemblages from archaeological sites, and "packrat" middens. All provide insights into vegetation and/or land-use history in dry or arid environments (e.g. [1], [3], [10], [27]), while inorganic sediments also provide information on past environmental change that can be linked with vegetation and land-use change (e.g. [12], [39]). The scope for application of paleoecology is thus wide. Adding the economic dimension to paleoecology requires a theoretical view on what human or environmental influences drive the system under study, and the ability to construct data sets of those influences that are measurable, such as climate change, prices and technological innovations. For this, the economist needs to work closely with colleagues in history and archaeology. But the gains from analysis seem likely to be great in terms of generating new insights into what drives long-term biodiversity change.

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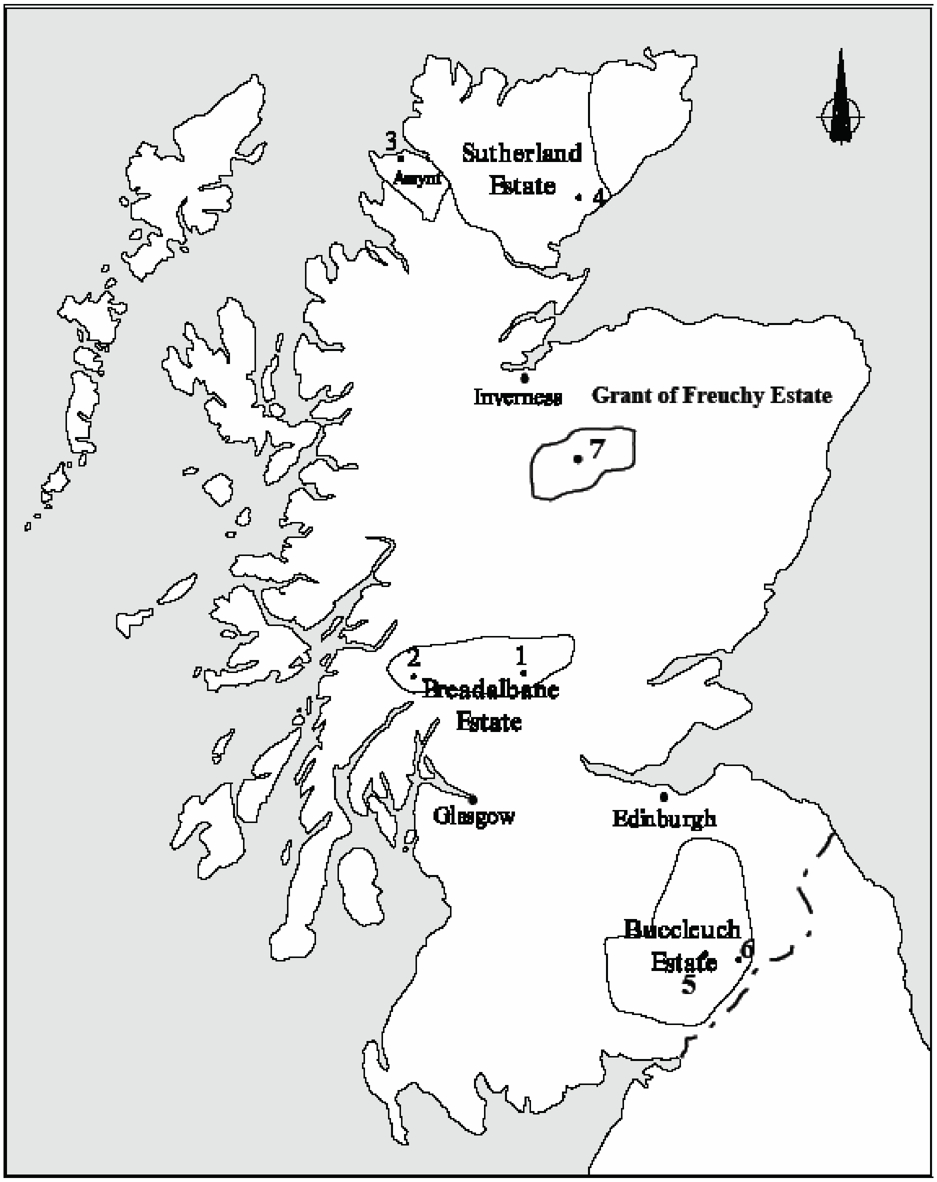

Figure 1. Locations of all sites investigated in project. *Breadalbane Estate*: (1) Leadour farm & shieling, Loch Tay, (2) Corries shieling, Glenorchy; *Sutherland Estate*: (3) Glenleraig farm & shieling, Assynt, (4) Rogart farm & shieling, Sutherland; *Buccleuch Estate*: (5) Bush of Ewes farm, Ewesdale, (6) Greenshiels shieling/farm, Liddesdale; *Grant of Freuchy Estate*: (7) Rynuie farm/shieling, Abernethy.

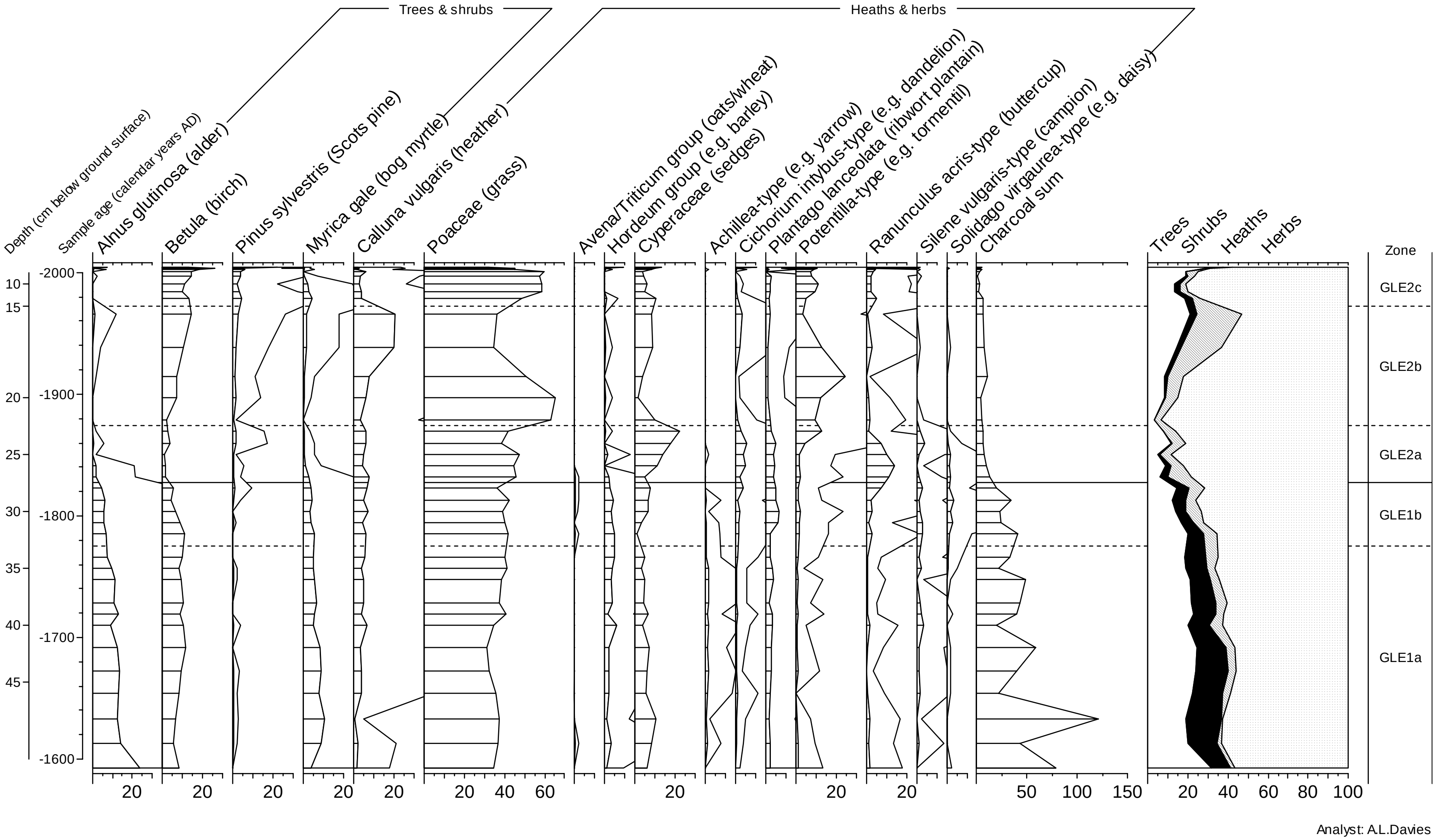

Figure 2. Selected percentage pollen data for Glenleraig farm, Assynt, c.1600 to present. The clear curve shows a x10 exaggeration for clarity. Horizontal lines (zones) depict periods of vegetation change (e.g. GLE1 farm occupation, GLE2a settlement abandonment for intensive sheep grazing, GLE2b-c less grazing), which are also recorded in the diversity analyses (see Figure 3).

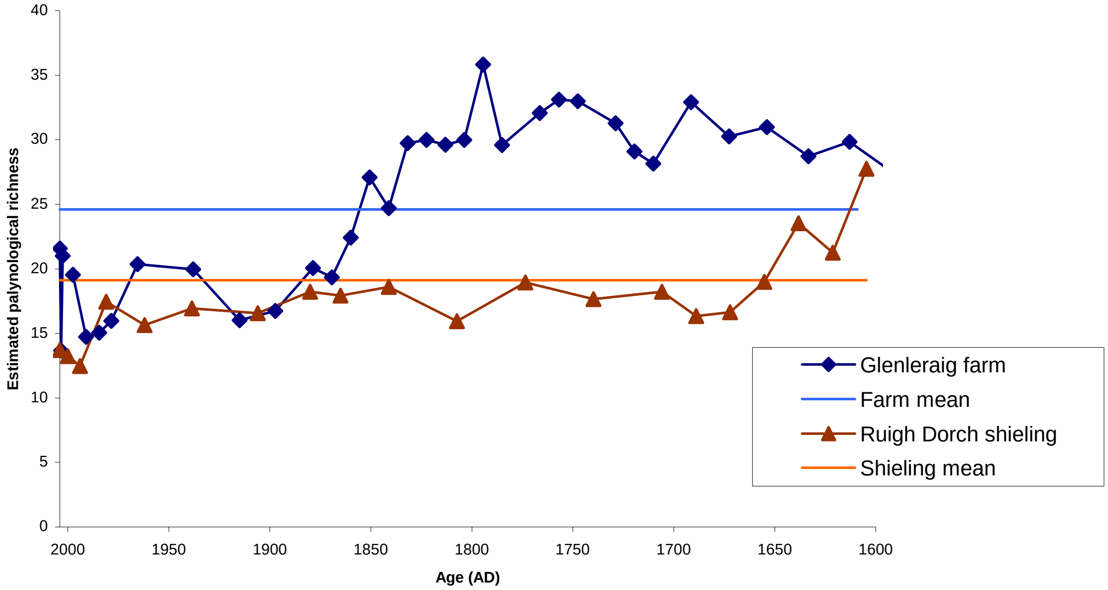

Figure 3: Estimated pollen diversity over time for two sites in Assynt, c.1600 to present.

Table One – Variables in data base

Variable Name, and Acronym if used in main model	Meaning	Main sources	**Type of data**
Dependent Variable:			
Diversity, B_{it}	estimated species count at site *i* in year *t*	Pollen analysis	Continuous
Explanatory Variables:			
Lagged diversity, B_{it-1}	Species diversity estimate in previous 20 year period	Pollen analysis	Continuous
Site management intensity *mginten*	Intensity of use through year (5=year round; 1= abandoned)	Estate records	Categorical
Size change, *sizechange*	Property amalgamation or split	Estate records	Count of occurrences per 20 yr period
Management change, *mgtchange*	Eg enclosures, draining	Estate records	Count of occurrences per 20 year period
Animal issues 1, *andisease*	Disease	Estate records	Yes/no in 20 year period
Animal issues 2, *annewbreed*	New breeds introduced	Estate records	Yes/no in 20 year period
Prices			
Sheep, *psheep*	Regional market price	Estate records; Royal Highland Agricultural Society,	In £/240
Cattle, *pcattle*	Regional market price	Estate records; Royal Highland Agricultural Society	In £/240
Environmental			
Temperature	Mean monthly	English data	Degrees C
Rainfall	total annual	English data	Mm
Extreme weather events, *extrweather*	Storms, floods unusual enough to be recorded.	Estate records	Count during 20 year period
Other			
Extreme civil events, *extrcivil*	War, disease, famine etc	Estate records	Count during 20 year period
Demand Drivers for use as instruments			
Bere (barley) price, *pbere*	Regional market price	Fiars data, estate records	In £/240
garrison	Whether a military garrison was stationed in the area	Historical Fact	Yes/No

union	Act of Union between Scotland and England enacted	Historical Fact	Yes/No
refrigeration	Introduction of refrigerated transport.	Historical Fact	Yes/No
popenglish	Population of England	Pre 1800: expert opinion Post 1800: Census	Count

TABLE 2: The effect of economic activity on biodiversity (livestock prices)

Dep. variable: **_Biodiversity index (B_t)_**	***(1)*** **2SLS**	***(2)*** **Fuller-LIML**	***(3)*** **2SLS**	***(4)*** **Fuller-LIML**	***(5)*** **Fuller-LIML**	***(6)*** **Fuller-LIML**
B_{t-1}	0.571**	0.571**	0.576**	0.576**	0.580**	0.586**
	(3.93)	(3.88)	(3.93)	(3.86)	(3.92)	(3.91)
pcattle	-0.006**	-0.006**	-	-	-0.006**	-
	(-2.16)	(-2.16)			(-2.06)	
psheep	-	-	-0.078**	-0.078**	-	-0.074**
			(-2.07)	(-2.06)		(-1.97)
sizechange	0.599	0.599	0.581	0.581	-	-
	(0.53)	(0.53)	(0.51)	(0.51)		
mgtchange	-0.090	-0.091	-0.075	-0.076	-	-
	(-0.40)	(-0.40)	(-0.33)	(-0.34)		
andisease	-0.615	-0.619	-0.581	-0.583	-	-
	(-0.56)	(-0.56)	(-0.53)	(-0.53)		
annewbread	1.628	1.626	1.638	1.637	1.343	1.374
	(1.15)	(1.15)	(1.15)	(1.15)	(1.09)	(1.11)
mgtinten	0.517**	0.516**	0.506**	0.505**	0.505**	0.494**
	(2.32)	(2.31)	(2.25)	(2.24)	(2.34)	(2.26)
extrweather	-0.228	-0.228	-0.218	-0.219	-	-
	(-0.62)	(-0.62)	(-0.60)	(-0.60)		
extrcivil	-0.093	-0.093	-0.109	-0.109	-	-
	(-0.13)	(-0.13)	(-0.15)	(-0.17)		
constant	7.784**	7.784**	7.738**	7.741**	7.557**	7.502**
	(2.49)	(2.46)	(2.43)	(2.39)	(2.37)	(2.30)

Sargan over-identification test	$\chi^2_{(4)} = 2.509$ (0.643)	$\chi^2_{(4)} = 2.509$ (0.643)	$\chi^2_{(4)} = 2.845$ (0.584)	$\chi^2_{(4)} = 2.840$ (0.584)	$\chi^2_{(4)} = 1.418$ (0.841)	$\chi^2_{(4)} = 1.731$ (0.785)
Anderson canonical correlations	$\chi^2_{(5)} = 38.52$ (0.000)		$\chi^2_{(5)} = 38.07$ (0.000)		$\chi^2_{(5)} = 37.20$ (0.000)	$\chi^2_{(5)} = 36.88$ (0.000)
Cragg-Donald under-identification	$\chi^2_{(5)} = 45.48$ (0.000)		$\chi^2_{(5)} = 44.87$ (0.000)		$\chi^2_{(5)} = 43.67$ (0.000)	$\chi^2_{(5)} = 43.23$ (0.000)
Stock-Yogo weak identification	6.05 (9.48)	6.05 (5.34)	5.97 (9.48)	5.97 (5.34)	6.12 (5.34)	6.05 (5.34)
First-stage F (B_{t-1})	$F(6,95) = 8.99$ (0.000)		$F(6,95) = 8.99$ (0.000)		$F(6,100) = 9.37$ (0.000)	$F(6,100) = 9.37$ (0.000)
First-stage F (*prices*)	$F(6,95) = 115.45$ (0.000)		$F(6,95) = 114.07$ (0.000)		$F(6,100) = 117.3$ (0.000)	$F(6,100) = 116.17$ (0.000)
Shea partial R^2 (B_{t-1})	0.277		0.274		0.269	0.267
Shea partial R^2 (*prices*)	0.672		0.665		0.654	0.648
SW normality test	0.992 (0.751)	0.992 (0.753)	0.992 (0.737)	0.992 (0.740)	0.993 (0.846)	0.993 (0.823)

Notes:1. There are 119 observations. All regressions include dummies for each site. 2. The instruments used are B_{t-2}, popenglish, garrison, union, refrigeration, pbere. 3. t-ratios are shown in parentheses below the estimated coefficients. An asterisk denotes significance at the 10% level and two asterisks at the 5% level. 2. LIML is Fuller's (1977) modified LIML with a=1. 5. The Sargan test is a test of overidentifying restrictions. Under the null, the test statistic is distributed as chi-squared in the number of overidentifying restrictions (the p-value is reported in parenthesis). 6. The Anderson (1984) canonical correlations is a likelihood-ratio test of whether the equation is identified. The Cragg and Donald (1993) test statistic is also a chi-squared test of whether the equation is identified. Under the null of underidentification, the statistics are distributed as chi-squared with degrees of freedom=(L-K+1) where L=number of instruments (included + excluded) and K is the number of regressors (the p-values are reported in parentheses). 7. The Stock and Yogo statistic is used to test for the presence of weak instruments (i.e., that the equation is only weakly identified). The critical value for a 10% bias in 2SLS is reported in parentheses (see Stock and Yogo (2005) for a tabulation of critical values). 8. The 1st stage F-statistic tests the hypothesis that the coefficients on all the excluded instruments are zero in the 1st stage regression of the endogenous regressor on all instruments (the p-value is reported in parenthesis). 9. Shea's (1997) "partial R-squared" is a measure of instrument relevance that takes into account intercorrelations among instruments. 10. The SW is the Shapiro and Wilk (1965) test for normality, for the residuals of the structural equation. The p-value of the test is reported in parentheses.

TABLE 3: The effect of economic activity on biodiversity (relative prices)

Dep. variable: ***Biodiversity index (B_t)***	***(1)*** **2SLS**	***(2)*** **Fuller-LIML**	***(3)*** **2SLS**	***(4)*** **Fuller-LIML**	***(5)*** **Fuller-LIML**	***(6)*** **Fuller-LIML**
B_{t-1}	0.592**	0.592**	0.601**	0.601**	0.607**	0.614**
	(3.96)	(3.95)	(3.95)	(3.93)	(4.08)	(4.05)
pcattle/pbere	-0.002*	-0.002*	-	-	-0.002*	-
	(-1.84)	(-1.84)			(-1.66)	
psheep/pbere	-	-	-0.030*	-0.031*	-	-0.027
			(-1.70)	(-1.70)		(-1.55)
sizechange	0.629	0.629	0.571	0.572	-	-
	(0.56)	(0.56)	(0.50)	(0.50)		
mgtchange	-0.100	-0.100	-0.065	-0.065	-	-
	(-0.45)	(-0.45)	(-0.33)	(-0.29)		
andisease	-0.655	-0.655	-0.571	-0.572	-	-
	(-0.59)	(-0.59)	(-0.51)	(-0.51)		
annewbread	1.601	1.601	1.602	1.602	1.03	1.305
	(1.14)	(1.14)	(1.12)	(1.12)	(0.97)	(1.04)
mgtinten	0.442*	0.442*	0.421*	0.420*	0.447**	0.424*
	(1.90)	(1.90)	(1.74)	(1.73)	(1.98)	(1.79)
extrweather	-0.261	-0.261	-0.249	-0.249	-	-
	(-0.72)	(-0.72)	(-0.68)	(-0.68)		
extrcivil	-0.117	-0.117	-0.157	-0.157	-	-
	(-0.17	(-0.17	(-0.22)	(-0.22)		
constant	7.771**	7.764**	7.727**	7.723**	7.778**	7.729**
	(2.27)	(2.26)	(2.16)	(2.14)	(2.14)	(2.04)

Sargan over-identification test	$\chi^2_{(3)} = 1.408$	$\chi^2_{(3)} = 1.408$	$\chi^2_{(3)} = 1.765$	$\chi^2_{(3)} = 1.765$	$\chi^2_{(3)} = 0.617$	$\chi^2_{(3)} = 0.890$
	(0.703)	(0.710)	(0.632)	(0.622)	(0.892)	(0.827)
Anderson canonical correlations	$\chi^2_{(4)} = 35.74$		$\chi^2_{(4)} = 34.87$		$\chi^2_{(4)} = 35.88$	$\chi^2_{(4)} = 34.79$
	(0.000)		(0.000)		(0.000)	(0.000)
Cragg-Donald under-identification	$\chi^2_{(4)} = 41.69$		$\chi^2_{(4)} = 40.52$		$\chi^2_{(4)} = 41.87$	$\chi^2_{(4)} = 40.41$
	(0.000)		(0.000)		(0.000)	(0.000)
Stock-Yogo weak identification	6.73	6.73	6.54	6.54	7.11	6.86
	(8.78)	(6.07)	(8.78)	(6.07)	(6.07)	(6.07)
First-stage F (B_{t-1})	$F(5,96) = 10.87$		$F(5,96) = 10.87$		$F(5,101) = 11.36$	$F(5,101) = 11.36$
	(0.000)		(0.000)		(0.000)	(0.000)
First-stage F (*prices*)	$F(5,96) = 88.65$		$F(5,96) = 91.75$		$F(5,101) = 93.65$	$F(5,101) = 97.91$
	(0.000)		(0.000)		(0.000)	(0.000)
Shea partial R^2 (B_{t-1})	0.261		0.256		0.261	0.255
Shea partial R^2 (*prices*)	0.593		0.586		0.597	0.588
SW normality test	0.991	0.991	0.992	0.992	0.993	0.993
	(0.721)	(0.721)	(0.737)	(0.748)	(0.821)	(0.823)

Notes:1. There are 119 observations. All regressions include dummies for each site. 2. The instruments used are B_{t-2}, popenglish, garrison, union, refrigeration. 3. t-ratios are shown in parentheses below the estimated coefficients. An asterisk denotes significance at the 10% level and two asterisks at the 5% level. 2. LIML is Fuller's (1977) modified LIML with a=1. 5. The Sargan test is a test of overidentifying restrictions. Under the null, the test statistic is distributed as chi-squared in the number of overidentifying restrictions (the p-value is reported in parenthesis). 6. The Anderson (1984) canonical correlations is a likelihood-ratio test of whether the equation is identified. The Cragg and Donald (1993) test statistic is also a chi-squared test of whether the equation is identified. Under the null of underidentification, the statistics are distributed as chi-squared with degrees of freedom=(L-K+1) where L=number of instruments (included + excluded) and K is the number of regressors (the p-values are reported in parentheses). 7. The Stock and Yogo statistic is used to test for the presence of weak instruments (i.e., that the equation is only weakly identified). The critical value for a 10% bias in 2SLS is reported in parentheses (see Stock and Yogo (2005) for a tabulation of critical values). 8. The 1st stage F-statistic tests the hypothesis that the coefficients on all the excluded instruments are zero in the 1st stage regression of the endogenous regressor on all instruments (the p-value is reported in parenthesis). 9. Shea's (1997) "partial R-squared" is a measure of instrument relevance that takes into account intercorrelations among instruments. 10. The SW is the Shapiro and Wilk (1965) test for normality, for the residuals of the structural equation. The p-value of the test is reported in parentheses.

TABLE 4: The effect of economic activity on biodiversity (livestock numbers).

Dependent variable: **Biodiversity index (B_t)**	***(1)*** ***Cattle numbers***	***(2)*** ***Sheep numbers***
B_{t-1}	0.222	0.428
	(0.72)	(1.62)
cattle	-0.002**	-
	(-2.45)	
sheep	-	-0.0001
		(-1.16)
sizechange	-14.821**	-16.955**
	(-2.62)	(-2.57)
mgtchange	1.498*	2.198* *
	(1.77)	(2.17)
andisease	-0.783	-0.512
	(-0.68)	(-0.37)
annewbread	4.644**	5.208**
	(2.09)	(2.09)
mgtinten	2.930**	2.099*
	(2.41)	(1.79)
extrweather	1.770**	0.963
	(2.03)	(1.19)
constant	13.558**	7.906
	(2.19)	(1.64)

Notes:1. There are 56 observations, starting in 1866. Livestock numbers are taken from the Parish Census of Agriculture. All regressions include dummies for each site. 2. The instrument used for B_{t-1}, is B_{t-2},. 3. t-ratios are shown in parentheses below the estimated coefficients. An asterisk denotes significance at the 10% level and two asterisks at the 5% level.

DATA APPENDIX

Site Data

Site data was gathered for (i) the biodiversity indicator (ii) the variables used in the "full" model reported in Table 2 of the paper and (iii) variables used as instruments in the estimation of Table 2. All of these data are shown below as Table A1, and may be downloaded from:

http://www.economics.stir.ac.uk/People/staff/Hanley/hanley.htm.

The dependent variable is B_{it}, the estimated number of plant species present at site i in time period t , obtained using palynological analysis of pollen remains in peat layers dated using a combination of carbon 14 and lead 210 dating. The diversity estimate was derived by applying rarefaction analysis to each of the pollen sequences [11]. This differs from ecological measures of biodiversity in that it incorporates a measure of both plant diversity and vegetation evenness, bearing in mind that not all pollen types can be identified to species level and that identical diversity values do not necessarily indicate identical plant assemblages.

"Time period" below refers to a 20 year interval. The independent variables are:

pcattle and *psheep*, cattle and sheep prices obtained for each region in which sites are located from entries in estate papers deposited and held in the National Archives of Scotland. Averages were obtained where multiple entries existed for a given site in a given time period. Detailed source files for these data, with GD Numbers, are available from the authors on request.

Sizechange is a count variable on the number of recorded instances when the area of the farm changed, either due to amalgamation with a nearby farm or due to the breaking up of estates. Information was again obtained from estate papers held largely in the National Archives.

Mgtchange is a count variable which represents changes such as enclosure and large-scale draining, again associated with the multiple major changes that formed part of the Improvement period, but also allowing us to trace the potential effects of small-scale change in other periods. Information was again obtained from estate papers held largely in the National Archives.

annewbreed is a dummy variable measuring the introduction, if any, at a given site of a new breed of sheep or cattle. Information was again obtained from estate papers held largely in the National Archives.

andisease is a dummy variable measuring whether a serious disease outbreak was recorded at the site in a given time period. Information was again obtained from estate papers held largely in the National Archives.

Mginten is a categorical variable which records the extent to which the site was used year-round for agriculture by the tenant farmer. A value of 5 means the site was used year-round (eg the grazing paddocks or “in bye” land closest to the farm steading), a value of 4 that the site was a summer shieling, 3 that the site was abandoned by the tenant but still occasionally cropped (a very infrequent event in the data), 2 that the site was abandoned but still occasionally grazed, and 1 that the site was completely abandoned from agricultural use.

Extrweather is a count variable which records how often the site documents discuss an “extreme weather event”, such as a flood, drought or heavy snowfall, during the time period.

Extrcivil is a count variable recording the number of instances of extreme civil events such as civil war or national famines occurred during the period.

Parish Data

Livestock numbers for the regression equation shown in Table 4 are taken from the agricultural census. These come from government surveys of farming in the UK, which were started in Scotland in 1866, and organised at the spatial level of a “parish”. This data collection continues to the present day, now on an annual basis. A first task was to match case study sites to parishes. This showed that sites could be found within 7 parishes: Lorne, Ewes, Abernethy, Kenmore, Castleton, Assynt and Rogart. Parishes were pre-existent administrative designations, the area of which varied considerably, as may be seen from Table A2 below. The County Statistical Accounts of 1834-45 do provide estimates of overall area, but they are rather vague. With the publication of the 1st edition of the Ordinance Survey from 1854 onwards, we have much better estimates of parish area. For some of our study parishes the maps pre-date the start of the agricultural census, but for some the maps are as late as 1883. There were many parish boundary changes made in 1891/92, with only minor changes made thereafter. Later data on areas is taken from the Land Cover 2000 dataset. These areas are reassuringly close to the 1st edition OS areas, with the exception of the parish of Kenmore.

TABLE A2. Areas of relevant Parishes (in hectares)

	1st edition Ordinance Survey, 1854	LC 2000
Glenorchy	**59327**	59344
Ewes	**10091**	10214
Abernethy	**31582**	31479
Kenmore	**27188**	23539
Castleton	**27455**	27075
Assynt	**44911**	44676
Rogart	**26812**	25476

Animal numbers data used in the analysis were as shown in figures A1and A2 below. Please be aware that these data do *not* relate to the case study sites specifically, but instead to the parish as a whole.

FIGURE A1 – CATTLE NUMBERS FROM\PARISH DATA

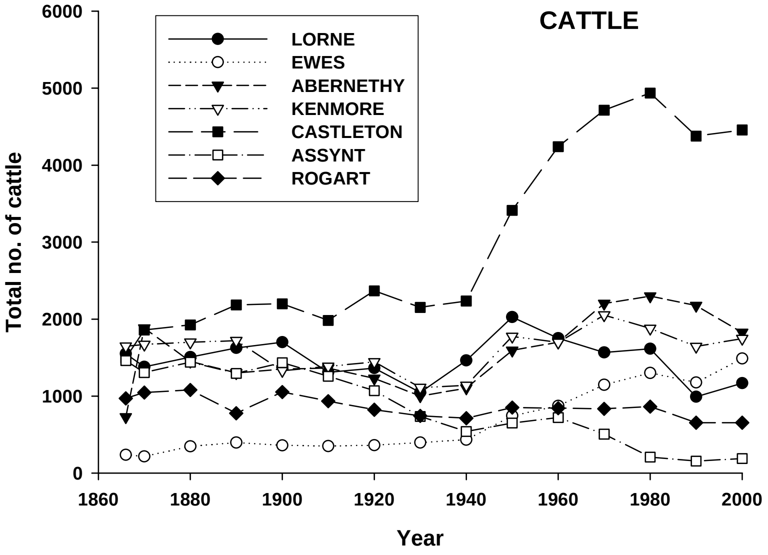

FIGURE A2 – SHEEP NUMBERS FROM PARISH DATA

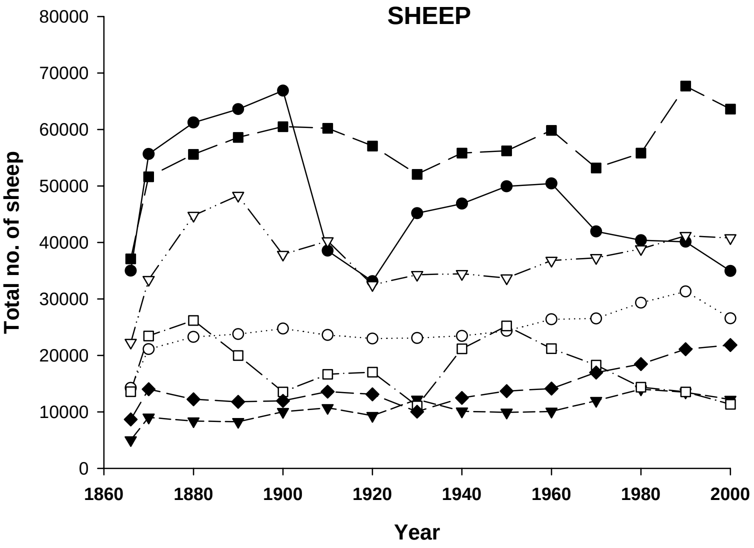

TABLE A1 DATA USED TO ESTIMATE MAIN MODEL

site	t	B_t	psheep	pcattle	mgintern	sizechange	mgtchange	andisease	annewbreed	extrweather	extrcivil	popenglish	garrison	union	refridgeration	pbere	Bt-1
LEDOUR farm	1601-20	23.2488	0.53	1.73	5	0	3	1	0	0	1	5800000	0	0	0	0.072	18.3254
LEDOUR farm	1681-1700	26.5193	0.45	3.07	5	0	1	1	0	0	1	6360000	0	0	0	0.129	26.2395
LEDOUR farm	1761-80	24.5754	1.00	8.92	5	0	1	0	0	0	0	7705333	0	1	0	0.144	23.0672
LEDOUR farm	1781-1800	27.8687	1.59	16.66	5	2	7	0	0	2	1	8006667	0	1	0	0.202	24.5754
LEDOUR farm	1861-80	23.1029	3.96	17.52	5	1	5	0	0	0	0	18776300	0	1	0	0.172	24.758
LEDOUR farm	1881-1900	26.2884	3.70	28.8	2	0	0	0	1	0	0	24402700	0	1	1	0.136	23.1029
LEDOUR farm	1901-20	24.8066	5.16	64.2	2	0	0	0	0	0	0	30515000	1	1	1	0.211	26.2884
LEDOUR farm	1921-40	23.92565	5.69	57.13	2	0	0	0	0	0	0	35230200	0	1	1	0.188	24.8066
LEDOUR farm	1941-60	23.2484	13.61	136.54	2	0	1	0	0	1	0	39200600	1	1	1	0.232	23.92565
LEDOUR farm	1961-80	20.4252	24.09	288.67	2	0	0	0	0	1	0	43983300	0	1	1	0.371	23.2484
LEDOUR farm	1981-2000	22.5428	35.44	405.79	2	0	0	0	0	1	0	46623500	0	1	1	0.4	20.4252
LEDOUR shieling	1661-80	28.0997	0.29	2.67	4	0	0	1	0	0	0	6220000	0	0	0	0.113	29.4514
LEDOUR shieling	1801-20	32.7933	2.05	31.21	4	0	4	0	1	1	1	8308000	1	1	0	0.274	30.0587
CORRIES farm	1901-20	21.02996	5.16	64.2	2	0	0	1	0	0	0	30515000	1	1	1	0.211	25.01977
CORRIES farm	1921-40	23.13118	5.69	57.13	2	0	0	0	0	0	0	35230200	0	1	1	0.188	21.02996
CORRIES farm	1941-60	22.75912	13.61	136.54	2	0	0	0	0	0	0	39200600	1	1	1	0.232	23.13118
CORRIES farm	1961-	20.57	24.09	288.6	2	0	0	0	0	0	0	4398	0	1	1	0.371	22.75

	80	415		7								3300					912
CORRIES farm	1981-2000	22.47836	35.44	405.79	2	0	0	0	0	0	0	46623500	0	1	1	0.4	20.57415
CORRIES shieling	1641-60	23.7948	0.52	2.6	4	0	0	0	0	0	2	6080000	1	0	0	0.125	22.8856
CORRIES shieling	1721-40	20.8593	0.89	3.68	4	0	0	0	0	0	0	6801333	0	1	0	0.114	23.2549
CORRIES shieling	1741-60	23.85265	0.95	8.36	4	0	0	0	0	0	1	7102667	1	1	0	0.115	20.8593
CORRIES shieling	1761-80	21.68905	1.26	8.92	4	0	0	0	0	0	0	7705333	0	1	0	0.144	23.85265
CORRIES shieling	1781-1800	20.0982	1.15	18.55	4	1	0	0	0	0	1	8006667	0	1	0	0.202	21.68905
CORRIES shieling	1801-20	21.35923	2.06	15.06	2	0	0	0	1	1	0	8308000	1	1	0	0.274	20.0982
CORRIES shieling	1821-40	22.13263	4.80	15.33	2	0	0	0	0	2	0	11158000	0	1	0	0.188	21.35923
CORRIES shieling	1841-60	19.91985	2.81	19.3	2	0	7	0	0	1	0	14866000	0	1	0	0.159	22.13263
CORRIES shieling	1861-80	22.4855	3.96	17.52	2	0	1	0	0	0	0	18776300	0	1	0	0.172	19.91985
CORRIES shieling	1881-1900	21.6356	3.70	28.8	2	0	2	0	0	0	0	24402700	0	1	1	0.136	22.4855
CORRIES shieling	1901-20	21.80483	5.16	64.2	2	0	0	1	0	0	0	30515000	1	1	1	0.211	21.6356
CORRIES shieling	1921-40	18.381	5.69	57.13	2	0	0	0	0	0	0	35230200	0	1	1	0.188	21.80483
CORRIES shieling	1941-60	21.4312	13.61	136.54	2	0	0	0	0	0	0	39200600	1	1	1	0.232	18.381
CORRIES shieling	1961-80	20.318	24.09	288.67	2	0	0	0	0	0	0	43983300	0	1	1	0.371	21.4312
CORRIES shieling	1981-2000	17.38305	35.44	405.79	2	0	0	0	0	0	0	46623500	0	1	1	0.4	20.318
ROGART farm	1901-20	30.3315	5.16	64.2	5	0	0	0	0	0	0	30515000	1	1	1	0.211	33.33665
ROGART farm	1921-40	29.28337	5.69	57.13	5	0	0	0	0	0	0	35230200	0	1	1	0.188	30.3315

ROGART farm	1941-60	28.0869	13.61	136.54	3	0	0	0	0	0	0	39200600	1	1	1	0.232	29.28337
ROGART farm	1961-80	22.66846	24.09	288.67	3	0	0	0	0	0	0	43983300	0	1	1	0.371	28.0869
ROGART farm	1981-2000	17.7918	35.44	405.79	3	0	0	0	0	0	0	46623500	0	1	1	0.4	22.66846
ROGART shieling	1681-1700	23.9992	0.43	2.71	4	0	0	0	0	0	0	6360000	0	0	0	0.129	18.5275
ROGART shieling	1701-20	18.6076	0.30	3.23	4	0	0	0	0	0	0	6500000	0	1	0	0.112	23.9992
ROGART shieling	1781-1800	19.19165	1.93	17.29	5	0	0	0	0	2	1	8006667	0	1	0	0.202	20.97153
ROGART shieling	1801-20	19.63025	2.74	15.06	5	1	6	0	1	3	2	8308000	1	1	0	0.274	19.19165
ROGART shieling	1821-40	21.2048	2.71	15.33	2	0	3	0	0	0	1	11158000	0	1	0	0.188	19.63025
ROGART shieling	1841-60	20.6413	2.81	19.3	2	0	3	0	0	0	0	14866000	0	1	0	0.159	21.2048
ROGART shieling	1861-80	21.6687	2.70	17.52	2	0	1	0	0	2	0	18776300	0	1	0	0.172	20.6413
ROGART shieling	1881-1900	18.4499	3.70	28.8	2	0	0	0	0	0	0	24402700	0	1	1	0.136	21.6687
ROGART shieling	1901-20	18.0177	5.16	64.2	2	0	0	0	0	0	0	30515000	1	1	1	0.211	18.4499
ROGART shieling	1921-40	16.59492	5.69	57.13	2	0	0	0	0	0	0	35230200	0	1	1	0.188	18.0177
ROGART shieling	1941-60	15.01605	13.61	136.54	2	0	0	0	0	0	0	39200600	1	1	1	0.232	16.59492
ROGART shieling	1961-80	13.9522	24.09	288.67	2	0	0	0	0	0	0	43983300	0	1	1	0.371	15.01605
ROGART shieling	1981-2000	15.72453	35.44	405.79	2	0	0	0	0	0	0	46623500	0	1	1	0.4	13.9522
GLENLERAIG farm	1641-60	30.9723	0.40	2.39	5	0	0	0	0	0	0	6080000	1	0	0	0.125	28.7078
GLENLERAIG farm	1661-80	30.2449	0.29	2.65	5	0	0	0	0	0	0	6220000	0	0	0	0.113	30.9723
GLENLERAIG farm	1681-	32.91	0.43	2.71	5	0	0	0	0	0	0	6360	0	0	0	0.129	30.24

	1700	22										000					49
GLENLERAIG farm	1701-20	28.6104	0.30	3.23	5	0	0	0	0	0	0	6500000	0	1	0	0.112	32.9122
GLENLERAIG farm	1721-40	31.2644	0.89	3.33	5	0	0	0	0	0	0	6801333	0	1	0	0.114	28.6104
GLENLERAIG farm	1741-60	33.0514	0.33	8.8	5	0	0	0	0	0	0	7102667	1	1	0	0.115	31.2644
GLENLERAIG farm	1761-80	32.0617	1.00	12	5	0	0	0	0	3	0	7705333	0	1	0	0.144	33.0514
GLENLERAIG farm	1781-1800	32.71505	1.93	17.29	5	0	0	0	0	2	1	8006667	0	1	0	0.202	32.0617
GLENLERAIG farm	1801-20	29.7962	2.74	15.06	2	1	7	0	1	3	2	8308000	1	1	0	0.274	32.71505
GLENLERAIG farm	1821-40	29.8603	2.71	15.33	2	0	1	0	0	0	1	11158000	0	1	0	0.188	29.7962
GLENLERAIG farm	1841-60	24.72877	2.81	19.3	2	0	3	0	0	0	0	14866000	0	1	0	0.159	29.8603
GLENLERAIG farm	1861-80	19.70745	2.70	17.52	2	0	0	0	0	2	0	18776300	0	1	0	0.172	24.72877
GLENLERAIG farm	1881-1900	16.7338	1.74	28.8	2	0	0	0	0	0	0	24402700	0	1	1	0.136	19.70745
GLENLERAIG farm	1901-20	16.0262	3.27	64.2	2	0	0	0	0	0	0	30515000	1	1	1	0.211	16.7338
GLENLERAIG farm	1921-40	19.958	5.69	57.13	2	0	0	0	0	0	0	35230200	0	1	1	0.188	16.0262
GLENLERAIG shieling	1641-60	19.008	0.40	2.39	4	0	0	0	0	0	0	6080000	1	0	0	0.125	22.3963
GLENLERAIG shieling	1661-80	16.6408	0.29	2.65	4	0	0	0	0	0	0	6220000	0	0	0	0.113	19.008
GLENLERAIG shieling	1681-1700	16.3367	0.43	2.71	4	0	0	0	0	0	0	6360000	0	0	0	0.129	16.6408
GLENLERAIG shieling	1701-20	18.2249	0.30	3.23	4	0	0	0	0	0	0	6500000	0	1	0	0.112	16.3367
GLENLERAIG shieling	1721-40	17.6575	0.89	3.33	4	0	0	0	0	0	0	6801333	0	1	0	0.114	18.2249
Bush of Ewes farm	1681-1700	23.7159	0.43	4.00	5	0	0	0	0	2	1	6360000	0	0	0	0.129	25.62775

Bush of Ewes farm	1701-20	21.7322	0.29	7.33	5	0	0	0	0	1	0	6500000	0	1	0	0.112	23.7159
Bush of Ewes farm	1721-40	27.5164	0.89	3.68	5	0	0	0	0	0	0	6801333	0	1	0	0.114	21.7322
Bush of Ewes farm	1741-60	27.068	1.20	8.36	5	0	1	0	0	0	0	7102667	1	1	0	0.115	27.5164
Bush of Ewes farm	1761-80	25.6885	1.00	8.92	5	0	2	0	0	0	0	7705333	0	1	0	0.144	27.068
Bush of Ewes farm	1781-1800	26.7481	2.01	18.55	5	0	0	0	0	2	0	8006667	0	1	0	0.202	25.6885
Bush of Ewes farm	1801-20	23.20355	3.41	15.06	5	0	0	0	0	0	0	8308000	1	1	0	0.274	26.7481
Bush of Ewes farm	1821-40	21.8878	2.81	16.31	5	0	2	0	0	0	0	11158000	0	1	0	0.188	23.20355
Bush of Ewes farm	1841-60	22.5915	2.64	19.94	5	0	0	0	0	0	0	14866000	0	1	0	0.159	21.8878
Bush of Ewes farm	1861-80	22.4913	3.96	17.52	5	0	0	1	0	0	0	18776300	0	1	0	0.172	22.5915
Bush of Ewes farm	1881-1900	27.5036	3.70	28.8	5	0	0	0	0	0	0	24402700	0	1	1	0.136	22.4913
Bush of Ewes farm	1901-20	20.9361	5.16	64.2	5	0	0	0	0	0	0	30515000	1	1	1	0.211	27.5036
Bush of Ewes farm	1921-40	24.3837	5.69	57.13	5	0	1	0	0	0	0	35230200	0	1	1	0.188	20.9361
Bush of Ewes farm	1941-60	22.80253	13.61	136.54	5	0	0	0	0	0	0	39200600	1	1	1	0.232	24.3837
Bush of Ewes farm	1961-80	22.84843	24.09	288.67	5	0	0	0	0	0	0	43983300	0	1	1	0.371	22.80253
Bush of Ewes farm	1981-2000	23.97993	35.44	405.79	5	0	0	0	0	0	0	46623500	0	1	1	0.4	22.84843
Greenshiels farm	1661-80	18.6564	0.29	2.65	5	0	0	0	0	1	0	6220000	0	0	0	0.113	24.1031
Greenshiels farm	1681-1700	15.2499	0.43	4.00	5	0	0	0	0	2	1	6360000	0	0	0	0.129	18.6564
Greenshiels farm	1701-20	16.746	0.29	7.33	5	0	0	0	0	1	0	6500000	0	1	0	0.112	15.2499
Greenshiels farm	1721-	26.63	0.89	3.68	5	0	0	0	0	0	0	6801	0	1	0	0.114	16.74

	40	3										333					6
Greenshiels farm	1741-60	26.1546	1.20	8.36	5	0	1	0	0	0	0	7102667	1	1	0	0.115	26.633
Greenshiels farm	1761-80	20.7191	1.00	8.92	5	0	0	0	0	0	0	7705333	0	1	0	0.144	26.1546
Greenshiels farm	1781-1800	21.26613	2.01	18.55	5	0	0	0	0	2	0	8006667	0	1	0	0.202	20.7191
Greenshiels farm	1801-20	21.79685	3.41	15.06	5	0	0	0	0	0	0	8308000	1	1	0	0.274	21.26613
Greenshiels farm	1821-40	20.96185	2.81	16.31	5	0	2	0	0	0	1	11158000	0	1	0	0.188	21.79685
Greenshiels farm	1841-60	25.98825	2.64	19.94	2	1	0	0	0	0	0	14866000	0	1	0	0.159	20.96185
Greenshiels farm	1861-80	24.74173	3.96	17.52	2	0	0	1	0	0	0	18776300	0	1	0	0.172	25.98825
Greenshiels farm	1881-1900	26.8394	3.70	28.8	2	0	0	0	0	0	0	24402700	0	1	1	0.136	24.74173
Greenshiels farm	1901-20	26.6845	5.16	64.2	2	0	0	0	0	0	0	30515000	1	1	1	0.211	26.8394
Greenshiels farm	1921-40	22.5252	5.69	57.13	2	0	0	0	0	0	0	35230200	0	1	1	0.188	26.6845
Greenshiels farm	1941-60	16.2204	13.61	136.54	2	0	0	0	0	0	0	39200600	1	1	1	0.232	22.5252
Greenshiels farm	1961-80	16.2556	24.09	288.67	2	0	0	0	0	0	0	43983300	0	1	1	0.371	16.2204
Greenshiels farm	1981-2000	16.2388	35.44	405.79	2	0	0	0	0	0	0	46623500	0	1	1	0.4	16.2556
Rhynuie shieling	1641-60	20.8471	0.40	2.39	5	0	0	0	0	0	0	6080000	1	0	0	0.125	22.5766
Rhynuie shieling	1661-80	26.1219	0.29	2.65	5	0	1	0	0	0	0	6220000	0	0	0	0.113	20.8471
Rhynuie shieling	1681-1700	26.0372	0.43	2.71	5	0	0	0	0	0	0	6360000	0	0	0	0.129	26.1219
Rhynuie shieling	1701-20	26.4875	0.3	3.23	5	0	0	0	0	0	0	6500000	0	1	0	0.112	26.0372
Rhynuie shieling	1721-40	23.669	0.89	3.33	5	0	1	0	0	0	0	6801333	0	1	0	0.114	26.4875

Rhynuie shieling	1741-60	26.0207	0.33	8.8	5	0	0	0	0	0	0	7102667	1	1	0	0.115	23.669
Rhynuie shieling	1761-80	24.3185	1.00	12	5	0	0	0	0	0	0	7705333	0	1	0	0.144	26.0207
Rhynuie shieling	1841-60	19.5475	2.81	19.3	5	0	1	0	0	0	0	14866000	0	1	0	0.159	17.9913
Rhynuie shieling	1861-80	25.471	3.96	17.52	1	0	1	0	0	2	0	18776300	0	1	0	0.172	19.5475
Rhynuie shieling	1881-1900	20.5672	3.70	28.8	1	0	0	0	0	0	0	24402700	0	1	1	0.136	25.471
Rhynuie shieling	1901-20	18.61875	5.16	64.2	1	0	0	0	0	0	0	30515000	1	1	1	0.211	20.5672
Rhynuie shieling	1921-40	12.7582	5.69	57.13	1	0	0	0	0	0	0	35230200	0	1	1	0.188	18.61875
Rhynuie shieling	1941-60	17.0605	13.61	136.54	1	0	0	0	0	0	0	39200600	1	1	1	0.232	12.7582
Rhynuie shieling	1961-80	13.1775	24.09	288.67	1	0	0	0	0	0	0	43983300	0	1	1	0.371	17.0605
Rhynuie shieling	1981-2000	13.49413	35.44	405.79	1	0	0	0	0	0	0	46623500	0	1	1	0.4	13.1775

ENDNOTES.

[i] There is thus no reason to suppose that a sample selection bias is introduced, since a priori there is no reason to suppose that sites which are more intact in terms of their pollen records will have systematically higher or lower levels of biodiversity over time.

[ii] Samples were taken from small flushes and mires, rather than large blanket peat or raised mire sites in order to provide records which are sensitive to ecological change on the scale of farm fields.

[iii] Although we only run the model from 1600 to 2000 due to the lack of historical sources prior to 1600, the pollen data is in fact available back as far as 5500 years ago for one of our sites. .

[iv] The 18th century saw the gradual replacement of native sheep breeds in Scotland with two new “imports”: the Cheviot and Blackface sheep. These rapidly spread through Scotland during the 18th and 19th centuries [13]. Cheviots were favoured for the higher price their wool could command, whilst blackfaced sheep were hardier than native breeds and could be over-wintered on the hill. Both new breeds also had bigger carcase weights than native breeds. Due to differences in their grazing behaviour, dry matter intake and length of time on the hill, the introduction of both breeds could be expected to have an effect on plant cover. Cheviots reached their peak in terms of geographic coverage of Scotland in the 1860s – 1870s, from when they were gradually replaced by blackfaced sheep and cross-breeds. Their decline is attributed to an over-extension of geographic range, falling wool prices due to imports from Australia and New Zealand, and changing preferences for sheepmeat. Note that we were unable to model the effects of wool prices due to a lack of data.

v We note that although B_{it} is estimated with 95% confidence intervals, there is no good reason to assume that this measurement error in the dependent variable of our model is correlated with the independent variables. Hence, there should be no bias in our estimates resulting from this error (see e.g. [50], p.71-72).

[vi] Our 2SLS estimator here is essentially the fixed effects 2SLS estimator whose properties are discussed in e.g. [15] and [8]).

[vii] In addition, important biases are introduced in the estimates for the coefficients of prices if we append the site dummies in the error term. Estimating the model by error-component 2SLS (see [8]), instead of fixed effects 2SLS, results in estimated coefficients for prices of about half the size of those reported in Table 2 – implying that a random effects panel would also lead to bias.